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Review

Passive solar dryers as sustainable alternatives for drying agricultural produce in sub-Saharan Africa: advances and challenges

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Abstract
The lack of adequate techniques for food processing is among the reasons underlying food losses and high levels of hunger in Sub-Saharan Africa; the application of solar energy to dry agricultural products is one potential solution. However, the total replacement of traditional uses of solar energy is still far from reality. Therefore, in this study, we systematically review the academic literature testing passive solar drying systems in order to assess their performance. Then the main limitations and challenges for passive solar dryers developed in Sub-Saharan Africa are derived. The literature search reveals very limited research and a lack of standardized methods to assess solar dryer performance. Studies mainly report parameters related to dryers' thermal performance and physical features, thus neglecting parameters related to the quality of dried products and economics. Standardized and robust methodologies are urgently needed for more accurate conclusions and comparability of study results. Moreover, successfully applying passive solar dryers as an alternative to the traditional use of solar energy requires overcoming challenges such as time consumption, limited quantities of dried products, and the periodic nature of solar radiation. Thus, given its ability to significantly improve the self-life of food and overcome the current limitations for effective utilization of solar dryers in SSA, the use of mixed mode passive greenhouse dryers is proposed.

Keywords Solar energy · Passive solar dryers · Food security · Nutrition · Food processing

1 Introduction

Recent evidence indicates a rising trend of world hunger since 2015. Approximately one out of every nine people in the world is undernourished [1]. In Sub-Saharan Africa (SSA), the prevalence of hunger increased from 20.7% in 2014 to 23.2% in 2017 [2]. In fact, most of the world's acute hunger occurs during the pre-harvest months, coinciding with the period when household food stocks from the previous harvest have run out, food prices are generally high, and off-farm income opportunities are scarce [3]. The high levels of hunger are, in part, driven by a lack of adequate techniques for food processing, which causes substantial food losses [4, 5]. The Food and Agriculture Organization (FAO) defines food loss as a "decrease in mass or nutritional value of food that was originally intended for human consumption," differentiating

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it from food waste, which is "food appropriate for human consumption being discarded, whether or not after it is kept beyond its expiry date or left to spoil" [6].

Worldwide, approximately 1.3 billion tons of food for human consumption is lost every year [7], which equals roughly one-third of total production (32.5%) [8]. The annual value lost is estimated at US$4 billion, which exceeds the total US$6.1 billion SSA received between 1998 and 2008 in the form of food aid. This US$4 billon lost is equivalent to the annual caloric requirements of at least 48 million people (at 2,500 kcal per person per day) [9]. In SSA, per capita food losses are 170 kg/year [7], representing approximately 14% of global food losses.

To address this challenge, diverse technologies and methods have been developed. For small-scale farmers in the developing world, the use of solar energy through solar food dryers—here defined as devices that use solar energy to dry substances, especially food products [10]—is highlighted as a particularly promising solution [11, 12].

Reasons for this claim are manifold, including benefits with regard to preservation of nutrients, improved time efficiency of different solar drying systems compared to traditional drying, and applicability for rural areas [13–21]. In addition, food drying works for many types of food, with dried food being lightweight, easily stored, and easily transported [22]. Consequently, various types and designs of solar drying systems have been developed. A review article by Sharma, Chen [23] outlines existing solar drying systems and presents solar dryers that can be suitably used in rural farming areas.

Depending up on how the heat is transferred to the food, solar dryers are classified as direct, indirect, or mixed-mode dryers [21, 24–26]. Direct solar dryers (DSD) consist of a transparent cover that allows direct exposure of food to solar radiation [14, 27]. In addition to reducing heat losses, the cover also protects products against external contaminants such as rain, dust, and insects [28]. Nevertheless, direct exposure to solar radiation can negatively affect the sensory and nutritional attributes of food [16, 29]. The use of indirect-type solar dryers (ISD) minimizes the negative effect of solar radiation on the dried product [21, 30], as the agricultural products are placed inside a drying chamber [31] and are dried through heated air coming from a separate solar air heater where solar energy is collected. Mixed solar driers (MSD) are an intermediate solution for PSD and DSD in which the product is heated by both a transparent drying chamber and an air heater [32]. Solar dryers are also classified as forced (or active) and natural (or passive) convective, based on the air movement mode [33]. Active solar dryers (ASD) combine solar energy with electricity or fossil fuels to provide heat and air circulation; therefore these are not optimal for rural and isolated areas, especially in SSA where electrification is uncommon and financial resources are scarce [34]. In fact, the economic vulnerability and the limited access to energy restricts the application of measures to reduce food loss and waste in developing countries [35]. Previous review studies of solar dryers indicate that passive solar dryers (PSD) are cheaper than ASD [16, 36], as such PSD are suitable for resource-constrained households like those in rural areas of SSA.

PSD is widely demonstrated as achieving high efficiency, shortening drying time [37–43], and protecting products against fungi, pests, and rodents compared to traditional open-sun drying (OSD) [33]. In addition, PSD requires low capital and maintenance costs. However, the level of solar dryers acceptance among smallholder farmers is still low [24], thus, its application as a strategy to sustainably preserve agricultural products and safeguard food storage is limited [14]. As such, the use of systematic approaches to learn about progress with respect to the development and performance assessment of food solar drying technologies can help to avoid underutilization of the existing knowledge base, thus allowing a better understanding and identification of the major constraints that discourage the effective utilization of solar energy for drying agricultural products.

This paper systematically reviews the academic literature in which passive solar dryers systems are tested to assess their performance and impact on food quality, with the latter defined as the sum of all properties and assessable attributes of a food item (sensory value, suitability value, and health value) [44]. Subsequently, we identify the main limitations and challenges for application of PSD as sustainable alternatives for drying agricultural products in SSA. To capture relevant documents, we apply a structured approach for paper identification based on Liberati, Altman [45]. Possible solutions and directions for future research are proposed and discussed based on existing research results.

2 Methods

In this review, we searched for peer-reviewed papers and conference proceedings in the following academic search engines and bibliographic databases based on overall scientific impact and multidisciplinarity: Google Scholar, Web of Science, Agris, and Scopus. Reference lists of retrieved articles were checked for additional and possibly suitable literature (cf. Fig. 1). The applied search terms and (combined) keywords were "solar drying systems," "solar dryer," "solar dry + direct," "solar dry + open sun," "solar dry + mixed-mode," and "solar dry + indirect." After article identification, duplicates were removed, and then the

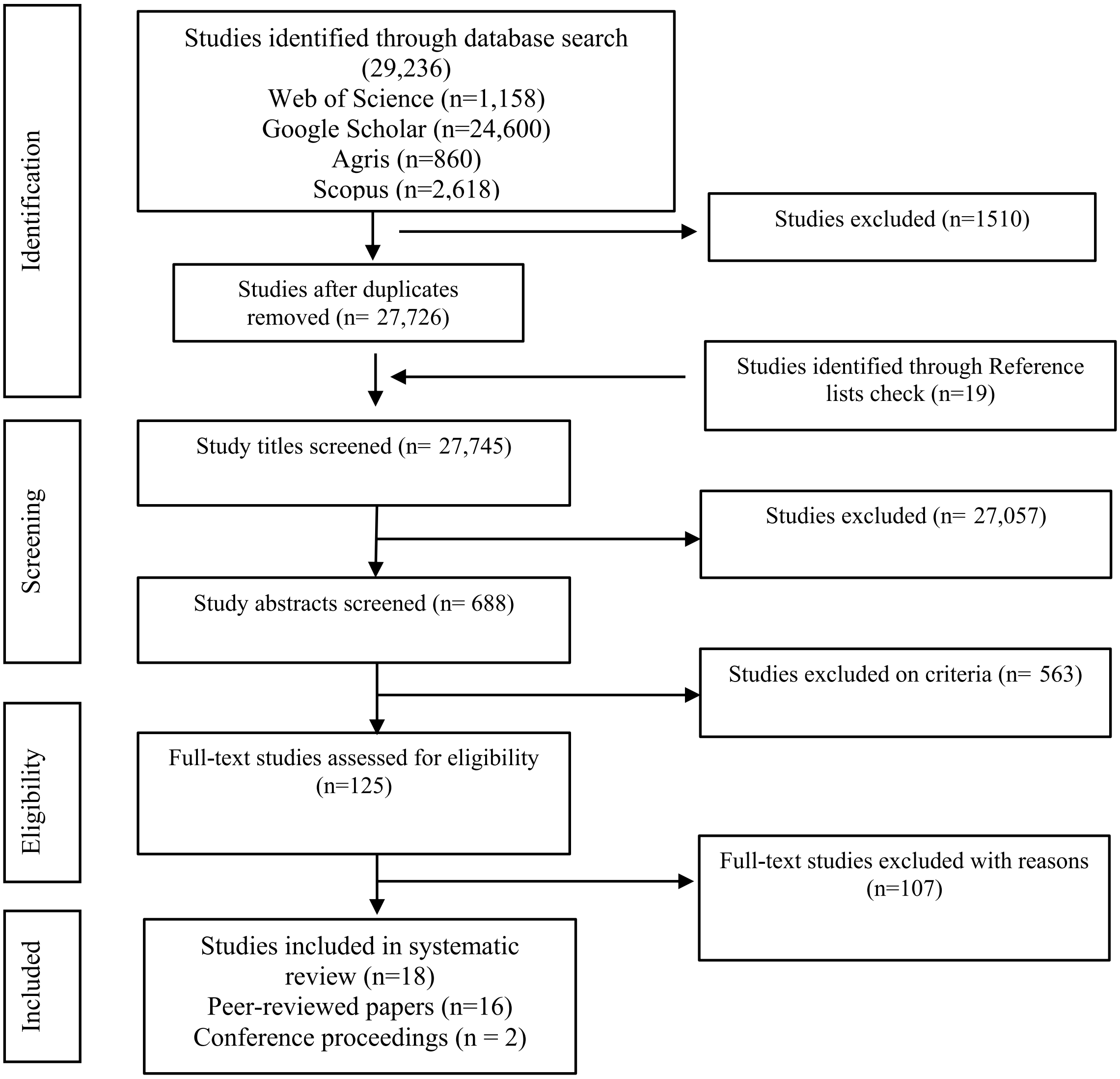

Fig. 1 Flow of information through the different phases

following three steps implemented to remove articles that were defined as irrelevant: (1) title screening; (2) abstract screening; and (3) full text screening (cf. Figure 1). The documents included in our review had to meet the criteria presented in Table 1. The number of studies screened, assessed for eligibility, and included in the review are presented in a PRISMA flow diagram [45]. From a total of 27,745 studies, 125 studies were assessed for eligibility, as presented in Fig. 1.

The type of solar dryer, the study location, and the type of dried products were extracted from the reviewed articles and reported in summary tables. The parameters used to assess the solar dryer performances and the key findings were also extracted from each study; thereafter the main limitations, challenges, and possible solutions for more sustainable application of PSD in the future were derived.

3 Results and discussion

3.1 General findings

The results from our literature search reveal that very limited research on solar drying for food processing in SSA dedicated to smallholder farmers has been conducted since 2000 (n = 18, cf. Figure 1). Starting with 27,745 studies, only 688 abstracts were screened (2.5%), as the titles of the remaining articles reported information that did not meet the inclusion

Table 1 Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Solar drying as method for agricultural products processing	Solar drying not intended for agricultural products
Sun is the only source of input energy	Active solar dryers
Must be published between 2000 and 2020 to guarantee up-to-date results	Inclusion of energy sources different to solar energy
Databased/indexed in English	Solar dryers for (agro)industry
Solar dryers for household level	Published prior to 2000
Peer-reviewed paper or conference proceeding	Not databased/indexed in English
Tests performance of solar dryers	Not peer-reviewed paper (e.g. conference proceeding, reviews, editorials, books, meeting documents etc.)
One or more food quality parameter is reported	Based on qualitative results
Includes only passive solar dryers	No food quality parameters reported
Based on empirical quantitative results	Study area is not Sub-Saharan Africa
Study area is Sub-Saharan Africa	

criteria (cf. Table 1). Of these, 670 studies were eliminated from the review, 563 for not meeting the criteria (cf. Table 1) and 107 due to lack of methodological clarity (28), type of solar dryer not mentioned (5), inclusion of non-passive solar dryers in the analysis (36), or a lack of included food quality parameters (38). Hence, only 18 studies are included in our review (Fig. 1).

3.2 Solar dryers' performance

The performance of the different types of PSD reported in the studies that were included in our review is summarized in Table 2. Agarwal, Seretse [46] develop a direct passive solar dryer in Botswana for drying various products with a drying rate of 0.01488 kg/hr. It took 4 h to dry the groundnuts at maximum ambient and drying temperatures of 43.6 °C and 79.2 °C, respectively. Dissa et al. develop and test both ISD and DSD for drying mango in Burkina Faso. In the DSD experiment, the observed drying rate was 0.15 $\mathrm{gkg}^{-1}\ \mathrm{s}^{-1}$, and the maximum drying efficiency was 34%. The ambient air humidity ranged from 30 to 66%, while the ambient temperature ranged from 30 to 36 °C [47]. For the ISD, the ambient air humidity ranged from 30.4 to 41%, while the ambient temperature ranged from 25.8 to 37.5 °C. The maximum drying rate observed was 0.18 $\mathrm{gkg}^{-1}\ \mathrm{s}^{-1}$. The drying temperatures reached a maximum of 37.5 °C, and the drying relative humidity ranged from 16 to 51%. In this experiment, the drying efficiency was 35.04% [48].

Another DSD was tested by Muhammadu and Abraham [49] in Nigeria to dry cassava. It took 76 h to reach a final water content of 12%. The maximum drying temperature was 43.8 °C, and the maximum ambient temperature was 30.3 °C. The observed drying efficiency was 52%, and the drying rate was 0.25 kg/hr.

Notably, there are very mixed results in terms of drying time and final water content among studies assessing the performance of solar dryers for the same crop. For example, Dissa, Bathiebo [47] needed 96 h to reach a water content of 24.8% for a variety of mangos, while Adepoju and Osunde [50] needed 8 h to reduce the water content from initially 85% to 6% while using the same crop; to reach 13% of the water content for mango, Gbaha, Yobouet Andoh [51] needed 27 h. Eke [52] reached 4% of the water content in tomatoes after 96 h of drying, reaching a maximum drying temperature of 60 °C, whereas Aliyu, Kabri [53] reached the same water content after 72 h with a maximum drying temperature of 47 °C. There are also differences in reported drying efficiencies and drying rates (cf. Table 2).

3.3 Challenges and limitations for the effective utilization of PSD in SSA

3.3.1 Limited research and difficult comparability between studies

Among the studies obtained during our literature search, only 18 met our inclusion criteria, which reveals a limited availability of academic literature on PSD in SSA. Most studies about solar dryers are on DSD, which are already proven inadequate for rural and low-income communities as they require additional energy sources and are not affordable. Moreover, based on Leon and Kumar [63] and Masud et al., [35], 27 parameters are important for different passive solar dryers' performance analyses. These parameters are grouped into four categories, as shown in Fig. 2. However, the majority of studies in SSA generally report only a few selected parameters, mostly related to the thermal performance

Table 2 Summary of the solar dryers' performance

No	Authors	Country	Study area	Solar Dryer Type	Products	Major findings
1	Agarwal, Seretse [46]	Botswana	-	direct	groundnuts	4 h to dry the groundnuts for final water content of 10.575% and 8.4% Drying rates of 0.01488 kg/hr and 0.01173 kg/hr Maximum drying temperatures inside chamber of 79.2 °C and 75.1 °C and the maximum ambient temperature of 39.5 °C and 43.6 °C Drying effectiveness of 39.125% and 30.9%
2	Dissa, Bathiebo [47]	Burkina Faso	Ouagadougou	direct	mangoes	4 days to dry to reach a final water content of 24.83% for Amelie variety and 66.32% for Brooks Drying efficiency ranged from 0 to 34% Drying rates of 0.150 $gkg^{-1}\ s^{-1}$ and 0.153 $gkg^{-1}\ s^{-1}$ Ambient air humidity ranged from 30 to 66% while ambient temperature ranged from 30 to 36 °C
3	Dissa, Bathiebo [48]	Burkina Faso	Ouagadougou	indirect	mangoes	3 days to dry to reach a final water content of 13.79% Maximum drying efficiency of 35.04% Maximum drying rate of 0.18 $gkg^{-1}\ s^{-1}$ Ambient air humidity ranged from 30.4 to 41% while ambient temperature ranged from 25.8 to 37.5 °C Maximum drying temperatures of 37.5 °C drying relative humidity ranged from 16 to 51%
4	Muhammadu and Abraham [49]	Nigeria	Minna	direct	cassava	76 h to reach a final water content of 12% Maximum drying temperature of 43.8 °C Maximum ambient temperature of 30.3 °C Drying efficiency of 52% Drying rate of 0.25 kg/hr

Table 2 (continued)

No	Authors	Country	Study area	Solar Dryer Type	Products	Major findings
5	Alonge and Adeboye [54]	Nigeria	Uyo	Direct and indirect	pepper, okra, Amaranthus	51 h for direct and 57 h for indirect to reach a final water content of 20% in okra 33 h for direct and 51 h for indirect to reach a final water content of 24% in pepper 30 h for direct and 36 h for indirect to reach a final water content of 20% in 400 g of amaranths Maximum drying temperature of 51 °C for direct solar dryer and 48 °C for indirect Maximum ambient temperature of 39 °C Average drying rate of 3.94 g/hr for drying pepper in direct mode and 2.55 g/hr in indirect mode Average drying rate of 17.65 g/hr for drying okra in direct mode and 15.79 g/hr in indirect mode
6	Eke [52]	Nigeria	Umuahia	direct	tomato	96 h to reach a final water content of 4% Maximum drying temperature of 60 °C 41.43% increase in temperature over the ambient temperature Drying efficiency of 27.24%
7	Aliyu, Kabri [53]	Nigeria	Yola	indirect	tomato	3 days to reach a final water content of 4% Maximum drying temperature of 47 °C Maximum ambient temperature 38 °C Drying efficiency of 64% Drying rate of 0.03906 kg/hr
8	Ayua, Mugalavai [55]	Kenya	Eldoret	direct and mixed-mode	nightshade, spider plant, amaranths, African birds eye chilies	270 min for spider plant and 3867 min for African bird's eye chili to reach a final water content below 10% Maximum drying temperature of 72 °C and 59.0 °C in the mixed modes and direct mode dryer, respectively Maximum ambient temperature of 39 °C
9	Bentil and Appiah [56]	Ghana	Kumasi	indirect	cassava	Reached a final water content of 6.8% Maximum drying temperature of 69.23 °C
10	Bechoff, Tomlins [57]	Uganda, Mozambique	-	direct	sweet potatoes	No significant differences were observed between pro-vitamin A retention in solar dryer and open sun

Table 2 (continued)

No	Authors	Country	Study area	Solar Dryer Type	Products	Major findings
11	Adelaja, Asemota [58]	Nigeria	Akoka	indirect	yam	3 days to reach a final water content of 17.75% Maximum drying temperature of 75 °C Maximum ambient temperature of 37 °C Drying efficiency of 54.76% Drying rate of 0.0481 kg/hr
12	Tewolde-Berhan, Remberg [59]	Ethiopia	Tigray	direct	cordia africana	5 days to reach a final water content of 40.4% using the direct solar dryer 65 days to reach a final water content of 46.82 using natural dry The taste of the fruit from the direct solar dryer was less preferred to those dried on the tree
13	Alonge and Adeboye [54]	Nigeria	-	indirect	yam	45 h to reach a final water content of 9% Maximum drying temperature of 47 °C Maximum ambient temperature of 37 °C Drying efficiency of 63%
14	Adepoju and Osunde [50]	Nigeria	Minna	direct	mango	8 h to reach a final water content of 6% Average drying temperature of 41 °C Drying rate of 40 g/hr
15	Mulokozi and Svanberg [60]	Tanzania	Singida district	direct	green leafy vegetables (amaranths, cowpea, pumpkin, sweet potato leaves, maroon cucumber, stinkweed, crotalaria, koyosa)	4 to 6 h to reach a final water content between 7 and 9% Maximum drying temperature of 55 °C Significant differences were observed between all-trans-α-carotene retention in solar dryer and open sun
16	Abubakar, Umaru [61]	Nigeria	Zaria	Mixed-mode	yam	3 h to reach a final water content of 17% Maximum drying temperature of 50.1 °C Maximum ambient temperature of 35 °C Drying efficiency of 24.20% Drying rate of 2.35×10^{-5} kg/s
17	Gbaha, Yobouet Andoh [51]	Côte d'Ivoire	Yamoussoukro	direct	cassava, banana, and mango	19 h for cassava, 22 h for sweet banana, 26 h for plantain banana, and 27 h for mango to reach a final water content of 13% Maximum drying temperature of 59 °C Maximum ambient temperature 39 °C Drying efficiency of about 42% Maximum drying rate of 6 g/hr

Table 2 (continued)

No	Authors	Country	Study area	Solar Dryer Type	Products	Major findings
18	Sekyere, Forson [62]	Ghana	-	Mixed-mode	pineapples	23 h to reach a final water content of 144% (d.b) Maximum drying temperature of 77.8 °C Average ambient temperature of 27.5 °C Drying efficiency of 0 to 66.5%

and physical features of the solar dryer. Nevertheless, when evaluating solar dryers, it is important to account for the requirements of both consumers and users.

Most studies included in our review report thermal performance-related parameters, especially ambient temperature, drying time/drying rate, and drying air temperature. Moreover, physical features of dryers are also frequently reported, mainly the size and shape of solar dryers, collector areas, and solar apertures. However, parameters related to cost are rarely reported (Table 3). Hence, the evaluation procedures of solar dryers generally neglect financial feasibility. Out of a total of six parameters related to the quality of dried food, the moisture content is the only parameter generally measured. Parameters such as sensory quality and nutritional attributes are generally neglected (cf. Table 3).

Although it is often generally assumed that solar drying is a good strategy to improve food preservation and nutrient retention, the data supporting this assertion is weak. A large heterogeneity in methods and parameters for assessing the performance of solar dryers is found among the included studies, which may explain the diversity and sometimes contradictory assessments of the technology. Mulokozi and Svanberg [60] report a higher retention of all-transβ-carotene with the use of a solar dryer compared to open-sun drying, whereas Bechoff, Tomlins [57] find no differences.

Variations in size, shape, color, and texture are usually observed in dried products [63–65], but the included studies rarely report these attributes. From our review, it can be derived that research on PSD in SSA rarely takes into account consumer needs, as it focuses on the thermal performance and physical features of the dryer, ignoring the final characteristics of the dried product. Leon, Kumar [63] report inconsistencies in the quality evaluation of dried products and further claim that there is "no quantification of food quality parameters in most literature, which makes evaluation and

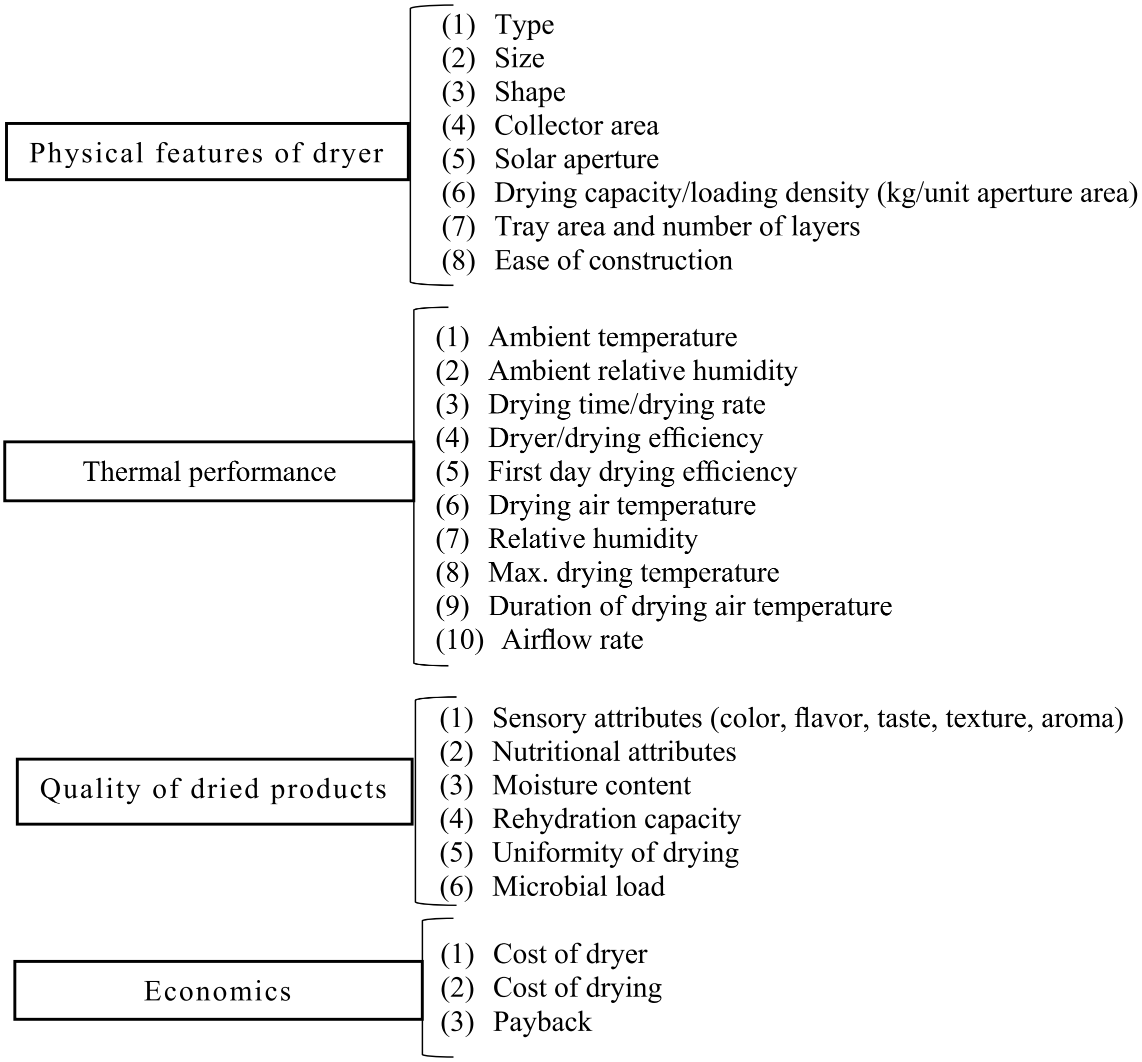

Fig. 2 Solar dryer evaluation parameters adapted from Leon and Kumar [63] and Masud et al., [35]

Table 3 Number of parameters used to assess solar dryer performance in each study

No	Authors	Number of Parameters used per Category				Grand total (Total = 27)	Percentage
		Physical features of dryer (Total = 8)	Thermal Performance (Total = 10)	Quality of dried products (Total = 6)	Economics (Total = 3)		
1	Agarwal, Seretse [46]	3	5	1	0	9	33%
2	Dissa, Bathiebo [47]	8	9	1	0	18	67%
3	Dissa, Bathiebo [48]	8	10	1	0	19	70%
4	Muhammadu and Abraham [49]	6	4	1	0	11	41%
5	Alonge and Adeboye [54]	5	4	1	0	10	37%
6	Eke [52]	7	7	1	1	16	59%
7	Aliyu, Kabri [53]	6	3	1	0	10	37%
8	Ayua, Mugalavai [55]	4	5	1	0	10	37%
9	Bentil and Appiah [56]	1	0	2	0	2	7%
10	Bechoff, Tomlins [57]	0	1	2	0	3	11%
11	Adelaja, Asemota [58]	5	7	1	0	13	48%
12	Tewolde-Berhan, Remberg [59]	0	1	3	0	3	11%
13	Alonge and Adeboye [54]	6	2	1	0	9	33%
14	Adepoju and Osunde [50]	0	3	2	0	5	19%
15	Mulokozi and Svanberg [60]	3	1	1	0	5	19%
16	Abubakar, Umaru [61]	6	8	1	0	15	56%
17	Gbaha, Yobouet Andoh [51]	7	5	1	0	13	48%
18	Sekyere, Forson [62]	7	10	2	0	19	70%
Total number of studies		15	17	18	1		

comparison between dryers difficult and often misleading." However, the quality of dried products is associated with how a product satisfies the requirements of the user [66]. It includes attributes such as aroma, taste, color, microbial load, retention of nutrients, texture, and porosity, etc. [35]. Assessing the quality of dried products is necessary, as different solar driers may result in different sensory and nutritional parameters [21, 67], which, in turn, affects the price of the dried products and, therefore, the economic viability and subsequent adoption rate of the technology.

Parameters related to economics are the least reported in studies on the performance of PSD in SSA. Tiwari [68] indicates that financial viability is a key component, as solar dryers are generally capital intensive compared to other investments by farming and processing households. In fact, costs are the main determining factor for scaling up these technologies [20].

3.3.2 Time consumption and small quantities of dried products

A principle limitation of solar dryers in general is the quantity of product that can be dried per drying process. For example, Agarwal and Seretse [46] obtain less than 600 g of dried ground nuts in one day of the experiment. Abubakar and Umaru [61] dry only 2 kg of yam, which had 77.5% of moisture content lost, in a two-day experiment. This constitutes an additional burden for farming households, as more dryers or much longer periods would be required to dry, for example, the total seasonal production of maize, which averages 1800 kg/ha in SSA [69]. In fact, long drying times were also reported as one of the major drawbacks of sun drying. It can take up to 30 days to finalize the drying process, depending on the crop and the weather conditions of the site [11]. This would be aggravated by the fact that additional attention is necessary to ensure safe storage of dried products and avoid contamination after the drying process. Some crops may require adequate pretreatment to produce safer dried products [70]. Thus, it is also necessary to establish a daily routine to perform and monitor the drying process, which can overload daily activities and, therefore, constitute a limitation to the continuous use of PSD.

Although PSD are considered suitable for rural areas and are relatively cheaper than ASD, the quantities of dried products obtained might lead to unrealistic expectations. The current levels of productivity and efficiency are not ideal, since despite being relatively cheap, the initial costs that are necessary to obtain PSD may not be recovered, which is an unbearable burden in the context of resource-constrained communities.

3.3.3 Safety of food

In general, bacterial pathogens, fungi, and most waterborne viruses are highly sensitive to solar radiation and high temperatures. During solar drying, especially in direct solar drying, food products are exposed to relatively high temperatures and ultraviolet (UV) radiation, which can prevent microorganisms from replicating. Nevertheless, it is still crucial to note that certain microorganisms can be resistant to drying temperatures, compromising food safety. In addition, food handlers or drying platforms with low sanitary standards can contaminate food after sun drying [71, 72]. Exposure to rain, wind, dust, insects, and other contaminants may also lead to a final increase in microbial populations [70]. Moreover, the food itself can offer protective compounds and structures that may increase the survivability of microorganisms [70]. Many compounds found in fruits and vegetables, such as sugars, polypeptides, amino acids, glycerol, and carboxylic acids, may increase the chances of microorganism survival during the drying process [73]. Nevertheless, in most of the studies, the only parameter related to food quality generally reported is the level of moisture content, which creates an urgent need to also incorporate the microbiological load during performance evaluation to ensure food safety during and after dying.

3.3.4 Periodic availability of solar radiation

The use of PSD depends largely on the availability of solar radiation and seasonal changes; therefore, the heating of air and/or the drying of food occurs in real time when solar energy reaches the solar dyer. Thus, when solar radiation is not available, the rate of drying decreases to almost zero. This means that during rainy days or cloudy days and during nights, drying by using PSD may not occur. Although some solar radiation arrives during cloudy days, the system's capacity to heat the air decreases and, in regions that experience successive days of rain, it becomes impractical to use PSD during the rainy season. Solutions such as the use of thermal storage systems, auxiliary energy sources, or larger solar collectors are proposed in the literature [74, 75]. However, these solutions are not affordable for low-income households in the Global South.

Most solar dryers assessed in the reviewed studies report drying temperatures below or equal to 60 °C, which indicate that they are ineffective for crops that require high-temperature drying. As such, these solar dryers can only dry a limited number of agricultural products (especially those that require low energy input). In this context, the development of low cost and efficient solar collectors should be a main focus of research on PSD in order to find a trade-off between energy efficiency and cost-effectiveness [75].

3.3.5 Socio-cultural barriers

Adopting new technology may alter social and economic organization, thus redefining people or communities' identity [76]. Therefore, during the implementation of a PSD, strategies must be undertaken to ensure that the number of people who decide to adopt and use the PSD are enough to outweigh what happens when individuals eventually abandon its use. Although PSD is potentially a beneficial technology, traditional uses of solar energy may persist due to people's familiarity with traditional practices. Moreover, individual social beliefs can strongly limit the acceptance, adoption, and continued use of new technologies. Therefore, the population must believe that PSD can effectively add value to agricultural products compared to traditional OSD for more effective utilization. They must have knowledge on how to operate the PSD correctly and have an interest in the idea of alternative technology use. In addition, the construction materials and labor necessary for installation, operation, and maintenance must be locally available.

3.4 Future directions for a more sustainable and effective utilization of PSD in SSA

Based on the main limitations identified in this study, it can be derived that the design and development of a solar dryer in SSA should consider the following aspects:

a. The solar dryers must be inexpensive and exclusively operated by solar energy;
b. It must not require high-skilled labor for construction;

c. It must be simple and easy to construct using locally available materials;
d. The temperatures inside the drying chamber must be higher than the ambient temperature;
e. It must be capable of drying crops that require both low energy and high energy drying;
f. It must be able to ensure a relatively rapid achievement of a safe moisture level;
g. It must dry relatively large quantities of products in the shortest time possible; and
h. It must maintain food quality attributes that appeal to general consumers (e.g., color, nutrients, texture, aroma, and taste).

The use of passive greenhouse dryers is a particular solution that can meet the requirements mentioned above. It can increase the volume of dried food and, consequently, shorten the time necessary for each drying process. A greenhouse dryer is a direct type of solar dryer that is easy to fabricate, presents a simple design; and does not have any operating costs. It can achieve large quantities of dried product, higher drying rates, and can be used throughout the year for different purposes (e.g. cultivation and drying); therefore, it is more economically feasible [77–79]. It also ensures that some doses of UV are received by the food, which is important for microorganism deactivation. Ideally, a solar collector should be incorporated, thus allowing a mixed mode operation to optimize the use of solar radiation and temperature.

Taking into account that agriculture in SSA is typically small scale and for subsistence purposes, producers are likely to have the same characteristics as consumers, so testing for many subjective quality aspects would be easy. However, a standard evaluation procedure is still necessary; for example, more rigorous statistical methods would have been used in this review, but the studies included use a variety of methodological approaches. One key factor of a successful study is replicability. Thus, a test protocol is necessary for studies evaluating the performance of solar dryers in order to reduce methodological differences between studies. The protocol should clearly state which parameters are crucial for solar dryers' evaluation, the procedures to conduct the experiments, and how the data should be analyzed and presented. Thus, future uncertainties are more likely to be avoided.

To ensure food safety, heated air and radiation must be enough to ensure complete deactivation of microorganisms. Thus, the use of a mixed mode greenhouse dryer may be able to increase temperatures above the optimum temperature for microbial growth, including those resistant to the drying process. In general, these temperatures must be above 40 °C [80]. Nevertheless, the application of effective procedures, including hygiene, cleaning, and disinfection, is still crucial for effectively avoiding the growth of harmful microorganisms during the drying process, especially foodborne pathogens. The latter are critically important and dangerous microorganisms, including bacteria, viruses, and fungi (mycotoxins), that are found in foods [81].

The use of PSD with higher capacity in terms of the daily quantity of dried food and better capacity to increase drying temperature can make it possible to reduce the large dependence on sunlight availability due to associated daily productivity and short exposure time necessary.

Efforts directed at overcoming social barriers should focus on the establishment of centers for community learning. Experience with solar dryer implementation shows that involving local communities, as well as local partners, such as local governments and universities or training institutes, is crucial for successful implementation, especially in rural contexts in developing countries.

4 Conclusion

In this paper, we systematically review the academic literature in which passive solar dryer systems are tested to assess their performance and impact on food quality in SSA. The results reveal a general shortage of research and a lack of study comparability regarding PSD performance in SSA. Furthermore, the few existing papers focus their analyses mainly on parameters related to the thermal performance and physical features of solar dryers. Parameters related to the quality of dried products and economics are rarely reported. The only parameter related to the quality of dried products generally reported is the water content after drying. Therefore, it is necessary to include not just the load density; size variation; shape, color, and texture of dried product; microbial load; costs of the dryer; operating costs; but also all 10 thermal performance parameters and 8 physical features parameters presented in Fig. 2. Moreover, more standardized and robust methodologies should be followed to achieve more accurate conclusions and improved comparability of results across studies. This would provide greater certainty on the potential benefits of PSD and avoid costly technology development and distribution, which may lead to economic losses for both potential producers of the PSD and clients (farmers). Recommendations for non-adapted and non-beneficial models can destroy the confidence of stakeholders not only with respect to the specific models but also the (potentially beneficial) technology in general, especially in SSA where the use solar drying technologies in very limited, despite the need to significantly reduce food loss and waste.

The small quantities of dried products obtained per drying process, inadequate handling of drying equipment, and the intermittent nature of solar radiation availability are some of the main limitations for the effective implementation, adoption, and continued use of PSD in SSA. Thus, given its potential to overcome most of these limitations, the use of mixed mode passive greenhouse dryers is proposed in this study. It can significantly improve the shelf-life of food and does not require external sources of energy. Future research should focus on developing and testing solar dryers that reflect the needs of both processors and consumers to ensure market penetration and effective utilization of PSD, thus improving the food loss and waste situation in SSA along with environmental sustainability.

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Declarations

Competing interests The authors declare no competing interests.

References

1. FAO, IFAD, UNICEF, WFP, and WHO. The state of food security and nutrition in the world 2018: building climate resilience for food security and nutrition. Food and Agriculture Organization of the United Nations; 2018.
2. UN. The Sustainable Development Goals Report 2019. United Nations: New York; 2019.
3. Vaitla B, Devereux S, Swan SH. Seasonal hunger: a neglected problem with proven solutions. PLoS Med. 2009;6(6):e1000101.
4. Guenha R, Salvador BDV, Rickman J, Goulao LF, Muocha IM, Carvalho MO. Hermetic storage with plastic sealing to reduce insect infestation and secure paddy seed quality: a powerful strategy for rice farmers in Mozambique. J Stored Prod Res. 2014;59:275–81.
5. De Steur H, Wesana J, Dora MK, Pearce D, Gellynck X. Applying value stream mapping to reduce food losses and wastes in supply chains: a systematic review. Waste Manage. 2016;58:359–68.
6. FAO, Food wastage footprint: Impacts on natural resources. 2013, Food and Agriculture Organization.
7. Gustavsson, J., C. Cederberg, U. Sonesson, R. Van Otterdijk, and A. Meybeck. Global food losses and food waste. FAO Rome; 2011.
8. Aggidis, G., I. Arbon, C. Brown, C. Clarke, J. Earp, T. Fox, D. Greenway, A. Smith, B. Stannard, and D. Warriner, Global food: waste not, want not.[IMECHE document]. 2013, Institution of Mechanical Engineers: London.
9. Zorya, S., N. Morgan, L. Diaz Rios, R. Hodges, B. Bennett, T. Stathers, P. Mwebaze, and J. Lamb, Missing food: the case of postharvest grain losses in sub-Saharan Africa, in Technical Report. 2011, The International Bank for Reconstruction and Development/The World BanK: Washington DC, USA.
10. Tiwari, G.N., A. Tiwari, and Shyam, Handbook of Solar Energy : Theory, Analysis and Applications, A. Tiwari and Shyam, Editors. 2016, Springer: Singapore
11. Belessiotis V, Delyannis E. Solar drying. Sol Energy. 2011;85(8):1665–91.
12. Ananno AA, Masud MH, Dabnichki P, Ahmed A. Design and numerical analysis of a hybrid geothermal PCM flat plate solar collector dryer for developing countries. Sol Energy. 2020;196:270–86.
13. Fudholi A, Sopian K, Bakhtyar B, Gabbasa M, Othman MY, Ruslan MH. Review of solar drying systems with air based solar collectors in Malaysia. Renew Sust Energ Rev. 2015;51:1191–204.
14. Kumar M, Sansaniwal SK, Khatak P. Progress in solar dryers for drying various commodities. Renew Sustain Energy Rev. 2016;55:346–60.

15. Lamidi RO, Jiang L, Pathare PB, Wang YD, Roskilly AP. Recent advances in sustainable drying of agricultural produce: A review. Appl Energy. 2019;233–234:367–85.
16. Mustayen AGMB, Mekhilef S, Saidur R. Performance study of different solar dryers: a review. Renew Sustain Energy Rev. 2014;34:463–70.
17. Ndukwu MC, Bennamoun L, Abam FI. Experience of solar drying in Africa: presentation of designs, operations, and models. Food Eng Rev. 2018;10(4):211–44.
18. Singh P, Shrivastava V, Kumar A. Recent developments in greenhouse solar drying: a review. Renew Sustain Energy Rev. 2018;82:3250–62.
19. El-Sebaii AA, Shalaby SM. Solar drying of agricultural products: a review. Renew Sustain Energy Rev. 2012;16(1):37–43.
20. Udomkun P, Romuli S, Schock S, Mahayothee B, Sartas M, Wossen T, Njukwe E, Vanlauwe B, Müller J. Review of solar dryers for agricultural products in Asia and Africa: an innovation landscape approach. J Environ Manag. 2020;268:110730.
21. Mohana Y, Mohanapriya R, Anukiruthika T, Yoha KS, Moses JA, Anandharamakrishnan C. Solar dryers for food applications: Concepts, designs, and recent advances. Sol Energy. 2020;208:321–44.
22. Puri, M., How access to energy can influence food losses. A brief overview. 2016, Food and Agriculture Organization of the United Nations.
23. Sharma A, Chen CR, Vu-Lan N. Solar-energy drying systems: A review. Renew Sustain Energy Rev. 2009;13(6):1185–210.
24. Chavan A, Vitankar V, Mujumdar A, Thorat B. Natural convection and direct type (NCDT) solar dryers: a review. Drying Technol. 2020;1:1–22.
25. Fudholi A, Sopian K, Ruslan MH, Alghoul MA, Sulaiman MY. Review of solar dryers for agricultural and marine products. Renew Sustain Energy Rev. 2010;14(1):1–30.
26. Visavale, G., Principles, classification and selection of solar dryers. Solar drying: Fundamentals, Applications and Innovations, Ed. Hii, CL, Ong, SP, Jangam, SV and Mujumdar, AS, Published in Singapore. 2012: 1–50.
27. Islam MK, Karim MS, Begum NN, Uddin KZ. Fabrication and performance study of a direct type solar dryer. Int J Eng Res. 2018;9(2):565–9.
28. Sandali M, Boubekri A, Mennouche D, Gherraf N. Improvement of a direct solar dryer performance using a geothermal water heat exchanger as supplementary energetic supply. An experimental investigation and simulation study. Renew Energy. 2019;135:186–96.
29. Al-Juamily KEJ, Khalifa AJN, Yassen TA. Testing of the performance of a fruit and vegetable solar drying system in Iraq. Desalination. 2007;209(1):163–70.
30. Tomar V, Tiwari GN, Norton B. Solar dryers for tropical food preservation: thermophysics of crops, systems and components. Sol Energy. 2017;154:2–13.
31. El-Sebaii AA, Aboul-Enein S, Ramadan MRI, El-Gohary HG. Experimental investigation of an indirect type natural convection solar dryer. Energy Convers Manage. 2002;43(16):2251–66.
32. Shalaby SM, Bek MA, El-Sebaii AA. Solar dryers with PCM as energy storage medium: a review. Renew Sustain Energy Rev. 2014;33:110–6.
33. Mekhilef S, Saidur R, Safari A. A review on solar energy use in industries. Renew Sustain Energy Rev. 2011;15(4):1777–90.
34. Duran G, Condorí M, Altobelli F. Simulation of a passive solar dryer to charqui production using temperature and pressure networks. Sol Energy. 2015;119:310–8.
35. Hasan Masud, M., A. Karim, A.A. Ananno, and A. Ahmed, Conditions for Selecting Drying Techniques in Developing Countries, in Sustainable Food Drying Techniques in Developing Countries: Prospects and Challenges. Cham: Springer International Publishing; 2020. 21–40.
36. Singh, P. and M.K. Gaur, Review on development, recent advancement and applications of various types of solar dryers. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2020: 1–21.
37. Arunsandeep G, Lingayat A, Chandramohan VP, Raju VRK, Reddy KS. A numerical model for drying of spherical object in an indirect type solar dryer and estimating the drying time at different moisture level and air temperature. Int J Green Energy. 2018;15(3):189–200.
38. Tedesco FC, Bühler AJ, Wortmann S. Design, construction, and analysis of a passive indirect solar dryer with chimney. J Solar Energy Eng. 2018;141:3.
39. Yadav S, Lingayat AB, Chandramohan VP, Raju VRK. Numerical analysis on thermal energy storage device to improve the drying time of indirect type solar dryer. Heat Mass Transf. 2018;54(12):3631–46.
40. Ghaffari A, Mehdipour R. Modeling and improving the performance of cabinet solar dryer using computational fluid dynamics. Int J Food Eng. 2015;11(2):157–72.
41. Mohammed S, Fatumah N, Shadia N. Drying performance and economic analysis of novel hybrid passive-mode and active-mode solar dryers for drying fruits in East Africa. J Stored Prod Res. 2020;88:101634.
42. Dasin D, Godi N, Kingsley O. Experimental investigations of the performance of passive solar food dryer tested in Yola-Nigeria. Int J Energy Eng. 2015;5(1):9–15.
43. Irtwange S, Adebayo S. Development and performance of a laboratory-scale passive solar grain dryer in a tropical environment. J Agric Extens Rural Dev. 2009;1(2):042–9.
44. Leitzmann CF, Quality—Definition and a Holistic View. in Safeguarding Food Quality. . Berlin. Heidelberg: Springer, Berlin Heidelberg; 1993.
45. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JPA, Clarke M, Devereaux PJ, Kleijnen J, Moher D. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. BMJ. 2009;339:e2700.
46. Agarwal A, Seretse OM, Letsatsi MT, Maele LT, Koketso D. Performance evolution of an improved solar thermal hot air heating system for drying ground-nuts. J Mech Eng Res Dev. 2019;42(3):1–5.
47. Dissa AO, Bathiebo DJ, Desmorieux H, Coulibaly O, Koulidiati J. Experimental characterisation and modelling of thin layer direct solar drying of Amelie and Brooks mangoes. Energy. 2011;36(5):2517–27.
48. Dissa AO, Bathiebo J, Kam S, Savadogo PW, Desmorieux H, Koulidiati J. Modelling and experimental validation of thin layer indirect solar drying of mango slices. Renew Energy. 2009;34(4):1000–8.
49. Muhammadu, M.M. and A.E. Abraham, Design, fabrication and testing of solar dryer for drying cassava chip. 2012.
50. Adepoju LA, Osunde ZD. Effect of pretreatments and drying methods on some qualities of dried mango (Mangifera indica) fruit. Agric Eng Int CIGR J. 2017;19(1):187–94.
51. Gbaha P, Yobouet-Andoh H, Kouassi-Saraka J, Kaménan-Koua B, Touré S. Experimental investigation of a solar dryer with natural convective heat flow. Renew Energy. 2007;32(11):1817–29.

52. Eke AB. Investigation of low cost solar collector for drying vegetables in rural areas. Agric Eng Int CIGR J. 2014;16(1):118–25.
53. Aliyu B, Kabri HU, Pembi PD. Performance evaluation of a village-level solar dryer for tomato under Savanna Climate: Yola, Northeastern Nigeria. Agric Eng Int CIGR J. 2013;15(1):181–6.
54. Alonge AF, Adeboye OA. Drying rates of some fruits and vegetables with passive solar dryers. Int J Agric Biol Eng. 2012;5:4.
55. Ayua E, Mugalavai V, Simon J, Weller S, Obura P, Nyabinda N. Comparison of a mixed modes solar dryer to a direct mode solar dryer for African indigenous vegetable and chili processing. J Food Process Preserv. 2017;41(6):e13216.
56. Bentil, B. and F. Appiah, Evaluation of the performance of three drying technologies and three loading densities for the production of cassava chips, in Xxix International Horticultural Congress on Horticulture: Sustaining Lives, Livelihoods and Landscapes, C.J. Birch, B. Searle, and E. Heuvelink, Editors; 2016. 227–232.
57. Bechoff, A., K.I. Tomlins, C. Dhuique-Mayer, D. Dufour, and A. Westby. Understanding carotenoid losses in orange-fleshed sweet potato in drying and storage. 2009.
58. Adelaja AO, Asemota OS, Oshiafi IK. Experimental determination of the moisture content pattern in yam during drying. J Appl Sci Res. 2010;6(8):1171–81.
59. Tewolde-Berhan S, Remberg SF, Abegaz K, Narvhus J, Abay F, Wicklund T. Impact of drying methods on the nutrient profile of fruits of Cordia africana Lam in Tigray, northern Ethiopia. Fruits. 2015;70(2):77–90.
60. Mulokozi G, Svanberg U. Effect of traditional open sun-drying and solar cabinet drying on carotene content and vitamin A activity of green leafy vegetables. Plant Foods Hum Nutr. 2003;58(3):1–15.
61. Abubakar S, Umaru S, Kaisan MU, Umar UA, Ashok B, Nanthagopal K. Development and performance comparison of mixed-mode solar crop dryers with and without thermal storage. Renew Energy. 2018;128:285–98.
62. Sekyere CKK, Forson FK, Adam FW. Experimental investigation of the drying characteristics of a mixed mode natural convection solar crop dryer with back up heater. Renew Energy. 2016;92:532–42.
63. Leon MA, Kumar S, Bhattacharya SC. A comprehensive procedure for performance evaluation of solar food dryers. Renew Sustain Energy Rev. 2002;6(4):367–93.
64. Raghavi LM, Moses JA, Anandharamakrishnan C. Refractance window drying of foods: a review. J Food Eng. 2018;222:267–75.
65. Nasri MY, Belhamri A. Effects of the climatic conditions and the shape on the drying kinetics, Application to solar drying of potato-case of Maghreb's region. J Clean Prod. 2018;183:1241–51.
66. Joardder MUH, Masud MH. Effectiveness of Food Preservation Systems, in Food Preservation in Developing Countries: Challenges and Solutions. Cham: Springer International Publishing; 2019. p. 127–52.
67. Gallali YM, Abujnah YS, Bannani FK. Preservation of fruits and vegetables using solar drier: a comparative study of natural and solar drying, III; chemical analysis and sensory evaluation data of the dried samples (grapes, figs, tomatoes and onions). Renew Energy. 2000;19(1):203–12.
68. Tiwari A. A review on solar drying of agricultural produce. J Food Process Technol. 2016;7(9):1–12.
69. Abate T, Shiferaw B, Menkir A, Wegary D, Kebede Y, Tesfaye K, Kassie M, Bogale G, Tadesse B, Keno T. Factors that transformed maize productivity in Ethiopia. Food Security. 2015;7(5):965–81.
70. Bourdoux S, Li D, Rajkovic A, Devlieghere F, Uyttendaele M. Performance of drying technologies to ensure microbial safety of dried fruits and vegetables. Compr Rev Food Sci Food Saf. 2016;15(6):1056–66.
71. Eze J, Agbo K. Comparative studies of sun and solar drying of peeled and unpeeled ginger. Am J Sci Industr Res. 2011;2(2):136–43.
72. Karabulut I, Topcu A, Duran A, Turan S, Ozturk B. Effect of hot air drying and sun drying on color values and β-carotene content of apricot (*Prunus armenica* L.). LWT Food Sci Technol. 2007;40(5):753–8.
73. Morgan CA, Herman N, White PA, Vesey G. Preservation of micro-organisms by drying. A review. J Microbiol Methods. 2006;66(2):183–93.
74. Azaizia Z, Kooli S, Hamdi I, Elkhal W, Guizani AA. Experimental study of a new mixed mode solar greenhouse drying system with and without thermal energy storage for pepper. Renew Energy. 2020;145:1972–84.
75. Hasan Masud M, Karim A, Ananno AA, Ahmed A. Challenges in implementing proposed sustainable food drying techniques, in sustainable food drying techniques in developing countries: prospects and challenges. Cham: Springer International Publishing; 2020. p. 169–85.
76. Curry, G.N., S. Nake, G. Koczberski, M. Oswald, S. Rafflegeau, J. Lummani, E. Peter, and R. Nailina, Disruptive innovation in agriculture: Socio-cultural factors in technology adoption in the developing world. J Rural Stud. 2021.
77. Prakash O, Kumar A. Historical review and recent trends in solar drying systems. Int J Green Energy. 2013;10(7):690–738.
78. Chauhan YB, Rathod PP. A comprehensive review of the solar dryer. Int J Ambient Energy. 2020;41(3):348–67.
79. Prakash O, Kumar A. Solar greenhouse drying: A review. Renew Sustain Energy Rev. 2014;29:905–10.
80. Vivar M, Pichel N, Fuentes M, López-Vargas A. Separating the UV and thermal components during real-time solar disinfection experiments: the effect of temperature. Sol Energy. 2017;146:334–41.
81. Lund, B., A.C. Baird-Parker, T.C. Baird-Parker, G.W. Gould. Gould. Microbiological safety and quality of food. Vol 1. New York: Springer Science & Business Media; 2000.