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Review article

Uncovering socioeconomic insights of solar dryers for sustainable agricultural product preservation: A systematic review

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A R T I C L E I N F O

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A B S T R A C T

This review explores solar dryers' use for agricultural products, focusing on their socioeconomic benefits in the community. Despite significant technical advancements in solar dryers, there is a notable lack of documentation regarding their socioeconomic impacts on society. This gap impedes awareness of the potential benefits of solar dryers, contributing to their low adoption rates and, consequently, limiting their overall impact on society. A decade of published articles from Google Scholar, Scopus, Embase, and Taylor and Francis were synthesized through content analysis to gather evidence on the socioeconomic benefits of this technology. The review found technical advancements from passive to hybrid systems, highlighting their potential to enhance drying efficiency, product quality, and economic, social, and environmental benefits. The evidence of the socioeconomic benefits, in particular, indicates that solar dryers can increase farmers' annual profits by $15,683, reduce drying operation costs by $757.31, and save up to 5 days of drying time. Furthermore, the study found that solar dryers contribute to environmental conservation initiatives by mitigating the emission of up to 430,714.76 tons of CO_2 in a year, minimizing overdependence on traditional energy sources, increasing energy accessibility, and optimizing drying space. However, the review identifies a need for further research to quantify solar dryers' impact on postharvest management, waste reduction, and job creation in the agricultural drying value chain. It also recommends involving society in technology co-creation and suggests that policymakers and practitioners incentivize their adoption through financial and non-financial support.

1. Introduction

Solar drying technologies have emerged as a critical solution for addressing diverse challenges related to food security, economic sustainability, and environmental conservation [1]. The use of solar dryers complements global efforts to combat food insecurity, aligning with policies like agricultural intensification aimed at enhancing agricultural productivity [2]. The high rate of postharvest losses (PHL) highlights that food security initiatives cannot be achieved solely through investments in agricultural productivity [3,4]. Due to PHL, approximately 1.3 billion tons of harvested products that could have fed 2 billion people are lost yearly [5,6]. Despite numerous ongoing efforts to reduce postharvest losses (PHL), innovative food preservation solutions, such as the use of improved drying technologies require special prioritization in tackling the increasing rate of these losses [7,8]. This is particularly important as the technologies align with traditional drying techniques of preserving agricultural products used for ages [9]. By removing excess

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moisture, drying inhibits microbial activity, extending the product's shelf life, and thereby reducing post-harvest losses [10]. Beyond post-harvest management, improved drying technologies can facilitate the storage and easy transportation of agricultural goods, positively impacting the communities' socioeconomic transformation [11].

In developing countries, the existence of a PHL rate of up to 50 % is associated with poor infrastructure and the use of poor post-harvest handling technologies [12–15]. Its impact accounts for the existence of 22.5 % of the population with famine and hunger and budgetary expenditure amounting to $13,336.8 million in a year for food importation [16–18]. The persistence of high post-harvest losses in these countries is largely driven by the widespread use of traditional open-sun drying for food preservation [19,20]. Traditional open-sun drying while accessible, often fails to adequately prevent spoilage and contamination of dried products, thereby contributing to significant losses of farmer incomes by up to 34 % [21,22].

Substantial resources have been invested to overcome these shortcomings by enhancing drying technologies such as solar drying, radiation, freeze drying, microwave and radiofrequency drying, osmotic drying, dielectric drying, spray drying, microencapsulation, and nanotechnology [23–25]. However, because drying is an energy-intensive process, mechanical drying technologies face significant criticism from a sustainability perspective. Studies indicate that approximately 30 % of the world's energy is used for drying food products, contributing to 30 % of global greenhouse gas emissions in the process [26–28]. In this context, solar drying technologies that utilize renewable energy sources emerge as a critical solution in sustainable food preservation [29–31]. Their advantages lie in the fact that the technology can be manufactured using locally available materials and primarily optimizes free and environmentally friendly solar radiation from the sun [32,33]. These advantages position solar dryers as a valuable tool for addressing multiple Sustainable Development Goals (SDGs), particularly those focused on poverty reduction, food security, sustainable agriculture, and environmental conservation. Specifically, this technology supports SDG 1 by improving the income of smallholder farmers, SDG 2 by enhancing sustainable food preservation, SDG 7 through optimization of clean renewable energy sources, SDG 8 through diversifying income generation activities in rural communities, and SDG 12 through converting biowaste to energy in drying process [34–37].

The fundamental components of a basic solar dryer include solar collectors and drying chambers, which are either separate or combined units [38]. Technological advancements have further developed solar dryers into four main types: direct, indirect, mixed, and hybrid-mode dryers, each offering unique improvements in drying efficiency and its associated benefits [39,40]. However, despite these advancements, the low adoption rate of solar drying technology remains a significant concern, prompting researchers to investigate further [20]. Low adoption is associated with various technical, operational, financial, and social barriers, such as low drying efficiency, dependence on weather conditions, high acquisition costs, and limited public awareness of the technology's availability and benefits [20,21,35,41–43]. Efforts to address these technical and financial challenges, including utilizing locally available renewable energy sources and materials, have shown progress. Yet, limited awareness among potential users persists as a major barrier to widespread adoption [44,45]. Moreover, while technical advancements are well-documented, relatively few studies focus on understanding the technology's socioeconomic impacts on communities, leaving an important area of research largely unexplored [46–48].

The study conducted by Ref. [49] to highlight the current status of solar dryers and their potential in Africa reveals a conspicuous gap in research, particularly in studies targeting the social acceptance of solar dryers among end users. Similarly [50], while focusing on emerging trends in hybrid solar dryer development, tried to highlight the economic viability of solar dryers, but their analysis fails to document the evidence on solar dryers' socioeconomic potential to significantly impact the lives of individuals. Furthermore [29], documents the advancements made in solar dryer technology, particularly in terms of thermal performance, economic sustainability, and environmental benefits. Their analysis emphasizes only energy cost reduction and carbon dioxide mitigation as the economic and environmental benefits of solar dryers. In this perspective, their analysis created an empirical gap in considering and extensively discussing all the economic, social, and environmental benefits that can be generated by this technology. This gap in research hinders our understanding of the broader impact of solar dryers and obstructs the development of strategies to maximize their adoption rate to widen their benefit potential to the wider community.

Hence, this study explores the growing field of solar drying technologies, with our focus extending beyond technological descriptions to present their broader impacts on society. We aim to provide valuable insights for researchers, policymakers, and practitioners alike on the potential of solar dryers in society's socioeconomic transformation in alignment with SDGs. As we navigate this innovation field, we explore the economic benefits arising from the use of solar dryers, their potential for environmental conservation, and their capability to boost social inclusiveness in society. All this exploration aims at addressing social acceptance and adoption challenges, recognizing that successful transfer hinges on community engagement, knowledge dissemination, and cultural context. Additionally, we aim to shed light on the areas that need further investigation to estimate the technology's wider impact on society.

2. Materials and method

2.1. Selection process and the information sources

To attain its objective, this study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method for identifying and selecting articles to be reviewed. The PRISMA framework is commonly used to outline the process of identifying, selecting, and excluding articles, aimed at enhancing the reporting quality of systematic reviews and meta-analyses [51]. Effective adherence to PRISMA guidelines ensures a transparent and complete reporting of the review process, including the methods used for searching, selecting, and synthesizing evidence from the literature with the minimization of selection biases [52]. Despite the method being originally designed for clinical studies, it has recently gained popularity in reviewing non-clinical studies since it helps to uphold high standards in the review process [53–56].

The articles reviewed in this study were sourced from Google Scholar, Scopus, Embase, and the Taylor and Francis electronic databases. These databases were considered for their inclusion of high-quality, freely accessible publications from a variety of journals. Initially, the search process yielded 341 documents: Scopus produced 139, Google Scholar 94, Embase 72, and Taylor and Francis 36. An initial examination excluded 85 duplicate documents, leaving 256 records for screening. A closer review excluded 29 articles that did not include 'solar dryer' in their titles, 11 review articles, 5 records without publication years, and 1 thesis. Subsequently, the abstracts of the remaining 210 records were thoroughly reviewed to assess their relevance to the study. This process led to the exclusion of 116 additional articles, leaving 94 for a comprehensive assessment. Following this in-depth review, 56 studies were excluded for focusing on non-agricultural solar dryers, resulting in 38 studies. These final 38 studies were critically analyzed, and evidence of the social, economic, and environmental benefits of solar dryers was collected, presented, and discussed in this article. Fig. 1 summarizes the selection and screening process for the articles included in this study.

2.2. Search strategy and eligibility criteria

The use of Boolean operators and the established eligibility criteria enabled the revision of the most relevant articles in this study. The keywords used to search for articles were solar drying, solar dryer, economic, benefits, environmental, and income. During the search process, these keywords were connected using Boolean operators to help collect the most relevant literature and evidence related to the research question. The initial iteration connected "solar drying" AND "economic," followed by subsequent iterations. Original journal articles were selected because they had the potential to produce up-to-date information, underwent an intensive peer review process, and are available in open access compared to other types of articles. The eligibility criteria employed in this article are presented in Table 1.

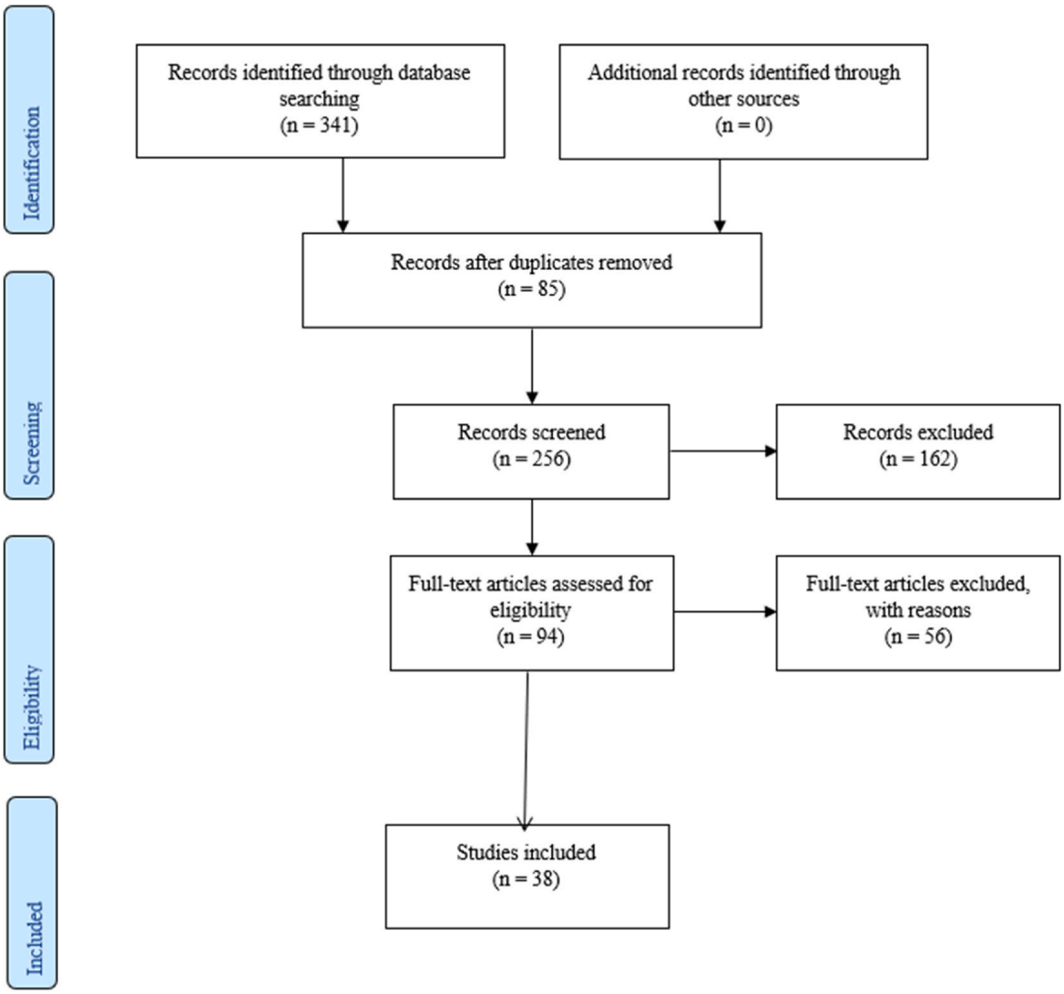

Fig. 1. PRISMA 2009 flow diagram of the selection and screening process of reviewed articles.

Table 1
Criteria used in the selection of reviewed articles in this study.

Criteria	Eligibility	Exclusion
Types of articles	Original journal article	Book chapter, Conference paper, gray articles, Reviews, Conference reviews, Letters, etc.
Language	English	Non-English published article
Publication year	From 2014 to October 2024	Articles published before 2014 and after October 2024
Publication stage	Final publication article	Articles in press/Accepted manuscript
Access	Open access and Research4life platform	Non-open, and non-Research4Life access articles

2.3. Data collection and synthesis

After the final selection of articles to be included in this review, the study engages in content analysis to extract data from each included article. The use of content analysis has gained popularity in addressing multidimensional qualitative issues [57]. This analysis focused on extracting data regarding the acquisition costs of solar dryers and their economic, social, and environmental benefits to society. From an economic perspective, the study examines factors such as drying costs, profit maximization, market price enhancement, and additional income generation opportunities for communities. Socially, the study highlights the impact of solar dryers on enhancing inclusivity in modern drying technologies, access to renewable energy in rural areas, and time savings for other socioeconomic activities. Environmentally, it aims to document their potential to mitigate environmental degradation by reducing carbon emissions, lowering dependency on traditional energy sources, and optimizing waste utilization within the circular economy frameworks. The benefits synthesized from the selected articles were organized into four categories of solar dryers, with each category individually assessed to collect the data necessary to meet the study objectives.

2.4. Methodological limitations

Despite this study successfully collecting and reviewing a substantial number of documents from various journals, it is limited to peer-reviewed articles published between 2014 and October 2024. It is furthermore limited to open-access articles and articles accessed under the Research4Life platform. The reliance on these articles may have excluded socioeconomic advancements reported in sources such as books and other subscription-based journals. Additionally, restricting the review to English-language publications may have overlooked valuable insights on socioeconomic benefits and developments in solar dryers reported in non-English sources. These methodological limitations, highlight the need for future studies to include a broader range of databases to include other subscribed-based journals to enhance the depth and breadth of the evidence on the socioeconomic impacts of solar dryers in the community.

3. Results and discussions

3.1. Distribution of publications from various countries

Scholars from various countries have worked on socioeconomic studies of solar dryers to determine their viability in the post-harvest management of agricultural products. Researchers from 14 different countries have contributed to the socio-economic analysis of solar dryers. Among the final articles reviewed, authors from India demonstrate a strong focus on showcasing the socioeconomic potential of various solar dryers. Key areas of emphasis in these studies include addressing technical and financial barriers to solar

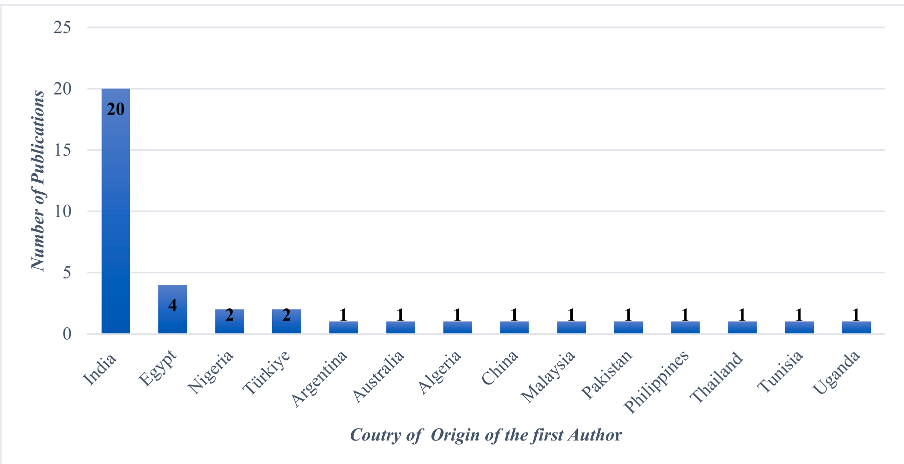

Fig. 2. Articles on socioeconomic studies of solar dryers by authors from various countries.

dryer adoption, assessing the environmental impact of solar dryers on the atmosphere, and exploring the social benefits that the technology can bring to communities [26,33,45].

In total, 20 articles were published by authors from India, 4 from Egypt, 2 from Nigeria, 2 from Türkiye, and one each in the remaining 10 countries, as summarized in Fig. 2. The substantial volume of publications from India has been influenced by the abundant solar radiation found in the country and by the financial incapability to access other mechanical agricultural drying technologies [58]. Researchers in other countries have similarly focused on addressing the limited availability and unsustainability of fossil fuels used to power mechanical drying technologies [59]. Many researchers across various countries believe that this technology is applicable in both developed and developing nations, as evidenced by the available articles from these regions. From this perspective, the advantages of solar dryers over conventional drying technologies and traditional open-sun drying methods should be widely communicated to enhance its adoption and thus minimize postharvest losses for the communities' socio-economic transformation [21,32]. However, further socio-economic research that includes community engagement on a global scale needs serious consideration to strengthen the justification for using renewable energy-powered drying technologies. The lack of community engagement studies contributes to low awareness of these technologies, which, in turn, affects their social acceptance. Case studies demonstrate that inclusive technology development fosters critical social alignment, leading to their broader adoption [60].

3.2. *Classification of the reviewed articles in the four categories*

Over the past decade, the analysis of the socioeconomic benefits of solar dryers has emerged in all four categories of solar dryers, as summarized in Fig. 3. However, the primary focus (44.7 %) has been on hybrid solar dryers, reflecting a strong intention to improve the technology's ability to dry agricultural products in the absence of solar radiation. Successfully operationalizing solar drying technologies under adverse weather conditions would make them a reliable and sustainable close substitute for fossil-fuel-powered dryers [37].

3.2.1. *Hybrid solar dryers*

Literature reviews of solar dryers over the past decades demonstrate that hybridizing solar dryers with thermal storage materials and supplementary energy sources is feasible for sustaining food preservation in society. Some of the explored thermal energy storage included batteries, hot water tanks, barium hydroxide octahydrate, waste stone chips, and paraffin wax [39,44,61–64]. Additionally, the integration of additional energy sources, such as a heat pump (Fig. 4), biomass (Fig. 5), geothermal heat exchangers, and electricity, was explored to enhance the continuous drying process of the dryers [37,65,66]. The use of thermal energy storage materials has demonstrated the enhancement of their drying efficiency and extended drying time by up to 5 h without direct solar radiation [61,67]. Further research into thermal energy storage materials is essential to extend drying times beyond the 5 h typically observed in most studies, allowing for continuous drying of high-moisture products even in the absence of sunlight. However, reliance on solar radiation for drying energy restricts the effectiveness of these innovations in challenging weather conditions, making them less feasible commercially.

Conversely, incorporating additional energy sources such as biomass and geothermal heat has proven effective in overcoming the challenge of intermittent solar radiation, ensuring continuous drying operations even when solar radiation is unavailable [37,66]. While integrating geothermal heat exchangers into solar dryers has proven techno-economically viable, this innovation is geographically constrained to regions with accessible geothermal resources, limiting its broader scalability [68]. However, the integration of biofuels, such as biomass and biogas, into this technology, provides broader scalability since these energy sources are accessible in all regions [37]. Although biomass combustion emits carbon dioxide, it is still considered a renewable resource due to its carbon-neutral lifecycle, resulting in a net-zero balance of carbon dioxide emissions [37,69]. Biogas, on the other hand, mitigates greenhouse gas emissions by capturing methane from organic waste, preventing its release into the atmosphere, and promoting a circular economy by turning waste into a valuable resource [70,71].

3.2.2. *Indirect mode solar dryers*

Indirect-mode solar dryers have continued to gain relevance in drying agricultural products. Out of the reviewed literature, 26.3 % of all the articles assessed and presented the potential of this mode in enhancing economic, social, and environmental benefits to

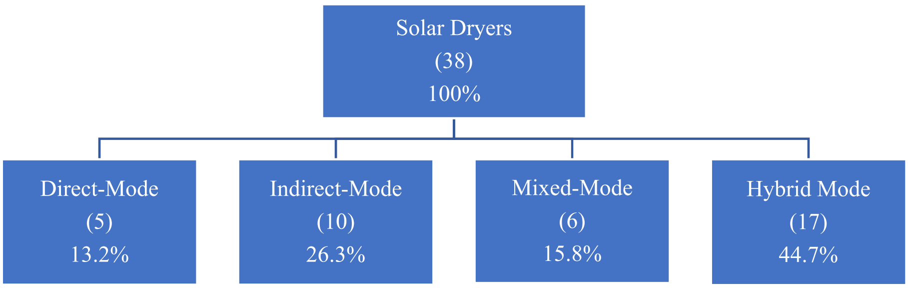

Fig. 3. Classification of reviewed articles presenting the socioeconomic benefits of solar dryers.

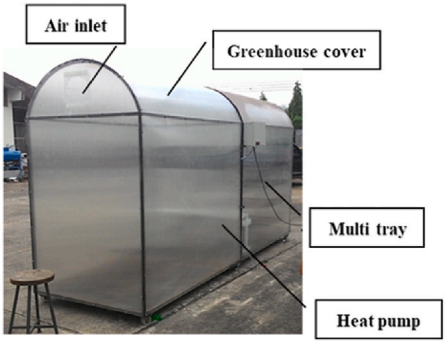

Fig. 4. Experimental setup of the solar-assisted heat pump dryer.
Source: [40].

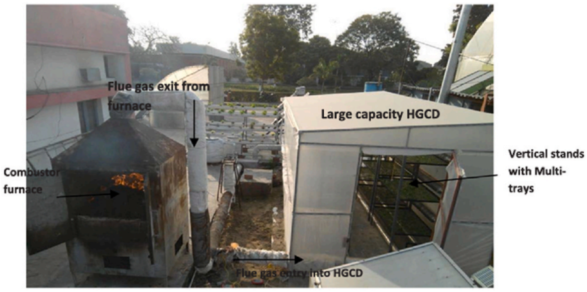

Fig. 5. Pictorial view of solar-cum-biomass hybrid greenhouse crop dryer.
Source [37].

society. An indirect-mode solar dryer usually consists of a solar heat collector, a heat exchanger to transfer the collected heat to the drying chamber, and a drying chamber. Heat from the exchanger can either be transferred to the drying chamber in active mode (Fig. 6) or passive mode (Fig. 7). The drying chamber and solar air collector in an indirect solar dryer can be installed separately or integrated into a single unit [38,72,73]. With advancements in digital technologies and the Internet of Things (IoT), the solar air collector can be designed to be either fixed or flexible, enabling it to track the non-stationary movement of the sun [74]. The flexible

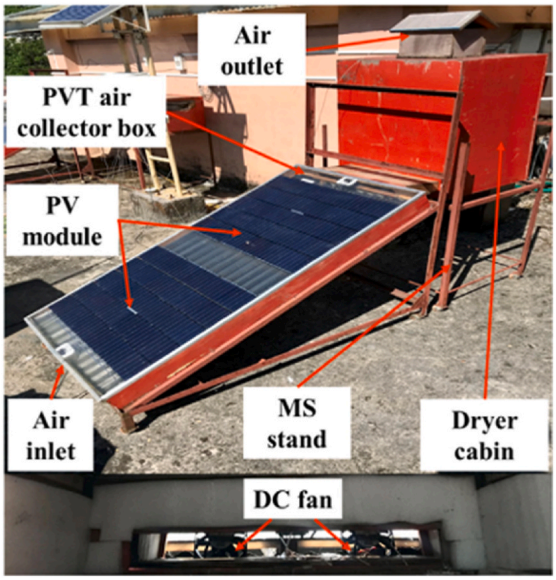

Fig. 6. An active-mode Indirect solar dryer.
Source: [72].

Fig. 7. Passive-mode Indirect Solar Dryer.
Source: [77].

solar air collectors have the potential to enhance the drying efficiency of solar dryers due to their ability to optimize solar radiation throughout the day [75]. Generally, indirect-mode solar dryers provide a considerate constant air temperature for drying agricultural products placed in an opaque drying chamber [76]. Since there is no direct exposure of the dried products to sunlight, these innovations usually produce high-quality dried products making them appealing for drying high-quality products [22].

3.2.3. Mixed mode solar dryers

Mixed-mode solar dryers combine the principles of both direct and indirect solar drying methods to optimize efficiency and practicability in drying agricultural products. The practicability of this mode has been observed in the last decade, with 15.8 % of the reviewed studies focusing on assessing its socioeconomic influence on society [1,78–80]. The materials used in designing the drying chamber can either be greenhouse materials (Fig. 8) or cabinet materials (Fig. 9) to develop a mixed-mode greenhouse dryer and cabinet dryer, respectively. By combining these methods, mixed-mode solar dryers can maintain a consistent drying environment while maximizing energy utilization and product quality. This innovation offers a balanced approach that enhances drying performance, product quality, and energy efficiency while being adaptable to small and large-scale needs [80,81].

3.2.4. Direct-mode solar dryers

Direct-mode solar dryers have consistently demonstrated their effectiveness in drying agricultural products over the past decade. While this innovation in comparison with open sun drying maintains a constant drying temperature within the drying chamber, it raises quality concerns due to the direct exposure of the dried products to sunlight [82,83]. The transparent drying chamber of this innovation can be designed in either a cabinet or greenhouse style (Figs. 10 and 11), making it suitable for drying high-moisture

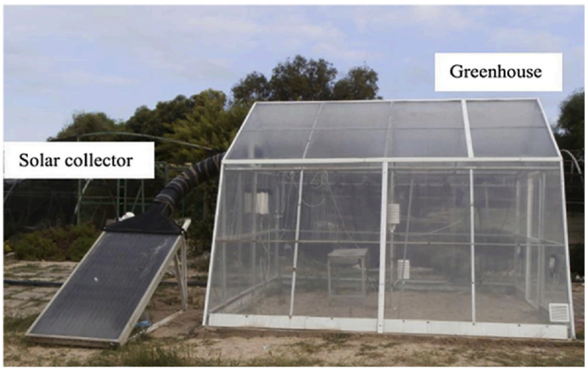

Fig. 8. Pictorial view of a mixed-mode greenhouse dryer.
Source [80]:

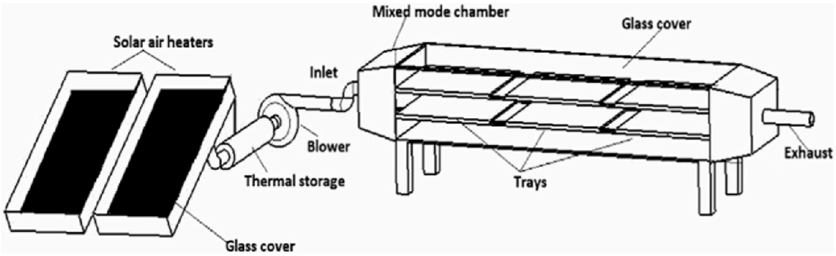

Fig. 9. Schematic diagram of an active mixed-mode cabinet solar dryer.
Source: [79].

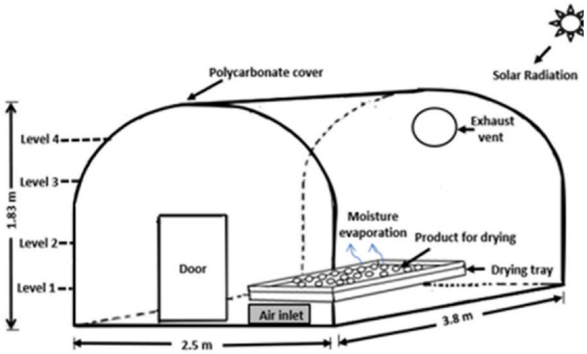

Fig. 10. Schematic representation of greenhouse solar dryer for agricultural products.
Source: [33].

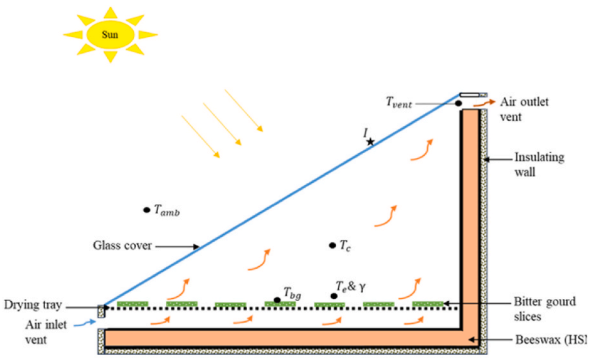

Fig. 11. Schematic of a beeswax-packed domestic solar dryer for domestic use.
Source: [34].

agricultural products [33,49,84]. However, if a direct-mode solar dryer is used to dry products with normal moisture content, the final dried product may be deteriorated in quality, leading to potential losses for users [73]. The analysis of this innovation in the last decade extends beyond its technical efficiency, with 13.2 % of the reviewed articles focused on its socioeconomic benefits to society [33,85]. However, despite its potential for both small-scale and large-scale drying, a major limitation of this design is that the intermittent nature of solar radiation makes the innovation technically infeasible in the absence of sunlight.

3.3. Solar dryer acquisition costs

High acquisition costs have been observed to be one of the barriers for smallholder farmers to adopt improved solar dryers [21]. In response to this challenge, researchers have directed their efforts toward minimizing dryer acquisition costs by optimizing the use of locally available materials [86]. Despite design simplicity being believed to offer greenhouse dryers the most cost-effective solution [33], the materials used and capacity are two important variables in determining dryer development costs. Considering a study conducted by Ref. [33], a total of $2631 was used to develop a greenhouse solar dryer capable of drying 100 kg of fruits and vegetables per batch. Similarly, within the same country [1], spent $6712.31 developing a greenhouse dryer with the capacity to dry 300 kg of agricultural products per batch, while [80] spent $1250 to develop a greenhouse dryer with the capacity to dry 222 kg of red pepper annually in Tunis.

Moreover, contrary to the common belief that hybrid solar dryers are excessively costly [45], demonstrated through their research focused on smallholder farmers that it is indeed possible to construct two solar dryers for a total cost of less than $200. Similarly [67], utilized $204.6 to create a 5 kg a mixed-mode hybrid solar dryer, integrated with paraffin wax as a phase change material. In contrast [37], invested $6785 in the development of a large-scale forced convection solar-biomass hybrid dryer for drying fenugreek leaves.

Table 2 summarizes some of the dryers' acquisition costs developed in different countries with different drying capacities. These examples highlight the substantial efforts to reduce the acquisition costs of solar dryer technology, particularly emphasizing how drying capacity influences total costs. The findings suggest that advancements in solar dryers present a significant opportunity for enhancing technological inclusivity, catering to both small-scale and large-scale farmers based on their specific needs. The availability of low-cost solar dryers, with expenses comparable to those of materials for open-sun drying, emphasizes the importance of raising awareness about the technological and their financial feasibility among individuals who perceive them as prohibitively expensive [34, 65]. The awareness campaign can be customized to target individuals with similar socio-economic and psychographic characteristics to have impactful strategies in their adoption within the communities [87].

3.4. Economic benefits of solar dryers

Economic gains from technology often play a pivotal role in guiding decision-making processes regarding its adoption and overall acceptance. Concerning economic gain, adopters mainly consider how technology can directly impact their income, productivity, or quality of life [89]. Theories suggest that a technology can be adopted if it promises greater benefits than its alternative [90]. In the drying process, competing alternatives to solar dryers include conventional powered dryers and the traditional open sun drying method [32,33]. This implies that, for solar dryers to be considered the best alternative, they must perform better economically than traditional open sun drying and conventional drying technologies.

3.4.1. Common methodology for estimating economic benefits of solar dryers

Before quantifying the economic benefits of solar dryers, it is essential to review the methodologies used to present these benefits. The goal is to ensure accuracy and guide decision-makers in making informed choices of the technologies. In the solar dryer field, the annualized cost and lifecycle savings methods have been the predominant approach for evaluating their economic viability [33,65,80]. This method typically estimates the costs and benefits of drying technologies over their useful life. While many of these technologies are economically feasible, important costs and benefits are often omitted. In most cases, the use of annualized cost-benefit methods limits the evaluation to factors such as annualized capital costs, maintenance costs, salvage value, fuel costs, and operating expenses for blowers or fans [32,79].

However, the post-harvest costs of drying agricultural products go beyond the direct expenses typically assessed. They encompass costs related to the transportation of fresh and dried products, labor associated with operating the technology, and expenses for preparation, loading, unloading, packaging, and branding. Including these factors in economic viability assessments enables a more precise estimation of the feasibility of innovative solar drying technologies, especially in field applications. Additionally, the benefits of such technologies extend beyond the per-unit cost savings estimated over the dryer's lifespan. For instance, savings arise from reduced transportation of undried products and minimized waste when drying is applied. This underlines the importance of a comprehensive methodological approach that accounts for all associated costs and benefits in the drying process.

Table 2
The summary of the dryers' investment costs from some selected articles.

No	Source	Country	Dryer Type	Dryer's Capacity	Dryer Acquisition Costs
1	[33]	India	Direct-Mode Solar Dryer	A greenhouse solar dryer with the capacity to dry 100 Kg of fruits and vegetables.	Acquisition costs were US$ 2631
2	[1]	India	Mixed-Mode Solar Dryer	A greenhouse dryer with the capacity of loading 300 Kg of turmeric was developed and investigated.	The investment cost was US$ 6712.31
3	[22]	India	Indirect-Mode Solar Dryer	A portable cylindrical solar dryer with the capacity to dry 50 Kg of cob maize.	Capital costs were US$ 581.9.
4	[38]	India	Indirect active solar dryer	The capacity is 45 Kg to dry fenugreek leaves and turmeric.	Investment costs were US$ 671.1
5	[80]	Tunisia	A mixed-mode greenhouse solar dryer	The capacity of drying 222 kg of red pepper and 250 Kg of grape in a year.	Dryer's Acquisition costs were found to be US$ 1250
6	[88]	Algeria	Hybrid solar dryer	A 5 Kg capacity to dry onions.	The capital cost of the dryer was US$ 373.13
7	[62]	Malaysia	Hybrid greenhouse solar dryer	A 1400 Kg capacity to dry kenaf.	The Capital cost of the dryer is US$ 57,870
8	[40]	Thailand	Hybrid greenhouse solar dryer	The capacity of drying 10 kg of chili pepper.	The capital costs were US$ 568.75
9	[67]	India	Hybrid cabinet solar dryer	The capacity of drying 5 Kg of bitter gourds.	The capital costs were US$204.6
10	[34]	India	Direct-Mode solar dryer	The capacity of drying less than 1 Kg of bitter gourds	The capital costs were US$ 35.42

3.4.2. Economic benefits of solar dryers

Solar drying technologies have gained significant attention in recent years due to their potential to enhance the economic viability of agricultural operations. As innovations in solar drying continue to evolve, they have become increasingly accessible to small-scale and large-scale farmers alike, driving reductions in operational costs while supporting sustainable practices [34,62]. Details of the economic benefits of solar dryers are presented below, highlighting key factors such as cost savings, increased productivity, improved product quality, and broader financial gains from adopting these technologies.

3.4.2.1. Reducing drying costs. Advancements in solar dryers have contributed to sustainable income growth for users by reducing both acquisition and operational costs. For example [91], demonstrated the economic benefits of solar drying technologies, showing that it is more cost-effective to acquire and operate solar dryers compared to electric convective dryers. Their study found that a natural convective solar dryer was 45 % cheaper to purchase than an electric convective dryer, which also requires substantial operating costs, amounting to $0.86 per kilogram of dried products. Similarly [33], concluded that the per unit cost of drying tomatoes, carrots, or bitter gourd is significantly lower using a solar dryer compared to an electric dryer. Specifically, they reported costs of $0.37, $0.11, and $0.16 for solar drying these vegetables, compared to $2.50, $0.77, and $1.05 per kilogram with an electric dryer, respectively. These findings highlight the substantial economic advantages of solar drying over conventional electric methods and emphasize its potential to enhance user income and profitability by lowering the acquisition and operational expenses.

3.4.2.2. Maximizes savings/profits. The use of solar dryers in drying operations has been reported to maximize lifecycle savings. The lifecycle cost and benefit analysis prove that the majority of investigated solar dryers in the last ten years have a positive net present value resulting from a positive saving per unit of dried product. The analysis done by Ref. [1], estimated that their new mixed-mode greenhouse solar dryer had a cumulative net worth amounting to $35,384.33 with a payback period of 1.1 years out of the dryer's lifetime of 20 years. With this capability, they further concluded that a user has the potential to improve its income generation by USD 4161.6 per acre of turmeric within a year. Similarly [79], concluded that their new solar dryer has the potential to accumulate a net savings of $12,738.5 over its useful life of 15 years with an internal rate of return (IRR) of 130 % and a payback period of 0.9 years. Despite these analyses being made in laboratory settings, they still offer the potential of solar dryers to enhance the income of smallholder farmers who are mostly characterized by low usage of technologies in postharvest handling. However, further investigations are recommended in engaging field experiments to validate and enhance these results [92,93].

3.4.2.3. Potential of generating additional sources of income to its users. The optimization of solar dryers presents an opportunity to expand income sources for users through the sale of additional energy produced during the drying process, as well as participation in carbon trading platforms. A study by Ref. [37] demonstrated the economic potential of generating excess energy, citing the sale of 240 kWh of electricity per day from a biomass combustor. Additionally, with the growing carbon market, solar dryers are recognized for their role in carbon mitigation. For example [72], estimated that a solar dryer with the capacity to mitigate 67.92 tons of CO_2 could generate $1018.79 in revenue through carbon credits. On a similar basis [94], estimated the mitigation of 20.2 tons of carbon dioxide with the potential of generating an additional revenue amounting to 56,700 Chinese Yuan ($7964.15) over the 35 years of their solar dryer's operation. However, due to low awareness and the voluntary nature of the carbon credit market in many developing countries, it remains challenging for users to fully capitalize on the carbon credit opportunity. Efforts are needed to raise awareness within communities and establish policy frameworks that acknowledge the carbon dioxide mitigation potential of solar drying technologies. Effectively optimizing this market will not only promote the adoption of solar dryers among individuals but also strengthen collective contributions toward minimizing the emission of greenhouse gases into the atmosphere.

3.4.2.4. Maximized production due to high drying efficiency. The drying efficiency of the solar dryer is one of the important parameters

Fig. 12. Tomato, Carrot, and Bitter guard dried under the solar greenhouse dryer vs. open sun drying technique.
Source: [33].

that enhance economic benefits to its users [73]. Compared to open sun drying, solar dryers offer higher efficiency due to the consistent heat distribution within the drying chamber. Despite the higher initial investment [62], demonstrated that hybrid solar dryers can generate an annual profit of $15,683, significantly higher than the $1560 from open sun drying. This is attributed to the hybrid dryer's ability to dry more kenaf fiber amounting to 30,336 kg, compared to only 7584 kg under the open sun method. Similarly [65], found that both active solar photovoltaic (SPE) and Indirect Passive Mode Solar Dryers (ISD) offer a higher Net Present Value (NPV) than open sun drying. These findings highlight the critical role of drying efficiency in determining and enhancing the economic benefits for users.

3.4.2.5. Market price enhancement due to high-quality dried products. By providing a stable, controlled drying environment, solar dryers have the potential to improve the quality of dried products compared to an uncontrolled environment under open sun drying (Fig. 12). The superior quality of solar-dried products increases their market value, allowing them to be sold at higher prices [33]. This price premium enhances the economic benefits for users by maximizing their financial savings in the agricultural drying process [72,77]. High-quality solar-dried products have been identified using numerous techniques including color change and appearance, chemical composition, bacteria composition, and elasticity [44,78,85]. From this perspective, the use of solar dryers has to be widely promoted since the technology not only improves product quality and economic returns for users but also contributes to sustainable agricultural practices through energy efficiency.

3.5. Social benefits of solar dryers

Integrating social sustainability into assessing technological benefits has become essential for the collective achievement of global SDGs [55]. This approach aims to measure the broader impact of technology on communities and individuals beyond economic gain, evaluating its contributions to social protection, health, safety, and inclusivity [95,96]. Understanding these social benefits informs policy and funding decisions, encouraging the adoption of technologies that support community development, build resilience, and contribute to long-term societal goals. Solar dryers align well with this approach, offering significant potential to enhance rural livelihoods, expand energy accessibility, and improve resilience in food preservation [66,80]. Highlighting these benefits will help position solar dryers as a responsible innovation that meaningfully supports social welfare. Details of the social benefits of solar dryers evidenced from the last decade's publications are presented and discussed in the below subsections.

3.5.1. Optimization of drying space

The growing population has intensified competition for limited drying space for agricultural products. Solar dryers offer a viable solution to this challenge, as they require substantially less space than traditional open sun drying methods. Research by Ref. [80] demonstrated that solar dryers require only 14.8 m^2 to dry a specific quantity of produce, in contrast to 120 m^2 needed for open sun drying. This difference presents a potential solution for minimizing land conflicts in densely populated areas. Similarly, findings by Ref. [63] confirm that hybrid solar dryers require considerably less space than open sun drying, emphasizing their sustainability in the context of land scarcity. This significant reduction in required space makes solar dryers not only suitable for densely populated areas or regions with limited land for agriculture but also enhances the effective utilization of available drying space.

3.5.2. Increasing energy accessibility in Off-grid areas

Optimizing locally available resources highlights the importance of solar dryers in promoting social inclusivity within modern agricultural technologies. In many rural areas, accessing grid electricity for domestic and farming activities remains a significant challenge. However, since solar dryers operate independently of grid power, they can be utilized effectively by individuals in both rural and urban settings [22,72]. This independence not only broadens access but also enhances social inclusivity in agricultural product drying across diverse communities. Moreover, optimizing hybrid solar dryers enables the generation of excess energy, which can be redirected to support other electricity-dependent activities [37]. These advancements position solar drying as an effective technology for reducing disparities caused by limited grid electricity access, thereby improving the quality of life in rural areas.

3.5.3. Reducing drying time

With their high drying efficiency, solar dryers have the potential to significantly reduce drying times, allowing users to allocate more time to additional socioeconomic activities. This increased efficiency not only boosts productivity but also enhances opportunities for income generation and community engagement. A study by Ref. [37] demonstrated that it is indeed possible to dry agricultural products during the winter season and the process can save up to 12 h in comparison to open sun drying when drying fenugreek leaves. Similarly [22], reported that cylindrical solar dryers enable users to save 26 h when drying maize cobs to the recommended moisture level, compared to traditional methods. Moreover [74], concluded the possibility of saving up to 5 days when using an active indirect solar dryer instead of the open sun method to dry date fruits in Egypt. These examples highlight the considerable time savings that solar dryer users can gain, allowing them more flexibility to engage in other social and economic activities.

3.6. Environmental benefits of solar dryers

Increasing environmental stress has made it critical to invest in technologies and practices that prioritize conservation. These efforts must be implemented collectively at both local and global levels to meet the 1.5 °C global warming target [97]. Solar dryers exemplify modern sustainable designs, emphasizing the need to integrate environmental preservation into technological innovations [55]. This technology not only reduces greenhouse gas emissions but also decreases pressure on traditional fossil fuels [61]. Additionally, it utilizes biomass waste as an energy source during the drying process, further enhancing its environmental benefits [71]. The technology's environmental and ecological benefits are quantified using a well-known Life Cycle Assessment (LCA) method which accounts for the environmental and ecological impacts of a product, process, or service in each stage across its entire life cycle [94,98]. This subsection examines the environmental benefits associated with advancements in solar drying technologies, focusing on net carbon dioxide reductions and the technology's potential contributions to the circular economy through the optimization of waste in food preservation.

3.6.1. Mitigating the emission of carbon dioxide to the atmosphere

Carbon dioxide contributes to more than 85 % of all greenhouse gas emissions in the atmosphere [99]. Substantial mitigation of this air mass plays a crucial role in minimizing the rate of global warming. Solar dryers, by harnessing clean solar energy for drying, have significantly contributed to carbon dioxide mitigation. The technology's CO_2 mitigation is measured by comparing the total carbon dioxide emitted from the production and operationalization of solar dryers with the conventional energy sources that are commonly used in the drying process [100]. The specific energy required to dry per unit kilogram of pink lady apple in either solar dryer or conventional drying technologies is 7.414 kWh/kg for which if a solar dryer instead of a coal-powered dryer will be used to dry this product, a total of 30.76 tons of CO_2 will be mitigated within a 15-year lifespan of the dryer [26]. Similarly [86], reported that using a hybrid solar dryer to dry ginger rhizome instead of coal could prevent the emission of 430,714.76 tons of CO_2 annually. Moreover, they noted that switching from grid electricity and diesel to a solar dryer for the same product can reduce CO_2 emissions by 15.96 and 1867.62 tons per year, respectively. Moreover [22], confirmed that using an active mixed-mode cylindrical solar dryer, with a capacity to dry 50 kg of maize cobs per batch, has the potential to mitigate 1.22 tons of carbon dioxide emissions over its 10-year lifespan. The potential for substantial CO_2 savings, as demonstrated in drying processes for products like pink lady apples, ginger rhizomes, and maize cobs, highlights the environmental benefits of this technology over its lifespan and its contribution potential to the minimization of global warming.

3.6.2. Preservation of limited traditional sources of energy

Energy security and affordability are fundamental parameters for achieving global sustainability goals [31]. The use of solar dryers through the optimization of clean sources of energy has expanded individuals' energy options, reducing overreliance on traditional fossil fuels for drying technologies. A study by Ref. [22], demonstrated that using a solar dryer can save approximately 1352.97 kWh of electricity or 128.18 L of diesel annually when drying cob maize. Similarly [61], concluded that a hybrid solar dryer for drying potato chips could save around 5604 kWh of electricity or 555.06 L of diesel each year. These findings prove the significant potential of solar dryers to enhance energy diversity, thereby supporting global energy security and sustainability objectives.

3.6.3. Optimizing waste for drying agricultural products

The circular economy model, which has recently gained global traction, emphasizes the responsible and cyclical use of resources to address environmental challenges such as resource depletion, pollution, and climate change [101]. Solar dryer technology has earned special recognition for its role in cyclical use of resources such as biomass waste. Biomass can be used either as a solid fuel or converted into biogas to enhance the solar dryers' operations. A study by Ref. [37] demonstrated the technical feasibility of using biomass to support continuous drying, even in the absence of solar radiation. Moreover, the integration of heat pump technology into solar dryers allows for the recovery and reuse of heat lost during the drying process [40]. These innovations while addressing the intermittent solar radiation in the drying process, align the technology with the principles of the circular economy, thereby improving environmental sustainability.

3.7. Roles of practitioners and policy makers in enhancing the adoption of solar dryers in rural areas

This study has noted the significant efforts of researchers in addressing technical barriers to the adoption of solar dryers. We have noted a technical and economically viable solar dryer in works around the clock even in the absence of solar radiation. However, these advanced initiatives will be meaningful if significant efforts have been made by practitioners and policymakers to address their adoption gap. Practitioners and policymakers which are comprised of industry and the public sector under the quadruple helix model are important stakeholders in enhancing the technological adoption ecosystem [104]. In this study, we are recommending the following initiatives to be employed by these important stakeholders to enhance the adoption of solar dryers in the community.

3.7.1. Creating and implementation of supportive financial policies

Despite there are significant efforts to reduce solar dyer acquisition costs, still, the challenge remains for the majority of rural farmers who rely on ineffective traditional open sun drying for post-harvest management. Traditional open sun drying is considered a cost-effective technology for the majority of smallholder farmers in rural areas [105]. This highlights the need for policymakers to create and implement favorable financial policies that include subsidization of materials used in the development of solar dryers. This initiative will sustainable enhances the continued efforts to minimize the solar dryer's acquisition costs and make the technology affordable to smallholder farmers who are dominating the agricultural sectors of developing nations [106].

Furthermore, policy makers in developing countries should capitalize on the ongoing global efforts of crediting the use of renewable energy as an effective way of minimizing the emission of carbon dioxide into the atmosphere. Despite initiatives being underway, still, less has been focused on the users of solar dryers as potential contributors to these efforts. The estimation of carbon mitigated has focused on available forests in these countries with less focus on these individual efforts. It is expected that the recognition of users of solar dryers in the mitigation of carbon dioxide emissions will act as an important initiative to boost their use in the community following the possible additional income that will be generated.

3.7.2. Inclusive business model

There is also a need for practitioners to implement a diversity business model that will enhance the accessibility and affordability of the diverse communities in the use of solar dryers. This sustainable business model can be co-designed by the local community to suit their specific needs and social settings. One of the recommended inclusive business models is the service-based model that ensures users pay for the drying services which indeed can help to address the financial barrier in rural areas [21]. This is considered a sustainable business model compared to the common of organizing farmers into groups and in the end, their willingness to pay for co-owning the technology significantly declines [107].

3.7.3. Awareness and capacity building campaign

Awareness among smallholder farmers about the availability, use, and effectiveness of solar dryers for drying agricultural products remains low, significantly limiting their adoption in the community. This study recommends enhanced initiatives by policymakers and practitioners to increase technological awareness, particularly among those in the agricultural sector. Given the diverse levels of technological readiness within communities, awareness campaigns should incorporate various strategies, such as establishing solar dryer demonstration centers where farmers can directly observe and learn about the technology in practice [87].

3.7.4. Enhancing collaboration with local and international communities

Policy Makers and Practitioners have a significant role in enhancing the workable collaboration with national and international organizations in the technology-adoption ecosystem. The collaboration, can enhance outreach efforts, share expertise, mobilize funds, and learn best practices from other regions that have successfully enhanced the development and optimization of solar drying technologies. Furthermore, it can enhance the continued improvement of the technology based on the collected feedback from the end users to ensure they remain effective and user-friendly in society.

4. Key findings and future research agenda

4.1. Summary of the key findings

Over the past decades, researchers have made substantial efforts to enhance the sustainability of solar dryers from economic, social, and environmental perspectives. These efforts aim to build on the well-established technical viability of solar drying technology within communities particularly for drying agricultural products [102]. In this review, studies reveal a broad range of socioeconomic advantages associated with solar dryers, highlighting their impact on cost savings, environmental conservation, and enhancing rural livelihoods. Specifically, key findings and their implications from this review include:

i. Solar drying technology has demonstrated sustainable potential for preserving agricultural products in both developed and developing countries. Notably, India has shown a strong commitment to advancing solar dryers for food preservation, with 52.6 % of all reviewed articles authored by Indian researchers. This calls for researchers in other countries, particularly in developing nations where the rate of postharvest loss is alarming to invest in researching and practicing this cost-effective technology for postharvest management in a more sustainable approach.
ii. Solar dryers have evolved significantly, from passive designs to hybrid systems that enable the technology to operate round the clock. Since biomass and geothermal heat have proven effective as clean energy sources to enable continuous solar drying, there is a pressing need for researchers and practitioners to explore additional sustainable materials within the local contexts to further enhance their techno-economic efficiency and scalability potential in the community.
iii. Advancements in solar dryer technology have increased farmers' income, improved energy accessibility, and reduced greenhouse gas emissions by utilizing locally available materials and renewable energy sources. These developments underline the importance of promoting solar dryers as a sustainable, techno-economically viable alternative to traditional open sun drying and conventional drying methods.
iv. The common methodology for assessing the techno-economic viability of solar dryers overlooks several key costs and benefits that may impact their commercial scalability. It is essential to closely consider all associated costs and benefits of solar dryers throughout the agricultural drying value chain.
v. Notably, there is a critical need to expand socioeconomic studies beyond benefit assessment by considering the end-user to make the technology commercially viable. This initiative will enhance the understanding of the social and psychographic setting of a community toward the acceptance and long-term uses of technology [87,103]. Optimization of this approach through the guidance of adoption theories and models can significantly address the adoption gap across diverse community groups and foster a broader uptake of solar drying technology for sustainable postharvest management.

4.2. Future research agenda

While solar drying technology has shown potential for sustainable postharvest management, further research is needed to enhance its scalability across a wider range of communities. This study noted significant advancements from a technical standpoint, with less emphasis on broader socioeconomic perspectives. Socioeconomic studies are equally important, as they enable the co-creation of technologies and expand their scalability potential. Focusing solely on technical advancements creates a critical gap in the adoption process, as the design and features of the technology may not align with the needs of end users. Based on this observation, this study, therefore, recommends further research in the below areas listed in chronologic order:

i. Extensive Consideration of Costs and Benefits across the entire value chain of solar dryers' operations

Although economic analyses generally support the viability of solar drying technology, the use of the annualized cost method and life cycle saving analysis used by many studies have overlooked significant potential benefits and costs involved in the drying value chain. This study therefore recommends a thorough evaluation of all associated benefits and costs, including the potential of carbon credits, labor, transportation, equipment disposal, raw product preparation, and packaging of dried products. A comprehensive analysis across the drying value chain will better inform potential adopters about the feasibility of using solar dryers for post-harvest management. Overlooking key costs and benefits can jeopardize the practical success of solar drying technology in the field. A comprehensive assessment through value chain analysis is essential, alongside a cost-benefit analysis that compares solar drying with open sun drying and the direct sale of raw, undried products. Such an approach will clarify how effectively the technology enhances business viability by reducing post-harvest losses, improving product quality, and increasing market value, thus supporting more informed adoption decisions.

ii. Consideration of Created Employment Opportunities

While solar dryers offer employment opportunities through job creation, this important socioeconomic benefit has been largely overlooked in the literature. Most studies focus on employment opportunities during the development phase of solar dryers, often disregarding other critical phases such as their operational use and the preparation of drying materials [40,67]. Recognizing the potential of solar dryers to boost employment across their lifecycle can help policymakers and practitioners promote this technology as a viable intervention to address rising unemployment in many communities. Quantifying these employment benefits through value chain analysis across production and operational stages would provide valuable insights into the broader socioeconomic impact of solar drying technology on society.

iii. Community Engagement Studies Regarding the Adoption of Solar Dryers

It is indeed proved that solar dryers are techno-economic viable in the post-harvest management of agricultural products. However, there is a significant need to engage the community in the co-creation of this technology for its scalability potential. The co-creation can be attained through social studies focusing on uncovering individual, social, and Institutional barriers to the adoption of solar drying technologies. This review has noted that the majority of solar dryers are focusing on technological characteristics and left behind the end-users side. Considering customers in solar dryer development will significantly contribute to their adoption as case studies demonstrated that successful adoption requires technological alignment with the economic realities and daily routines of end-users to ensure they are both accessible and relevant [108]. This analysis can be done by examining factors such as user readiness, perceptions, and willingness to pay for the improved solar drying technologies. To achieve this, researchers can apply a mix of quantitative and qualitative methods, utilizing frameworks such as the Technology Readiness Index (TRI), Technology Acceptance Model (TAM), and Contingent Valuation Method [103,107,109]. Insights from these studies will inform targeted marketing strategies to boost adoption, contributing to the socio-economic transformation of rural communities.

iv. Quantification of Minimized Waste from Agricultural Products

Agricultural postharvest loss does not only affect the income of farmers, rather it contributes significantly to increased agricultural waste, which in turn drives environmental stress and associated waste management costs [110,111]. Since solar dryers have the potential to reduce these losses, documenting and quantifying the decrease in agricultural waste resulting from their use as well as the associated environmental and economic impact of waste management became an important area of consideration. This data will offer valuable insights into the environmental benefits of solar drying technology and support efforts to curb agricultural waste. Ultimately, these insights will advance sustainable development by addressing the environmental and economic repercussions of postharvest losses. This study can be conducted under the guidance of waste management and postharvest loss frameworks in the field of both environmental and agricultural management.

v. Field Experiment for the Quantification of the Impact of Solar Dryers on Postharvest Management

While the primary goal of solar dryers is to enhance postharvest management, most of the reviewed studies have yet to document the quantified data on their effectiveness in achieving this goal. It is indeed important to quantify the impact of this technology to have a clear measure toward SDG 2 by ensuring sustainable food production systems and resilient agricultural practices [112]. Unlike laboratory settings which are highly used in the reviewed studies, field experiments consider variables like weather fluctuations, crop varieties, and user practices that directly influence drying efficiency and product quality. This approach builds a more comprehensive understanding of solar dryers' scalability and practical value for improving food security and reducing waste. Impact evaluation techniques such as quasi-experiment designs which have gained the attention of intervention studies can perform better the analysis coming up with minimal biased findings [113].

5. Conclusion

Solar dryers, advancing from passive to hybrid designs, offer a promising solution for drying agricultural products. These technological advancements have proven the technology to be techno-economically feasible for drying agricultural products beyond sunny hours. This review informs policymakers, researchers, and practitioners on the effective use of this technology for sustainable food preservation, particularly in economic, social, and environmental dimensions. It is indeed demonstrated that solar dryers have the potential to offer significant economic benefits by enhancing farmers' incomes through reduced drying costs and increasing the market value of agricultural products. Socially, solar dryers improve rural livelihoods by providing accessible energy solutions and advanced agricultural technology, even in areas without reliable grid access. Additionally, solar dryers contribute to sustainable agriculture by lowering emissions and conserving natural resources, making them a valuable tool for climate change mitigation. Despite these benefits, low adoption rates highlight the need for expanded socioeconomic studies focused on potential end-users to foster community engagement and co-create the technology effectively.

CRediT authorship contribution statement

Dismas Kimaro: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Anthony Nyangarika:** Writing – review & editing, Visualization, Supervision. **Thomas Kivevele:** Writing – review & editing, Supervision, Funding acquisition.

Data availability

No data were used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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