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REVIEW ARTICLE

Experience of Solar Drying in Africa: Presentation of Designs, Operations, and Models

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Abstract
Africa has a very high solar insolation and a large agrarian sector with a lot of drying of agricultural products carried out with mostly open sun drying. However, efforts have been made by researchers based in Africa working, under changing climatic conditions, to develop solar drying systems, using materials that are locally available. The challenge was that the solar dryers should be used to dry different kinds of products including fish, medicinal plants, fruits, wood, and vegetables and bring the studied material to low moisture content. Most of this research has been obscured since Africa is not at the forefront of solar research, coupled with technological and economic laid-backness. The solar dryers' designs consist of direct, indirect natural or forced convection dryers or even mixed mode. These collectors are mostly tilted southwards at an angle of inclination ranging from 0° to 60° to the horizontal. Design has focused on the utilization of available local materials with some dryers that can be equipped with supplementary heating source or a storage of energy. Solar drying research among the African countries is very low generally and requires investment to boast it. Therefore, this review highlights solar dryers evaluated within the African region, including the quality of the final product, their efficiency, and prediction of its behavior using simulation and mathematical modeling. Pointing the area of future research and development is also emphasized.

Keywords Africa · Design · Auxiliary source · Energy efficiency · Storage · Mathematical modeling · Medicinal plants

Nomenclature

A	Dryer surface area (m^2)
A_s	Surface of the solar collector (m^2)
Cp	Specific heat (J kg^{-1} K^{-1})
C_t	Overall mass transfer coefficient (kg s^{-1} m^{-2} kPa^{-1})
dm	Dry matter
e^*	Saturation vapor density of air at T_a
e	Thickness (m)
f	Solar fraction (%)
F'	Collector efficiency factor (dimensionless)
F_R	Heat removal factor
h	Coefficient of heat transfer by convection (W m^{-2} K^{-1})
h_{cv}	Volumetric heat transfer coefficient (W m^{-3} K^{-1})
hr	Adapted radiative exchange coefficient (W m^{-2} K^{-1})
H_s	Hourly solar radiation on the horizontal surface (W m^{-2})
I	Irradiance (W m^{-2})
k	Adapted conductive exchange coefficient (W m^{-2} K^{-1})
k_{ca}	Air film mass transfer coefficient (kg s^{-1} m^{-2} kPa^{-1})
k_t	Skin mass transfer coefficient (kg s^{-1} m^{-2} kPa^{-1})
L or Lv	Latent heat of vaporization (kJ kg^{-1})
m	Mass (kg)
m_v	Mass of water evaporated (kg)
$\dot{m}$	Air mass flow rate (kg s^{-1})
M	Moisture content (decimal in dry basis)
Mi	Instantaneous moisture content (decimal in dry basis)
M_{loss}	Moisture loss rate from the product (kg s^{-1})
mp	Mass of the drying chamber walls (kg)
P_A	Flux of energy absorbed by the absorber (W m^{-2})

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P_s	Water vapor pressure of the evaporating surface (kPa)
Pv	Flux of radiation absorbed by the glass calculated in watts per square meter
Q_l	Latent heat of water evaporation at 25 °C and 1 atmosphere pressure (kJ kg^{-1})
Q_u	Gained heat energy (J)
S	Surface of the product (m^2)
surf	Surface (m^2)
Sv	Surface of one wall of the drying chamber (m^2)
t	Time (s)
T	Temperature (°C or K)
T_∞	Cold stream temperature (K)
U	Overall heat loss coefficient (W m^{-2} K^{-1})
V_d	Vapor deficit (kg m^{-3})
w	Absolute humidity (kg of water/kg of dry air)
X	Moisture content (kg of water/kg of dry matter)
*	Previous tray
ΔS	Elemental area (m^2)

Subscripts

A	Absorber
ach	Heated air
am	Ambient media
b	Brick
c	Skier vault
dry	Dry matter
e	Exterior
ext	External
f	Product
I	Insulator
i	Interior
int	Interior
ma	Moist air
o	Dryer outlet temperature
p	Polystyrene
pr	Product
s	Sky
sol	Ground
v	Glass
vap	Vapor
w	Wall
we	External wall
wi	Internal wall

Greek symbols

α	Absorptivity of coatings
ε	Emissivity of plates
η_f	Fin efficiency
Ø	Relative humidity
σ	Stefan–Boltzmann constant
τ	Transmittance
θ_z	Dimensionless fin base temperature

Introduction

The potential for solar energy in Africa is enormous. The global yearly horizontal solar radiation for this continent is ranging between 1500 and 2800 kW m^{-2} [103] as shown in Fig. 1. According to Bennamoun [18], Algeria for example has an overall solar potential that is equal 5000 times the country's electricity consumption and 60 times the energy consumed by the European countries. The average daily solar insolation for most African capitals is presented in Table 1. In West Africa, the global radiation ranges from 4.21 to 4.8 kWh m^{-2} day^{-1} in the coastal countries and 5.98–6.57 kWh m^{-2} day^{-1} toward the countries around the Sahara region [34]. This shows that the African region in general has great solar potential that can be developed and applied to solve the energy shortfall. Globally, emphasis on fossil fuel is going down with focus on renewable energy. At the end of 2009, the actual global solar energy generation was 24 GW from total thermal solar installed capacity of 151.7 GW. These solar collectors covered an area of about 217,000,000 m^2 and are mostly located in Organization for Economic Co-operation and Development OECD countries [34]. However, solar application and utilization in Africa is very low although many African countries have developed policies and framework to integrate renewable energy into the energy systems to solve their energy deficit.

Solar energy utilization in Africa has one of two options: either solar thermal systems or photovoltaic systems. Nevertheless, technology for the former is easily adaptable for drying purposes although the latter can still be applied for drying. Panwar et al. [88] recommended solar drying as a promising option for drying materials for tropical and subtropical regions like Africa. Ramde and Forson [91] stated that among all the available energy for drying purpose in Africa, thermal solar drying is the cheapest because it offers limitless, free, and nonpolluted energy with low investment. Solar dryers are safe from foreign body contamination and offer flexibility in terms of design depending on the size of the enterprise and availability of material resources. While many parts of the world have gone far into solar drying because of its benefits, it is still a recent experience in Africa judging from the existing literature. Open sun drying is commonly used for drying, mainly for agricultural products despite its encumbrance due to vagaries of weather. Nevertheless, several researchers have investigated different applications of solar drying systems in different African counties. However, the present status of solar drying in many African countries is still not well documented. The only effort in trying to document this experience was in Algeria done by Bennamoun [18]. Solar drying is a well-known process, but climates and local demands modify its structure; therefore, adaption to the local climate, local material, and the need has been noticed in the structural design of solar dryers all over the world. Therefore,

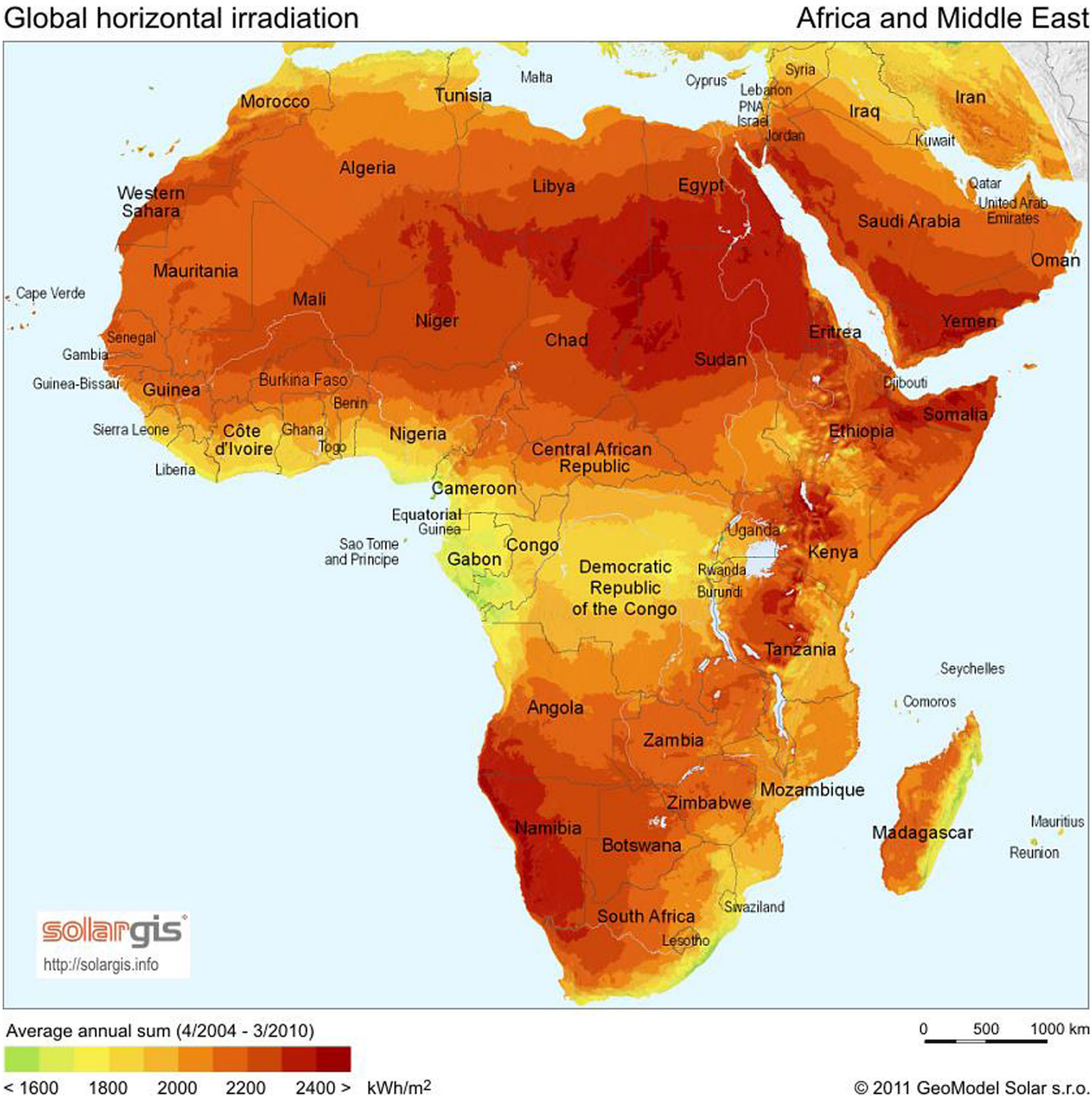


Fig. 1 Yearly sum of global horizontal radiation, 2004–2010 (source: Solargis, http://solargis.info)

this review brings to the fore several solar dryers designed and tested in some African countries and presents mainly experimental and modeling results. The study points to the way forward for future solar drying research in the African continent.

The aim of this review is to present the experience of solar drying and highlights the potential gap that exists in solar drying application in the different African regions. The research highlights the output of different solar drying systems in relation to local geography and provides bases for assessment of solar dryer deployment and economic benefits in Africa. This review paper cannot cover all the works on solar drying in all the African countries, but those reviewed will give an overview of what is going on in solar drying research in the African continent.

Classification of Solar Dryers

Solar dryers can be classified on the basis of the mode of air circulation or the mechanism of hot air contact with the dried product. They are termed

Table 1 Mean daily insolation for Africa over 10 years (source: SolarFine Photoelectric Technology. http://www.solarfine.com)

Country	State/city	Latitude	Longitude	Year mean insolation for 10 years
Burkina Faso	Ouagadougou	12° 24′ N	1° 30′ E	6.02
Central African Republic	Bangui	18° 32′ N	120° 36′ E	5.12
Cameroon	Yaoundé	3° 48′ N	11° 30′ W	4.98
Djibouti	Djibouti	11° 33′ N	43° 09′ E	6.37
Algeria	Algiers	36° 50′ N	3° E	4.45
Egypt	Cairo	29° 35′ N	31° 09′ E	5.68
Ethiopia	Addis Ababa	9° 2′ N	38° 42′ E	5.84
Ghana	Accra	5° 36′ N	0° 12′ W	5.2
Gambia	Gambia	13° 28′ N	16° 39′ W	5.76
Guinea	Conakry	9° 36′ N	13° 36′ E	5.78
Kenya	Nairobi	1° 16′ S	36° 48′ E	5.62
Liberia	Liberia	6° 30′ N	9° 30′ W	5.03
Libya	Tripoli	32° 54′ N	13° 11′ E	5.48
Morocco	Rabat	32° 32′ N	9° 17′ W	5.21
Mali	Bamako	12° 30′ N	7° 54′ E	6.09
Mauritania	Nouakchott	17° 45′ N	15° 45′ E	6.55
Niger	Niamey	13° 30′ N	2° 12′ W	6.12
Nigeria	Abuja	9° 12′ N	7° 11′ E	5.61
Sudan	Khartoum	15° 33′ N	32° 32′ E	6.31
Sierra Leone	Freetown	8° 29′ N	13° 14′ W	4.8
Senegal	Dakar	14° 38′ N	17° 27′ W	5.56
Somali	Mogadishu	2° 02′ N	45° 20′ E	6.04
Tunisia	Tunis	36° 47.8′ N	10° 6.8′ E	4.7

- Passive when air circulation through the dryer is by natural convection
- Active when the movement is in forced convection mode using blowers or fans
- Mixed convection mode when the air circulation method combines passive and active mode [38–40] with variable cost implications [102]

These dryers can be further subclassified based on the reception of the solar radiation as follows:

- Direct or integral type solar dryers—the collector and the drying chamber form a single unit.

The dried material is directly exposed to the direct incident solar radiation. Direct solar dryers can be cabinet type and referred to as cabinet solar dryers or hot box with transparent covering as well [53, 75, 94]. Some designs can be in the form of greenhouse or a transparent blanket or canopy over the drying tray [79]. They are relatively cheap and simple in design. Air movement either in passive or active mode through the dryer is created by opposite openings on two sides of the box or sometimes a chimney can be attached. These dryers in passive modes have a very low initial investment or additional running costs. El-Sabaii and Shalaby [45] listed one of their disadvantages: condensation can take place (after a long process time) inside the collector leading to the reduction of their efficiency. This may not always be the case in some African countries with very low humidity and fast moving of the air coupled with high solar insolation.

- Indirect or distributive solar dryers—the drying system is divided into two parts: solar collector where the air is first preheated before going inside the drying chamber. Method of collection and channeling of the heat to the drying chamber can be based on bare flat plate or covered flat collector (single or double air pass, with or without fins) or through evacuation tubes [51, 59, 90, 101]. It is common to see during indirect solar drying the use of additional instruments that give control on the operating conditions, such as a heater or heat storage material.
- Mixed-mode solar dryers—some designs incorporate two heat reception mode in mixed mode. Accordingly, the drying chamber is glazed with transparent covering, so that they also receive direct solar irradiance as the collector.
- Hybrid solar dryers incorporate other materials such as heat pump, biomass, photovoltaic cells, thermal storage systems (rock-gravel bed, desiccant bed, water), and any

other auxiliary heat source to supplement heat during off-sunshine hours. Consequently, the drying process continues which will avoid rewetting the product [72, 16, 17, 33, 35, 52, 64, 104].

Chaudhari and Salve [30] listed the advantages and the disadvantages of direct solar drying versus indirect solar drying, which were summarized into the following points:

- Drying rate is usually higher during indirect solar drying due to the use of control instruments. Accordingly, the effect of the ambient conditions is less important.
- Because of the application of controlled operating conditions during indirect solar drying, a better quality of the final product, including preservation of nutrients, can be obtained.
- The loss in product during indirect solar drying, due to overexposition to solar radiation or bacterial contamination, is less important.
- The initial cost of an indirect solar dryer is usually higher than a direct solar dryer.
- Contrary to the direct solar dryer, the control of the operating conditions in the indirect solar dryer allows using it in unfavorable weather conditions, such as the night, the rainy days, and winter. This can reduce the payback time of the indirect solar dryer.

Presentation of the Experience of Africa in Solar Drying

Climatic, economic, and design factors affect directly the performances of solar dryers. The African continent is a very large continent characterized by tropical, subtropical, and temperate climate with on average a low income. These numerous factors led having many designs available both in terms of the choice of design material, performance, and even esthetics. This review presents published solar drying studies in some African regions which includes North Africa, West Africa, East Africa, and Southern Africa. This type of presentation is chosen due to regional economic and climatic variations, which has a direct effect on the design and, in some cases, the product evaluated.

North Africa

In this part, the focus will be on Algeria, Tunisia, Morocco, and Egypt. The Algerian capital Algiers (36° 50′ N, 3° E) receives average daily insolation of 4.45 kWh m^{-2} day^{-1} as shown in Table 1 which is enough to drive solar drying application. The total solar energy potential for Algeria has been projected to be about 169,440 TW h per year which has been estimated to average 5000 times the yearly electricity consumption in the country [18]. Therefore, the country has an enormous potential for solar energy application although the current major solar project in Algeria is the Hassi RMel 25-MW power plant for electricity generation [11]. Tunisia lies at the northeast of Africa with similar climate with Algeria, Morocco, and Libya with lower average solar insolation of 4.7 kWh m^{-2} day^{-1} (Table 2). This radiation is one of the lowest in Africa but still high enough to find solar energy applications. In Tunisia, agriculture consumes about 7% of the current energy generation, placing it at the lowest level of energy utilization [96]. The use of solar energy can reduce the cost of energy in agriculture and other small- and medium-scale energy users. Currently, Tunisia has about 253 MW of installed solar capacity for all energy uses with the hope of increasing it to 1700 MW by 2030 [96]. Although this is huge, the figure is a conservative estimate because solar energy utilization in drying does not follow a grid system in most cases and therefore is underreported. Egypt receives around 2300–2800 kWh m^{-2} per year of solar irradiation as shown in Fig. 1. As in 2011, Egypt has an installed PV capacity of 20 MW [103]. This is low considering the enormous potential of Egypt as a solar energy hub with average daily solar insolation of 5.68 kWh m^{-2} day^{-1} (Table 1). However, several solar dryers, in particular for food processing, were developed in this region. Renewable energy constitutes about 0.4% of energy needs of Morocco excluding biomass. However, there is a serious encouragement for the increase of its use. Accordingly, the country is working on the accomplishment of a huge project that should be completed by 2020. The project is about the construction of the world's largest solar farm for energy generation in the country. Based on the solar radiation map in Fig. 1, Morocco receives the highest amounts compared to most other African countries. It lies about 2500–2800 kWh m^{-2} per year. The country has high rates of solar insolation of about 3000–3600 h of sunshine per year. Morocco is hot and dry during the summer, while it has a temperate climate during the winter with occasional rain. Therefore, drying is mostly applied using open sun drying. However, some solar dryers had been developed in the country in order to dry agricultural products and medicinal plants.

Experience of North Africa in Solar Drying

Solar drying experience in Algeria, albeit relatively new, has been presented in detail up to 2010 by Bennamoun [18]. Most of these dryers are developed at the Development of Renewable Energies Center (C.D.E.R in French). This review, therefore, will only highlight the omitted publications and the new studies. A summary of the reviewed dryers as presented by Bennamoun [18] is shown in Table 2.

A simple dryer with chimney (Fig. 2b) was studied by Chouicha et al. [31] on the valorization of treated Deglet-

Table 2 Summary of solar dryers reviewed by Bennamoun [18]

Author (s)	Type	Operating mode	Products	Outcome	Location
El Mokretar et al. [44]	Direct cabinet solar dryer	Passive	Mint, vervain, laurel, grape, prune, banana, fig, date, and pepper	Drying time of 1 kg = 8 to 268 h Inclination of the collector = 55°, 15°, vertical Drying air temperature = 46 °C	Algiers
Miri et al. [73]	Indirect solar dryer	Passive	Mint, vervain, laurel, grape, pepper	Drying time of 0.2 to 0.3 kg in 30–268 h Collector dimensions = 2 m × 0.94 m × 0.12 m Drying air temperature = 50–60 °C	Algiers
Boubekri et al. [25, 26])	Indirect solar dryer	Passive	Date fruit	Drying time from 0.55 to 0.35 kg/kg in 1–9 h Collector dimensions = 2 m × 1 m × 0.13 m Collector inclination = 16° Drying chamber dimensions = 1 m × 0.8 m × 0.8 m	Ouargla
Ferradji et al. [49]	Indirect solar dryer	Passive	Grapes	Drying efficiency of about: 52% Solar collector area: 1.72 m^2 Drying chamber area: 0.91 m^2 Mass: 8 kg Constant air temperature: 65 °C Use of auxiliary heating source	Algiers
Boulemtafes-Boukadoum et al.[29]	Indirect solar dryer	Active	Tomatoes, tobacco, figs, mint, and laurel	Drying time = 5 to 10 h Solar collector area = 1.88 m^2 Collector inclined by 36° Drying chamber volume = 1 m^3 Constant air temperature = 50 °C Auxiliary heating source	Algiers
Boughali et al. [27]	Indirect solar dryer	Active (hybrid)	Tomato	Drying time of 2 kg = 5.5 to 11.5 h Temperature = 50–75 °C Solar collector area = 2.45 m^2 Drying chamber dimensions = 1.65 m × 1 m × 0.6 m Use of auxiliary heating source Collector efficiency = 19–52% Overall efficiency = 13–47.5%	Ouargla
Ferradji et al. [50]	Indirect solar dryer	Active	Apricot	Reduced the moisture by 50% in 10 h Length of the solar collector = 24 m	Algiers
Ferradji et al. [49]	Indirect solar dryer	Ameliorated active	–	Increased collector efficiency by 49.23% Use of hot gas as auxiliary heating source	Algiers

Nour dates and operating in a direct forced convection mode. It consisted of a cylindrical chimney (1 m long and 0.1 m in diameter) and a drying room with six covering glass panels positioned at the front, back, and on the sides with two of the glass panels tilted at 31° from the horizontal. Four of the glass panels were positioned on a galvanized steel sheet and insulated with polystyrene. The drying room consists of two steel sheets separated with polystyrene layer. Further details about this dryer in terms of energy consumption or capacity of the dryer are not presented. The operating temperature ranged from 48.2 to 68 °C. This temperature is sufficient to destroy yeasts or molds in the final product. Utilization of several glass components on the body of this dryer makes it very fragile and increases the initial cost of the dryer. Nevertheless, this dryer operates passively which makes it attractive to be used in rural areas, and the relatively low maintenance cost makes it commercially viable for low-income setting like most African countries where income per person can be less than 1$. Yet again, because the drying rate was faster than the open sun drying, consequently, time can be saved compared to traditional drying systems. However, the study revealed its major disadvantage which showed that the moisture content decreased quickly which deteriorates sensitive components and leads to caramelization of sugar. This study gives a proof that in a country like Algeria with very high solar radiation, adopting this type of dryer can lead to a bad final product with deterioration of color and other sensory attributes. However, this design is not common in Algeria as the literature review revealed. The only similar dryer was used by El Mokretar et al. [44].

Boulemtafes-Boukadoum and Benzaoui [28] studied solar drying of mint using an indirect solar dryer developed at the C.D.E.R. The description of the developed solar dryer has

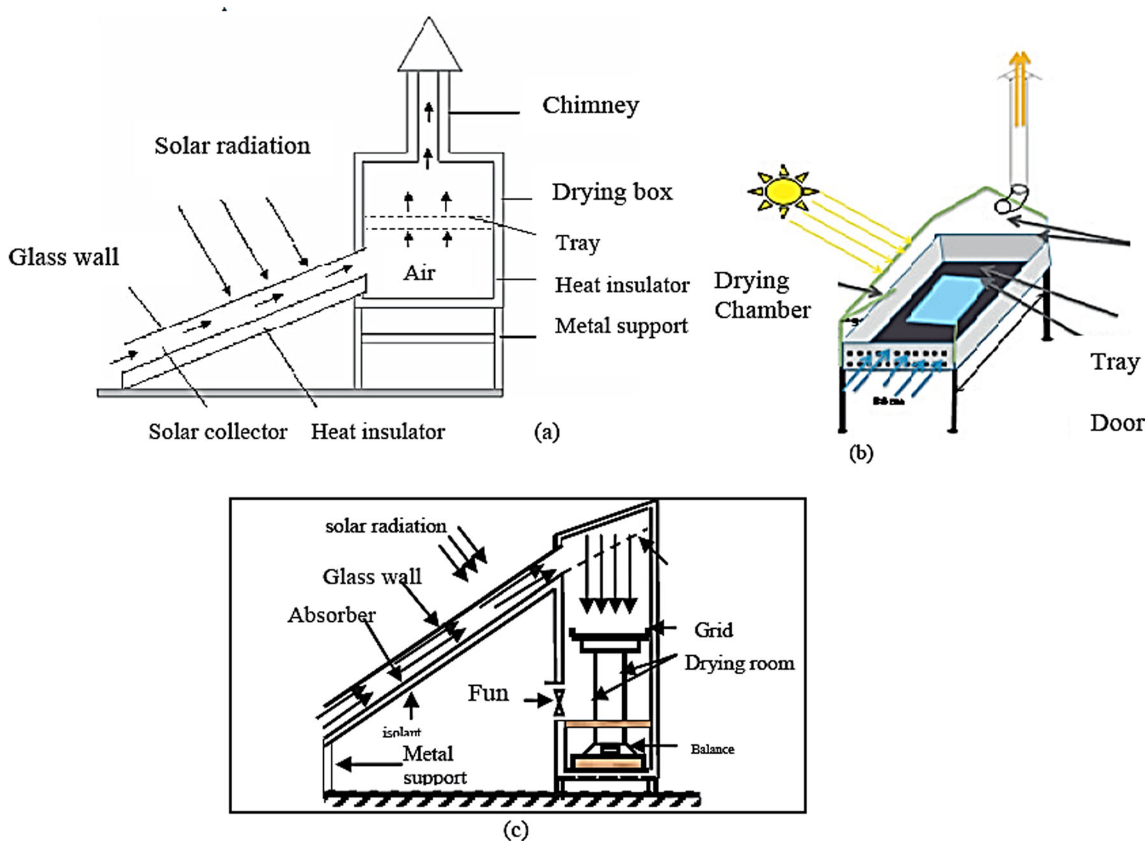


Fig. 2 **a**–**c** Three different solar dryers [31]

been presented by Bennamoun [18]. The collector area of this dryer was 2 m^2. Evaluation of the dryer showed that as the global radiation in the region of the test changes between 400 and 850 W m^{-2}, it takes 14 h to reach the wanted moisture content of the mint. The esthetics of this dryer was very good, and because the solar radiation is not directly incident on the product, caramelization and localized thermal damage did not arise. This type of dryer can be useful for drying vegetables and green medicinal plants in which vitamins and color are highly sensitive to the radiation and the drying method. Moreover, because they have high operating temperatures, the dryers can be suitable for deep layer drying of crops. However, like other similar dryers, fluctuation in air temperature of the drying chamber can lead to rewetting of the dried products. This dryer design is more intricate and requires more investment and maintenance cost. However, it can be advantageous for large farms or industries with high capital since the quality of the final product is better and throughput capacity is higher than direct solar dryers. The results of the evaluation of the dryer showed that the efficiency of the solar dryer changed from 10 to 30% which is very low. According to the study, the reason for the low efficiency of the dryer as expected was because the air going through the bed of mint was flowing by natural convection with an average speed less than 0.2 m/s. It is generally acknowledged that forced convection dryer of this type performed better than natural convection with better quality of the final product [17, 18]. Therefore, integrating the dryer with fans or blowers usually improves its efficiency but at an increased cost which may likely alienate most rural farmers in Africa without basic electricity. The solution for this is powering the dryer with photovoltaic cells which again will increase cost and may not be affordable to the poor farmers in the continent. The authors [28] performed energy and exergy analysis to estimate the total useful energy used for drying purposes and losses. Based on the energy analysis, the maximum energy consumption under such drying conditions was 300 and 450 W for the first and the second day, respectively. Meanwhile, the exergy efficiency reported was less than 50%. However, the research did not asses the overall quality of the product which should be included in the overall drying system performance. Yet again, the cost of this dryer cannot be assessed due to nondisclosure of the choice of material for the design. Chouicha et al. [31] presented two sets of indirect solar dryers with application to Deglet-Nour dates (Fig. 2a, c). One of the two dryers is the one used by Boulemtafes-Boukadoum and Benzaoui [28] which is a passive indirect solar dryer, while the second dryer (Fig. 2c) is an active hybrid indirect solar dryer equipped with cylindrical chimney and 1.5 kW auxiliary heater. The inclination of the two dryers was 16 and 31°, respectively, from the horizontal and they were directed to the south. The results of the experiment showed that the two dryers dried the date from 0.5 to 0.35 kg water/kg dry matter in the range of 12.5–22 h. Although the integration of an auxiliary heater to the solar dryer will solve the problem of off-sunshine hours and rewetting of the product, it will also increase the cost of the dryer. Therefore, there is a need to perform techno-economic assessment of these dryers to ascertain its cost effectiveness in a poor continent like Africa. In assessing the color quality of dried dates, it was concluded that the indirect natural convection dryer has given a better quality of the final product. Khama et al. [66] presented an industrial scale indirect solar dryer (Fig. 3) for drying tomatoes in Ouargla in the southeast of Algeria. The dryer can operate in mixed convection mode with a flat plat solar collector measuring 1.90 m × 1.14 m × 0.16 m and covered with glass and can be tilted southwards between 0 and 60°. The dryer reduced the moisture content of tomatoes from 14.32 to 0.14 kg water/kg dry matter in 12 h when the crop was spread in a single layer. The authors [66] reported that the collector efficiency was about 66.56% when applying forced convection and 46.32% during natural convection. Therefore, the end users have the option of choice based on operational and economic factors. They found out that increasing solar radiation has more effect on the temperature of the solar collector in passive than the active convection mode. Benhamou et al. [15] studied a forced convective solar dryer in the region of Algiers (altitude 5 m, latitude 36° 39′, longitude 2° 42′ east) and tested olive pomace and colocynth. The detailed description of this dryer was not presented. However, the dryer achieved a temperature of up to 57–66.6 °C with an average value of 30 °C. Required

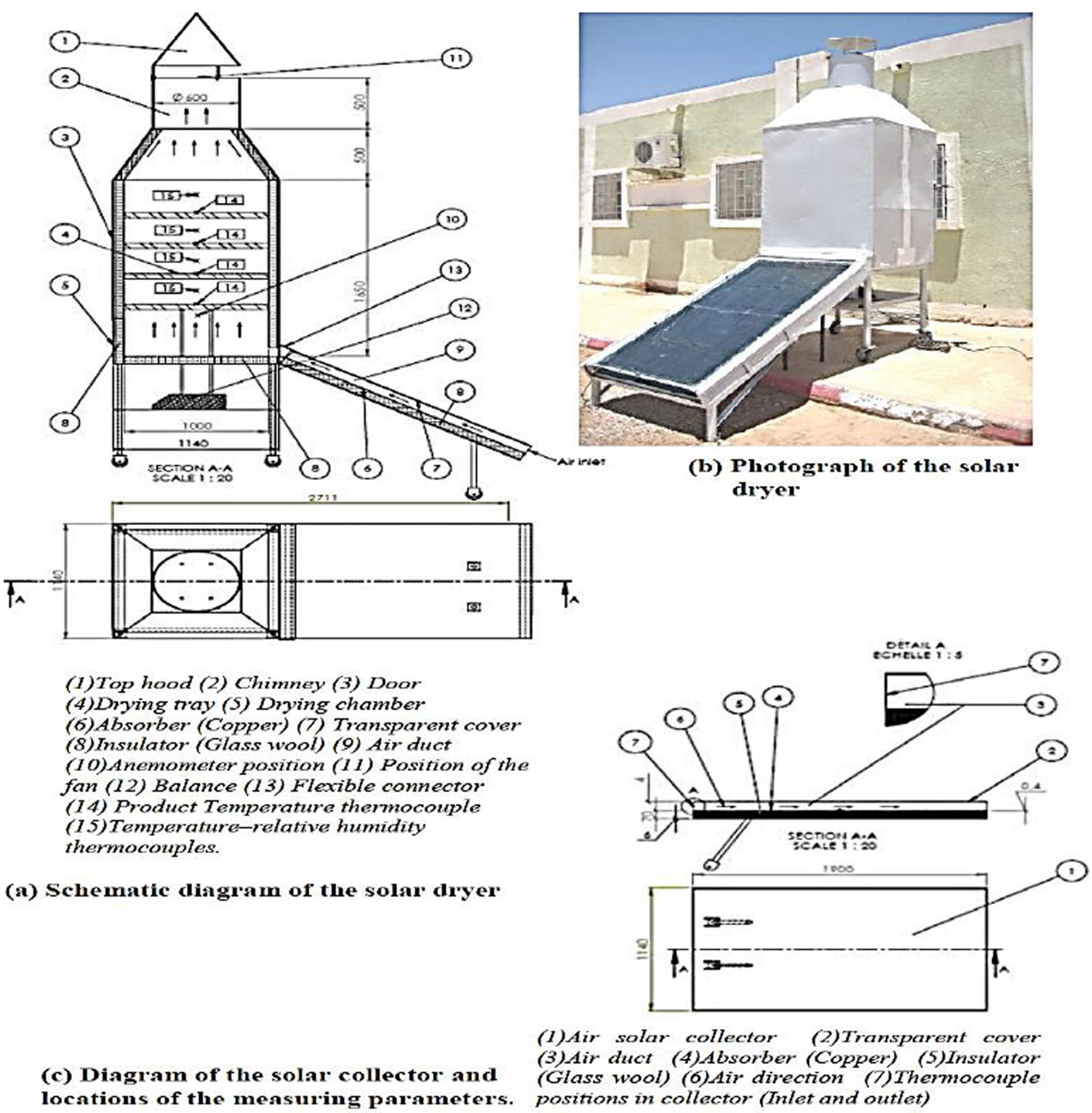


Fig. 3 Indirect solar dryer [66]

moisture content was achieved between 5 and 9 h for the two products. The results also show that increasing the drying temperature increased the dryer humidity because the moisture released by the product in steam form was absorbed by the drying air. Simulation of the solar dryer was also performed using GRAPHER software and the best equation relating temperature and radiation was written under the following form:

$$T = \left(3.35046^{-5}\right)I^3 - \left(6.82243^{-5}\right)I^2 + (0.0863886)I - 0.070889 \quad (1)$$

An experimental study of a hybrid indirect solar dryer equipped with auxiliary heater of 4 kW was carried out by Nour-Eddine et al. [80] in order to dry spearmint leaves (*Mentha spicata*). As solar drying operates during sunshine hours, rewetting of the products usually occurs during off-sunshine hours, and integration of an auxiliary heater can solve the problem. The authors [80] opted then for integration of auxiliary heaters with recycled air. This solution added to the initial investment cost of the solar dryer. There is a need to perform techno-economic assessment of these dryer as well as previously stated to ascertain its cost effectiveness in a poor continent like Africa. The dryer consists of flat air solar collector tilted 31° southwards and linked to a parallelepiped drying chamber (0.93 m × 0.65 m × 1.9 m) through a stainless evacuation tube (0.15 m in diameter) linked to a suction fan (0.1 kW). The need for electricity or supplementary power to operate the fans and heater will pose a challenge in rural Africa with mostly no basic electricity. The solution will also be as suggested in Boulemtafes-Boukadoum et al. (2011), with similar consequences. The authors [80] found out that peak solar fraction can be attained with low weight of the dried product, high air recycling rate, and for drying air temperature of about 30 °C. Additionally, the solar fraction reaches its maximum value at lower mass flow rates, and the collector area has a considerable effect on the solar fraction. Drying 10 kg of the product achieved the solar fraction and collector efficiency of about 60 and 50% with collector area of 2 m^2. However, the energy consumption and quality of the final product were not investigated.

Several active solar dryers had been developed in Tunisia for drying purposes. A mixed-mode solar greenhouse dryer was developed at the Research and Technology Centre of Energy (CRTEn) in Borj Cedria North of Tunisia by El Khadraoui et al. [43] (Fig. 4). The greenhouse dryer was tested for red pepper. The dryer constituted of a solar collector that had the following dimensions 2.0 m × 1.0 m × 0.28 m and was covered with a transparent glass, giving a gap of 0.05 m. The absorber is 0.001 m thick insulated with polyurethane. The collector was tilted at 37° southwards. The floor area of the greenhouse is 14.8 m^2 placed at the center with the wall and roofs covered with plexiglass and equipped with centrifugal fan. The red pepper (80 kg) was dried to 0.17 (g water/g dry matter) from an initial moisture content of 12.15 (g water/g dry matter) in 17 h. Economic analysis was carried out based on annualized cost method. The result showed a payback period of 1.17 years with a lifetime of 20 years for the dryer at maximum drying capacity of 80 kg. In fact, just one material was tested to check if it will be useful to test other food materials to have an idea if the material affects the payback period and the lifetime of the solar dryer. This dryer is an improved version of most mixed-mode dryers reported and can operate in an industrial scale with attractive esthetics. This is common

Fig. 4 Mixed-mode greenhouse solar dryer [43]

to all the dryers found in Tunisia with the exception of few. However, due to elaborate design, it will require high investment cost which might be beyond the financial capacity of most rural farmers in Africa. Nevertheless, due to its scaled-up size, farmers can pull together resources to obtain one for combined use. The only limitation will be using it in regions without electricity, so fans cannot be used. The exergetic and energetic studies are also necessary because it will give more information about the optimum design, for example the use of one fan or several small fans and their distribution within the greenhouse chamber. Slama and Combarnous [95] studied the effect of baffles on drying of orange peels using an indirect forced convection solar dryer (Fig. 5). This unique design consists of transverse, mixed, or longitudinal baffles (2 m × 1 m) that were placed directly on the insulator or absorber to increase air turbulence and heat transfer. The reason for placing baffles is to increase the collector efficiency, but it will still add to the initial cost of the dryer. The results showed that the use of baffles and their placement affected the efficiency as it increased by 14% compared to the collector without baffles. This dryer runs on natural convection and the use of baffles eliminated the deployment of fan or blower for air conveyance with improved efficiency. Therefore, this dryer will be useful even in rural areas where there is no electricity in Africa, and rigorous research including techno-economic analysis should be pursued on it because it shows promising results. The drying results showed that a day was enough to dry the peel to 15% wet basis moisture content. Fadhel et al. [46, 47] dried grapes and pepper using the same solar tunnel dryer and a natural convection solar dryer. However, the authors did not give a description of the second dryer. The dryers were developed at the Research and Technology Center of Energy, Hammam-Lif, Tunisia. The area of the greenhouse was 100 m^2. Their findings showed that the natural convection solar dryer was more effective than the solar tunnel dryer for grapes and red pepper in terms of drying time. In fact, the natural convection dryer dried the grapes and pepper in 77 and 73 h, while the tunnel one dried the grapes in 119 and 79 h, respectively. The performance of an indirect forced convection solar tunnel dryer (Fig. 6) developed at the Centre for Research and Technologies of Energy was performed by Oueslati et al. [87]. The system consisted of four solar collectors connected to a galvanized iron sheet tunnel (4 m × 2 m × 1.8 m) tilted 36.7–45° toward the south. The tunnel served as the drying chamber and the wall was insulated with polyurethane 0.15 m thick. The dryer is supported with natural gas heating at the north side of the tunnel that went inside the drying chamber using a fan. The air exit was through the chimney mounted on the tunnel. Around 200 min was necessary to dry the product at a temperature range of 55–75 °C.

An active solar dryer integrated with gravel as thermal storage was developed by Ayadi et al. [7] for drying medicinal and aromatic plants in Radés area of Tunisia. The dryer consists of corrugated absorber (2 m × 1 m) with single glazing tilted by 60° to the horizontal. The collector which can be detached during the nighttime was linked to parallelepiped shaped thermal storage chamber. This parallelepiped shaped thermal storage chamber (2.1 m × 0.4 m × 0.33 m) was then connected to the drying chamber by an insulated waterproof air duct. The flexibility of the design makes it adaptable to weather conditions; however, powering the fans will face the same challenge as similar dryers in the African setting. A drying efficiency of 42.78% was achieved with this dryer. This efficiency can be considered as an excellent result compared to the efficiency of other designs. However, quality characteristics of the dried product were not investigated. Bahloul et al. [9] presented the effect of solar drying on the quality characteristics of olive leaves. The authors [9] used a forced convection solar dryer equipped with an auxiliary heater developed and tested in Sfax area of Tunisia. It was

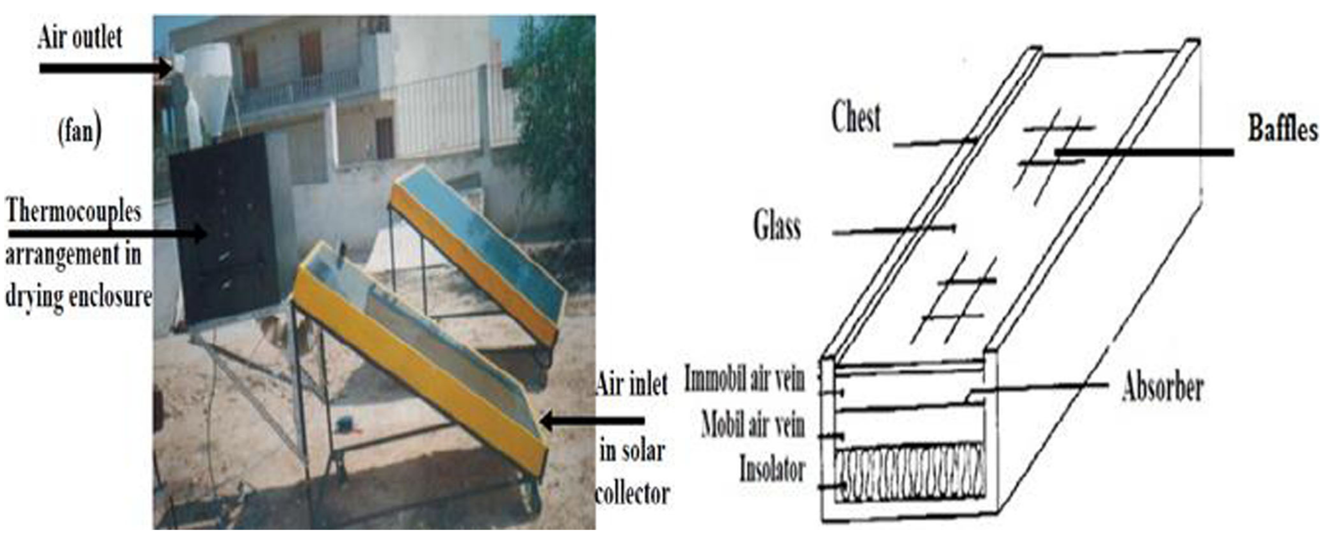


Fig. 5 Solar dryer with baffles [95]

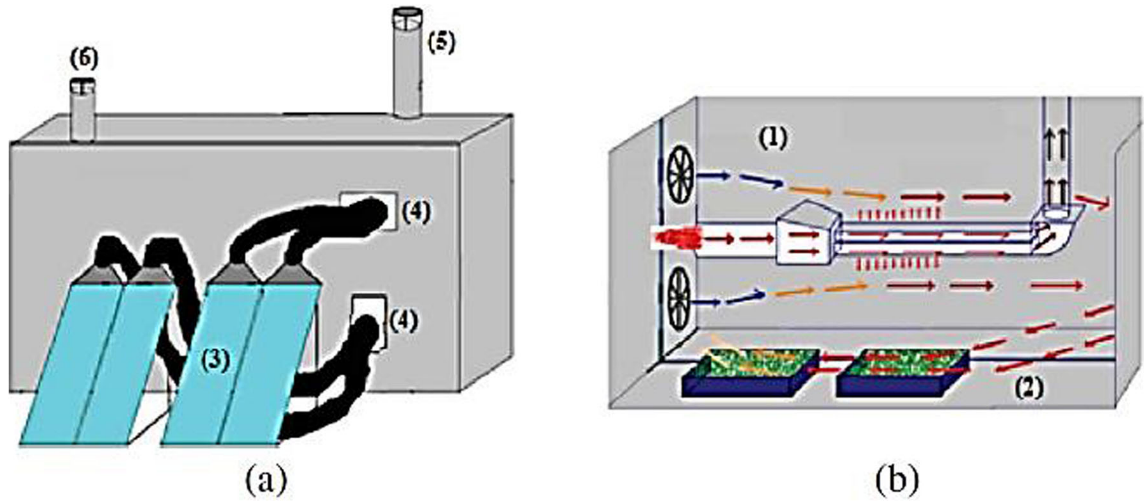


Fig. 6 Schematic view of the hybrid solar tunnel dryer. **a** Isometric view. **b** Exploded view. (1) Supplementary heating path, (2) drying chamber containing the trays, (3) four solar air collectors, (4) solar airflow tubes, (5) gas heater chimney, (6) moist air outlet [87]

concluded that the color characteristics and bioactive compounds were significantly affected by the drying operating conditions.

Two passive direct solar dryers are presented by Hassanain [56] for drying of medicinal plants in Ismailia, Egypt. One was unglazed passive solar dryer (Fig. 7), while the other was greenhouse passive solar dryer. The unglazed passive solar dryer was equipped with 4-m-high black-painted chimney which was shortened to 1 m during the drying trials in March because of wind. The drying rack was the basement of the drying system which enlarges the dryer capacity. The greenhouse solar dryer measured had an area of about 12 m^2 oriented east-west with an uneven roof that slopes southwards. Drying trial was carried out in March, April, and August. This period was characterized with low average solar radiation (597 W m^{-2} in March and 602 W m^{-2} in August), temperature (26.2 °C in March and 31.5 °C in August) and low relative humidity (42.1% in March and 47.5% in August). It was able to decrease the moisture content of the sage (*Salvia officinalis* L.) using this drying system, from 70% w.b. to 45.96–58.32% in 10 days, in March. Meanwhile it took 30, 48, 30, and 70 h to dry henna, rosemary, marjoram, and moghat, respectively. Unfortunately, no information regarding either the efficiency of the drying system or the quality of the final product is

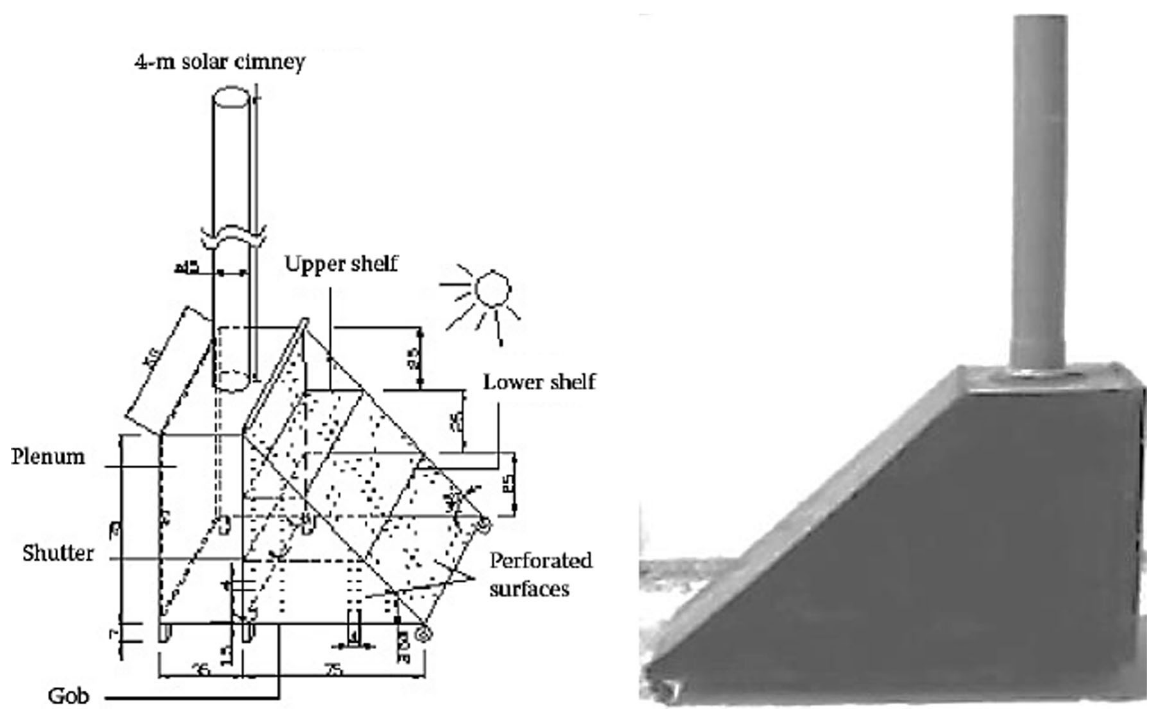


Fig. 7 Unglazed natural convection solar dryer [57]

provided in this work. Sallam et al. [93] compared the performances of two dryers, one being a direct solar dryer (Fig. 8) and a second indirect solar dryer for mint. These dryers were installed on a building roof in Giza, Egypt. The direct dryer was covered with a transparent polyethylene film, while the indirect one was covered with black polyethylene film. This dryer (Fig. 7) is similar to most dryers found in Nigeria based on the material of construction and will have the same prospects although Egypt is less humid than most parts of Nigeria. Therefore, susceptibility to microbial attack necessitated by high humidity will be less. However, they are of lower capacity when compared with most solar dryers developed in Nigeria. It took about 30–32 h to dry the mint for both dryers. There was no significant variation in drying time for the two methods, due to the high air velocity. This still calls to question the benefit of solar drying in Egypt. Hassanain [58] investigated a mixed-mode solar dryer for drying banana in Ismailia, Egypt (30.5° N, 32.41° E). The dryer consists of a solar collector (1 m × 0.5 m × 0.1 m) made from 50-mm-thick wood with an inclination of about 30° to the horizontal. The absorber was aluminum plate insulated with polyethylene and painted matt black. The cover was transparent glass pane. The drying chamber was made flexible from aluminum plate and could be positioned vertically (Fig. 9a) or horizontally (Fig. 9b). The drying chamber was covered with the same transparent glass pane. During evaluation, the maximum irradiance was about 750–900 W m^{-2} with a dryer temperature reaching 46–55 °C for the two orientations. The results show that when drying the crops with the drying chamber placed in the horizontal orientation, the crops dried 3 days faster than when the drying chamber is placed in the vertical orientation.

Fig. 8 Direct solar dryer [93]

Bahnasawy and Shenana [10] presented a passive indirect solar dryer (Fig. 10) with application to fermented dairy products, and the system was tested in Benha area of Egypt. The dryer consisted of two solar collectors tilted at an angle and placed opposite sides of the base of the drying chamber (0.6 m × 1.0 m × 1.65 m). The absorber was made up of 1 m^2 black sheet. Evaluation of the dryer showed that drying time of about 50 h for most products which was similar to sun drying. This showed that Egyptian climate favored sun drying at lower cost due to mostly windy weather with low humidity which encouraged the application of sun drying as also found out by Sallam et al. [93]. It implies that passive solar dryers might give similar results to open sun drying in terms of drying time unless a different design is adopted. The utilization of two solar collectors tilted in opposite direction might not have much desired effects, rather it will increase cost and also make the design too elaborate. The quality of the final products and the payback of the systems must be the most important points to investigate to make decision about the most adequate drying system. Aissa et al. [4] presented forced convection solar dryer for drying sponge cotton under the climatic conditions of Aswan, Egypt (N 23° 58′ and E 32° 47′). The wooden drying chamber measured 1.0 × 0.6 × 1.2 m^3 with hollow chimney 0.4 m high attached to it and painted in black. During the test, the average daily solar radiation ranged between 645.71 and 714.39 W m^{-2} with maximum values reaching 1218 to 1259 W m^{-2}. The average daily temperature was 42.35 °C and the drying temperature attained 53.68 °C. Evaluation of the test results showed a maximum drying efficiency of 18.6% of the developed drying system.

A solar dryer was developed at the Centre de Mise en Valeur (CMV) at Haouz [54]. The solar dryer runs with both electricity and photovoltaic cells to power the fans which control the drying temperature. The dryer was made of hollow bricks which was supported by reinforced concrete frame and used to dry fruits, vegetables, and medicinal plants. The length of the dryer and collector was adjustable depending on the needs; however, the entire length was 30 m with a width of 2 m. When the dryer was operating using PV mode, it runs an axial fan, but when in electricity mode, it runs on radial fan. The absorber had an area of 18.8 m^2 mounted on a plastic sheet and served as the solar collector. During drying of fruits and vegetables, the drying chamber was located closer to the collector due to the high temperature required but was connected through a passage to the drying chamber when used for medicinal plants. Lahsasni et al. [70] and Lamharrar et al. [71] presented the same indirect, forced convection solar dryer (Fig. 11) with 4 kW auxiliary heater for drying prickly pear cladode (*Opuntia ficus indica* and *Artemisia herba-alba*). The collector had the following dimensions: 1 m × 2.5 m with an absorber made from galvanized iron and painted in black. The collector was made of wood and covered with transparent glass oriented toward the south at 31° to the horizontal. The wooden drying chamber (1.4 m × 0.5 m × 0.9 m) contained

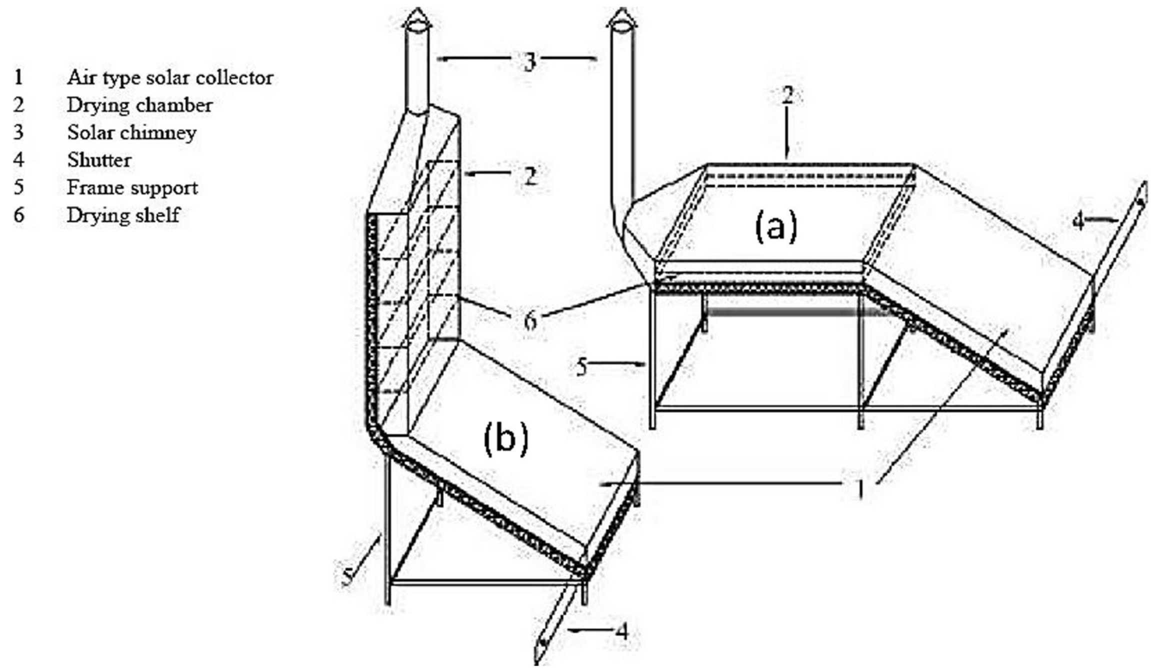


Fig. 9 **a**, **b** Mixed-mode solar dryer [58]

ten shelves. The use of wood and deployment of fans will pose the same problem as similar dryers previously discussed. The dryer had two fans for sucking out air and for fresh air circulation in the drying chamber. Drying tests were performed between 50 and 80 °C for both crops. Drying was accomplished within 1–8 h of active drying. Mathematical modeling on the drying curves showed that Page's equation best predicted the drying behavior of prickly pear cladode, while the Midilli-Kuck model was the best model that could be fitted for *Artemisia herba-alba.* Chimi et al. [32] dried figs using an industrial solar dryer developed by UNIDO for small-scale operations in northern Morocco. Drying time was 3–8 h and

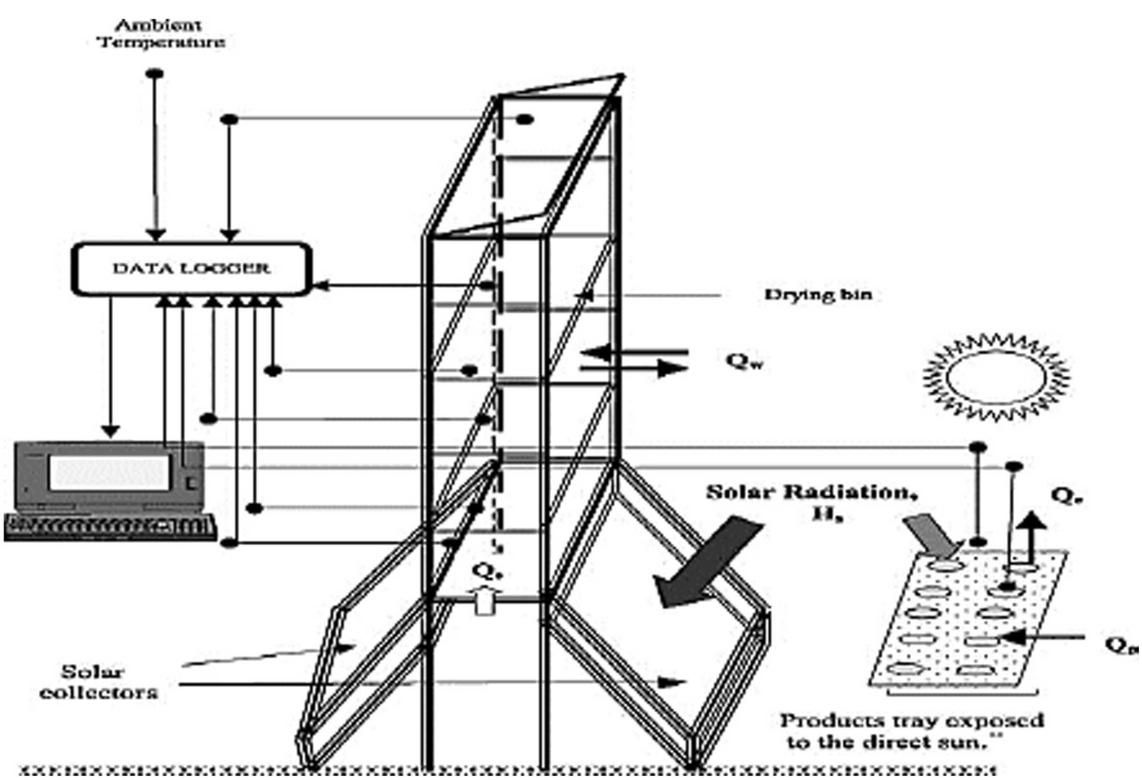


Fig. 10 Schematic diagram of double collector passive solar dryer [10]

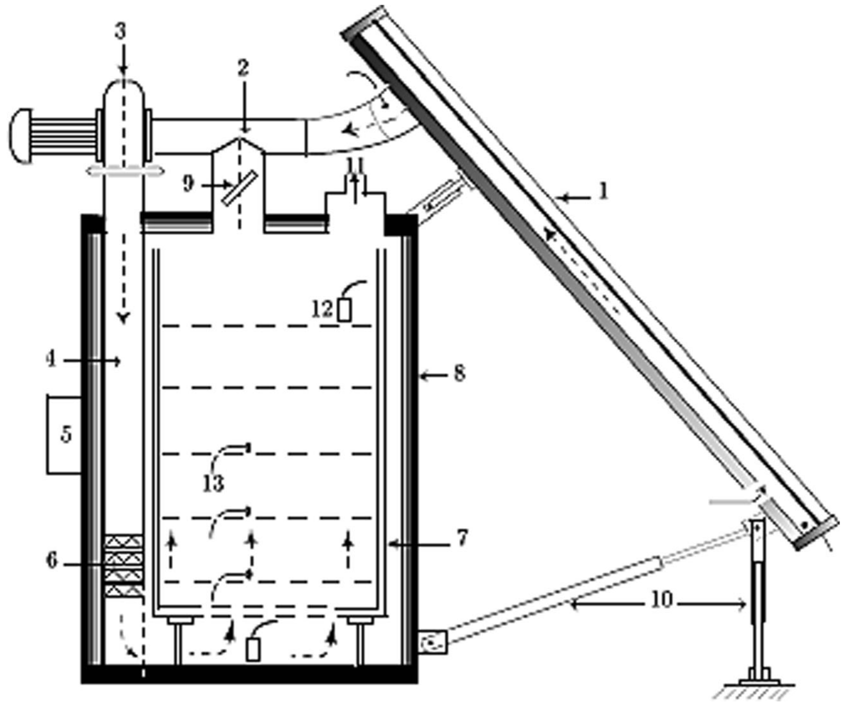


Fig. 11 Forced convection solar dryer [71]. (1) Solar collector, (2) direction of fan, (3) fan, (4) direction of aspiration, (5) control box, (6) auxiliary heating system, (7) mobile wagon, (8) drying cabinet, (9) recycling air, (10) control foot, (11) exit of air, (12) humidity probes, (13) thermocouples

depended on several parameters such as the intensity of the solar radiation, air movement, and humidity.

Bekkioui et al. [13, 14] presented a forced convection greenhouse solar dryer to dry wood plates. This dryer had also been used by Youssefi [105] and Elkannafi [42]. It had the following dimensions: 2.5 m × 1.8 m × (1.45 on south wall, 2.25 m on north wall). The roof was a 6-mm-thick glass that sloped southwards at an angle of 25°. The east, west, and south walls of the absorber used single glass. The walls were made of polystyrene placed in between cork and concrete. A circulation fan was placed above the rack and the air vent flowed through holes on the north wall. The dryer took 17 days to dry 1 m^3 of pine of pine lumber from 35 to 10% moisture content. A simulation study carried out using the numerical approach on this dryer using the climate of Rabat (32° N, 7° E) and Essaouira, Morocco, enabled the close prediction of moisture content of the lumber at various thicknesses and temperatures of the drying chamber.

Mathematical Modeling of Solar Dryers in North Africa

Mathematical modeling and simulation had been another part used in order to study theoretically the behavior of different solar drying systems. Generally, models and simulation can be mechanistic or empirical; however, the choice depends on the simplicity of computation, cost, and the underlying mechanics of the problem [78]. It interconnects different components of the system and generates a system of mathematical differential equations. In order to simplify the obtained equations, most of the models suppose that the flow of the air is unidirectional. Bennamoun and Belhamri [19] presented a mathematical modeling and simulation study of solar thermal energy in Constantine at the northeast of Algeria for an indirect convective solar dryer. The model is to simulate the characteristics of an indirect solar dryer. The model was proposed for brick wall drying chamber with cuboid configuration which tapers at the exit where a fan is rotating to suck out hot air. Heat balance was applied to different parts of the collector and the drying chamber as follows.

The external surface of the glass:

$$\frac{m_{\mathrm{v}}\mathrm{Cp}_{\mathrm{v}}}{\mathrm{Surf}}\left(\frac{\mathrm{d}T_{\mathrm{v,ext}}}{\mathrm{d}t}\right)=P_{\mathrm{v}}+\mathrm{hr}_{\mathrm{v,c}}.\left(T_{\mathrm{c}}-T_{\mathrm{v,ext}}\right)+h_{\mathrm{v,am}}.\left(T_{\mathrm{am}}-T_{\mathrm{v,ext}}\right)+k_{\mathrm{v}}.\left(T_{\mathrm{v,int}}-T_{\mathrm{v,ext}}\right) \quad (2)$$

The internal surface of the glass:

$$\frac{m_{\mathrm{v}}\mathrm{Cp}_{\mathrm{v}}}{\mathrm{Surf}}\left(\frac{\mathrm{d}T_{\mathrm{v,int}}}{\mathrm{d}t}\right)=\mathrm{hr}_{\mathrm{v,A}}.\left(T_{\mathrm{A}}-T_{\mathrm{v,int}}\right)+h_{\mathrm{v,A}}.\left(T_{\mathrm{A}}-T_{\mathrm{v,int}}\right)+k_{\mathrm{v}}.\left(T_{\mathrm{v,ext}}-T_{\mathrm{v,int}}\right) \quad (3)$$

The absorber is governed by

$$\frac{m_{\mathrm{A}}\mathrm{Cp}_{\mathrm{A}}}{\mathrm{Surf}}\left(\frac{\mathrm{d}T_{\mathrm{A}}}{\mathrm{d}t}\right)=\mathrm{hr}_{\mathrm{v,A}}.\left(T_{\mathrm{v,int}}-T_{\mathrm{A}}\right)+\mathrm{hr}_{\mathrm{v,A}}.\left(T_{\mathrm{v,int}}-T_{\mathrm{A}}\right)+\mathrm{hr}_{\mathrm{v,I}}.\left(T_{\mathrm{I,int}}-T_{\mathrm{A}}\right)+h_{\mathrm{air,A}}.\left(T^{*}-T_{\mathrm{A}}\right)+P_{\mathrm{A}} \quad (4)$$

Heat balance for the internal surface of the insulator is governed by

$$\frac{m_{\mathrm{I}}\mathrm{Cp}_{\mathrm{I}}}{\mathrm{Surf}}\left(\frac{\mathrm{d}T_{\mathrm{I}}}{\mathrm{d}t}\right)=hr_{v,I}.\left(T_{\mathrm{A}}-T_{\mathrm{I,int}}\right)+k_{\mathrm{I}}.\left(T_{\mathrm{I,ext}}-T_{\mathrm{I,int}}\right)+h_{\mathrm{air,A}}.\left(T^{*}-T_{\mathrm{I,int}}\right) \quad (5)$$

Heat balance for the external surface of the insulator:

$$\frac{m_{\mathrm{I}}\mathrm{Cp}_{\mathrm{I}}}{\mathrm{Surf}}\left(\frac{\mathrm{d}T_{\mathrm{I,ext}}}{\mathrm{d}t}\right)=k_{\mathrm{I}}.\left(T_{\mathrm{I,int}}-T_{\mathrm{ext}}\right)+\mathrm{hr}_{\mathrm{sol,I}}.\left(T_{\mathrm{sol}}-T_{\mathrm{I,ext}}\right)+h_{\mathrm{v,am}}.\left(T_{\mathrm{am}}-T_{\mathrm{I,ext}}\right) \tag{6}$$

Heat balance for the air flowing through the drying chamber:

$$m_{\mathrm{ach}}\mathrm{Cp}_{\mathrm{air}}.\left(T^{*}_{\mathrm{ach}}-T_{\mathrm{ach}}\right)=h_{\mathrm{ach,f}}S_{\mathrm{f}}.\left(T_{ach}-T_{\mathrm{f}}\right)+4h_{\mathrm{ach,pl}}S_{\mathrm{v}}\left(T_{\mathrm{ach}}-T_{\mathrm{pi}}\right) \tag{7}$$

Exchange between the product and the heated air:

$$m_{\mathrm{f}}\mathrm{Cp}_{\mathrm{f}}\left(\frac{\mathrm{d}T_{\mathrm{f}}}{\mathrm{d}t}\right)=h_{\mathrm{ach,f}}S_{\mathrm{f}}.\left(T_{\mathrm{ach}}-T_{\mathrm{f}}\right)-\mathrm{Pev} \tag{8}$$

Heat balance in the internal surfaces of the brick wall

$$\frac{mP\mathrm{p}}{4}.\mathrm{Cp}.\left(\frac{\mathrm{d}T_{\mathrm{pi}}}{\mathrm{d}t}\right)=h_{\mathrm{ach,}}S_{\mathrm{v}}.\left(T_{\mathrm{ach}}-T_{\mathrm{pi}}\right)+k_{\mathrm{b}}S_{\mathrm{v}}\left(T_{\mathrm{p}}-T_{\mathrm{pi}}\right) \tag{9}$$

Heat balance at the polystyrene wall

$$\frac{mP\mathrm{p}}{4}.\mathrm{Cp}_{\mathrm{p}}.\left(\frac{\mathrm{d}T_{\mathrm{pe}}}{\mathrm{d}t}\right)=k_{\mathrm{p}}S_{\mathrm{v}}\left(T_{\mathrm{p}}-T_{\mathrm{pe}}\right)+h_{\mathrm{am,pe,}}S_{\mathrm{v}}.\left(T_{\mathrm{am}}-T_{\mathrm{pe}}\right)+\mathrm{hr}.S_{\mathrm{v}}\left(T_{\mathrm{c}}-T_{\mathrm{pe}}\right) \tag{10}$$

Heat balance between the polystyrene and brick wall

$$\frac{mP\mathrm{p}}{4}.\mathrm{Cp}_{\mathrm{p}}.\left(\frac{\mathrm{d}T_{\mathrm{p}}}{\mathrm{d}t}\right)+k_{\mathrm{p}}S_{\mathrm{v}}\left(T_{\mathrm{pe}}-T_{\mathrm{p}}\right)=\frac{mP\mathrm{p}}{4}.\mathrm{Cp}_{\mathrm{p}}.\left(\frac{\mathrm{d}T_{\mathrm{p}}}{\mathrm{d}t}\right)+k_{\mathrm{p}}S_{\mathrm{v}}\left(T_{\mathrm{pe}}-T_{\mathrm{p}}\right) \tag{11}$$

Sv represents surface of one chamber dryer wall calculated in square meters. Pev is a function of the drying kinetic and varies from one product to another. It is important to mention that in this study shrinkage of the tested product and its effect on the bed porosity of the different trays were taken into consideration which was not the case for the majority of the studies dealing with solar drying.

The models allow following the variation of different temperatures related to the solar collector or the drying chamber and observe variation of the moisture content of the dried product, which was onion, placed on ten trays and in thin layers. Nour-Eddine et al. [80] proposed a similar mathematical model for a hybrid solar dryer equipped with auxiliary heater with part of the exit air recycled. The drying chamber is complete cuboid shaped with six drying trays experimented for spearmint. Heat and mass balance were calculated for the glass cover, absorber, insulator drying cabinet, drying air, and spearmint. The heat balance at the cover of the glass, absorber, and insulator followed the same approach as Bennamoun and Belhamri [19] described earlier. However, Nour-Eddine et al. [80] designed the drying chamber differently and the application of heat and mass balance conducted to the following equations:

Heat balance at the external surface of the dryer cabinet

$$\frac{m_{\mathrm{w}}\mathrm{Cp}_{\mathrm{w}}}{S_{\mathrm{we}}}\left(\frac{\partial T_{\mathrm{we}}}{\partial t}\right)=k_{\mathrm{we-wi}}\left(T_{wi}-T_{\mathrm{we}}\right)+h_{\mathrm{we-amb}}\left(T_{\mathrm{amb}}-T_{\mathrm{we}}\right)+\mathrm{hr}_{\mathrm{we-s}}\left(T_{\mathrm{a}}-T_{\mathrm{we}}\right)+\mathrm{hr}_{\mathrm{we-sol}}\left(T_{\mathrm{sol}}-T_{\mathrm{we}}\right) \tag{12}$$

Heat balance for the internal surface of the cabinet

$$\frac{m_{\mathrm{w}}\mathrm{Cp}_{\mathrm{w}}}{S_{\mathrm{wi}}}\left(\frac{\partial T_{\mathrm{wi}}}{\partial t}\right)=h_{\mathrm{wi-air}}\left(T_{\mathrm{air}}-T_{\mathrm{wi}}\right)+k_{\mathrm{wi-we}}\left(T_{\mathrm{we}}-T_{\mathrm{wi}}\right) \tag{13}$$

Heat balance for the drying air

$$\dot{m}_{\mathrm{air}}\mathrm{Cp}_{\mathrm{air}}.\left(T_{\mathrm{air}}-T^{*}_{\mathrm{air}}\right)=h_{\mathrm{air-pr}}S_{\mathrm{pr}}\left(T_{\mathrm{air}}-T_{\mathrm{pr}}\right)+h_{\mathrm{air-wi,}}\Delta S_{\mathrm{wi}}\left(T_{\mathrm{f}}-T_{\mathrm{wi}}\right)+m_{\mathrm{dry}}\mathrm{Lv}\left(\frac{\partial X}{\partial t}\right) \tag{14}$$

Where $\partial X/\partial t$ is the drying rate expressed in kg water kg dm^{-1} s^{-1}.

Heat balance for the spearmint leaves

$$m_{\mathrm{pr}}\mathrm{Cp}_{\mathrm{pr}}\left(\frac{\partial T_{\mathrm{pr}}}{\partial t}\right)=h_{\mathrm{cv,pr-air}}e_{\mathrm{pr}}\Delta S_{\mathrm{pr}}\left(T_{\mathrm{air}}-T_{\mathrm{pr}}\right)-m_{\mathrm{dry}}\mathrm{Lv}\left(\frac{\partial X}{\partial t}\right) \tag{15}$$

The equations developed enabled the variation of the area of the solar collector, mass flow rates, and temperature.

Theoretical and experimental studies in solar drying in Tunisia leading to several mathematical models and simulations are presented in this section. Ayadi et al. [7] modeled the dryer discussed previously. The authors [7] applied heat and mass transfer balances and assumptions such as considering the flow unidirectional. The heat balance equations for the collector were similar to those presented by Bennamoun and Belhamri [19]. In order to determine the process parameters at each tray level, the various heat balance equations were discretized and then written under a matrix form, as follows:

$$[A]X=B \tag{16}$$

Where A is the matrix coefficient, X is the unknown parameter, and B is the known factor also called the source. The subsequent iteration was done with MATLAB 7.0 and the result was in good agreement with the experimental results. Mathematical modeling and parametric study of the dryer shown in Fig. 6 was described by Oueslati et al. [87]. A model was developed based on the application of heat and mass transfer to tomato. The heat balance equations for the solar collectors and insulators were similar to the ones discussed earlier with the exception of the moist air in the drying chamber due to the application of another configuration. Accordingly, the heat balance for the moist air in the tunnel drying chamber was given as

$$C_{\mathrm{ma}}\frac{\mathrm{d}T_{\mathrm{ma}}}{\mathrm{d}t}=\left(h_2+h_{\mathrm{evap}}\right)\left(T_{\mathrm{pr}}-T_{\mathrm{ma}}\right)A_{\mathrm{pr}}-h_3\left(T_{\mathrm{ma}}-T_{\mathrm{w}}\right)A_{\mathrm{w}}-C_{\mathrm{d}}A_{\mathrm{s}}\sqrt{2g\Delta H}\Delta P \tag{17}$$

Where h_2 is the convective heat transfer coefficient between the agricultural product and the moist air. h_3 is the convective heat transfer coefficient between the moist air and the inner wall. ΔP is the difference in partial pressure and ΔH is the difference in pressure given in (m) and C_d is a constant coefficient.

The simulation results show different effects of the operating conditions. Accordingly, increasing the temperature allowed faster decease in the moisture content. This effect was less important at the change of the heated air velocity.

Modeling was presented for an indirect solar dryer (Fig. 10), and heat and mass balance was applied to the different parts of the dryer [10] yielded to the following equations for inlet temperature (T_{in}), mass loss rate (M_{loss}), and vapor deficit (V_{dw}), respectively, as follows:

$$T_{in} = \frac{A_{pr}C_t(P_s - P_{amb})Q_1 - 0.9H_s + 10^{-12}T_{amb}{}^{1.5} + h\ \ A_s(T_s + T_{amb}) + m_{pr}cp_{air}T_{amb} + k_wA_wT_a}{m_pc_p + k_wA_w/0.03} \quad (18)$$

For the rate of moisture loss

$$M_{loss} = \frac{A_{pr}(\text{VPD})}{{}^1/_{k_{ca}} + {}^1/_{k_t}} \quad (19)$$

For water vapor pressure deficit (VPD)

$$\text{VPD} = 0.293 + 0.0741T + 0.0029\varnothing - 0.0015T*\varnothing + 0.0019T^2 \quad (20)$$

With the model, the drying temperature and moisture loss of the dried product can be predicted in line with the variation of the ambient condition.

Summary of Solar Drying in North Africa

The review has shown that several dryers of different air conveyance mode had been developed in Algeria with a measured degree of success. Recent studies show that the researchers had evaluated new dryers with auxiliary heating mode. However, hybrid dryers which incorporate mixed heat sources such as heat pump, biomass, photovoltaic cells, etc. still have not been reported in operation. The investigation of the dryers is not widespread but is limited to the locations of the research institutes as can be seen in Table 3. Taking these dryers to different parts of the countries will be good for proper evaluation and documentation of solar drying application in the entire country. However, few simulation studies had been done under Algerian climate which can be generalized in this environment. The integration of solar absorption beds or phase change materials should be pursued in this area, and the application to more materials not just plants and food should be encouraged. Generally, it was noted from most designs of these solar dryers from Algeria that emphasis is not only on the reduction of drying time, attention was paid to the quality of construction of both the drying chambers and the collector. This is very important for marketability of the developed solar dryers, probably at improved cost to the end users. Tunisia showed the prevalence of active solar dyers (Table 4). It has also made progress into hybrid dryers that couple auxiliary sources of heat due to the low solar insolation in the region. Almost all of the dryers were indirect solar dryers with few with greenhouse which have higher capacity (about 80 kg) than other type of dryers. Egypt is not encouraging their adoption although different types of solar dryers have been reported in the country (Table 5). This is because Egypt is characterized with high wind and low humidity with high irradiance. Therefore, most of the researches were focusing on sun drying, and comparing direct and indirect solar drying, almost no difference in terms of drying time was observed. However, it is known that sun drying and solar do not give the same quality of the final product. In Morocco, few of the reviewed solar dryers were working on active or indirect type and mostly used for drying medicinal plants as shown in Table 6. Most of the published studies coming from this country were dealing with experimental studies and modeling of sorption and desorption isotherms and drying kinetics. However, some cited studies were dealing with industrial dryers.

Most of the presented studies in North Africa were focusing on determination of drying curves and drying time. So, it is important to mention that studies dealing with solar drying should imply energy, exergy, and efficiency analysis, as well as determination of the quality of the final product.

West Africa

Nigeria receives an average annual global incident solar radiation of 1831.06 kWh with a mean daily value of 5.25 kWh m^{-2} day^{-1} [1, 86]. The average daily solar insolation is 3.5 h for the coastal areas to 9.0 h toward the north [5, 83]. It has been postulated that if 1% of Nigeria land area is covered with solar modules, it is possible to generate 1850 × 10^3 GWh of solar electricity per year [92]. The positioning of Nigeria within this high sunshine belt makes solar drying applicable to different degrees. Pilot's solar activities in Nigeria

Table 3 Summary of dryers developed in Algeria excluding those reviewed by Bennamoun [18]

Type of solar dryer	Mode	Country	Location	Author(s)	Angle of tilt of collector	Product dried
Indirect	Passive	Algeria	C.D.E.R	Boulemtafes-Boukadoum et al. [29]	16°	Mint
Indirect	Passive	Algeria	C.D.E.R	Chouicha et al. [31]	16°	Deglet-Nour dates
Direct	Active	Algeria	C.D.E.R	Chouicha et al. [31]	31°	Deglet-Nour dates
Indirect	Active	Algeria	C.D.E.R	Chouicha et al. [31]	31°	Deglet-Nour dates
Indirect	Active or passive	Algeria	Bejaia	Khama et al. [66]	0–60°	Tomato
Indirect	Active	Algeria	Western Algiers	Benhamou et al. [15]	–	Olive pomace and colocynth
Indirect	Active	Algeria	C.D.E.R	Nour-Eddine et al. [80]	36° N	Spearmint leaves

are mostly developed by the National Center for Energy Research and Development (NCERD) and Sokoto Energy Research Center (SERC) under the supervision of the Energy Commission of Nigeria (ECN). So far, across the length and breadth of the country, several solar dryers had been tested. In Nigeria's renewable energy 2012–2030 action plan, the country targeted to deploy 150 solar dryers in the short term, 2000 solar dryers in the medium term, and 6000 solar dryers in the long-term masters' action plan [12]. Because of a lack of research dealing with solar drying, the representative country of the region will then be Nigeria.

Experience of Solar Drying in West Africa

Several pilot studies on solar drying were undertaken by SERC and NCERD which are the two major solar research centers in Nigeria. These dryers had been exhibited around the country although detailed design specifications were not always given. They are built from local materials with local farmers in mind and, therefore, are cheap. Because of this, less attention was paid to esthetics and building the dryers with wood makes it highly susceptible to damage by weather changes, microbial attack, or termites if not properly treated. They are mostly mixed-mode cabinet dryers with transparent cellophane covering or solar greenhouse as shown in Fig. 12a–d. The danger in using cellophane covering is that they can easily be punctured by animals or children and even by wind. However, the advantage is that these materials are readily available and affordable and can easily be replaced. Other advantages and disadvantage are the same as suggested in the section "Experience of North Africa in Solar Drying" for Boulemtafes-Boukadoum et al. [28]. However, it was discovered that most of the dryers found in Nigeria follow the same construction trends as will subsequently be reviewed and therefore will face the same challenges but differ in capacity and orientation of components. The dryers reported by Bala [12] are presented to "Danjiwa" villagers, and some of the dryers have a very large capacity. These dryers were evaluated in situ by the end users who are the farmers, and the results presented as just satisfactory to excellent. Direct solar cabinet dryer has been investigated at Ogbomosho around north central Nigeria by Tunde-Akintunde [100] for drying pretreated and untreated chili. The solar collector is directly on top of the drying chamber (1610 cm^2) and covered with glass tilted 11° to the horizontal, held with hinges. The average temperature of the drying chamber was 45 °C and the drying time ranged from 35 to 50 h. The authors found out that the pretreated chili dried faster than the untreated chili. Analysis of the final quality of the product was not done although for most direct solar dryers like this one, decomposition of chlorophyll occurred in certain products due to sunlight; however, it is highly suggested to study the flavor changes for some products. Regarding modeling, drying kinetics were modeled with various semitheoretical models. The author [100] concluded that Page's model fitted well with the experimental results of red chili during solar drying. Ekechukwu and Norton [39, 40] studied an integral-type natural convection

Table 4 Summary of some dryers developed in Tunisia and the products dried

Type of solar dryer	Mode	Country	Location	Author(s)	Angle of tilt of collector (°)	Product dried
Indirect	Mixed mode	Tunisia	Borj Cedria	EL Khadraoui et al. [43]	37	Red pepper
Indirect	Active	Tunisia	Gabès	Slama and Combarnous [95]	–	Orange peel
Indirect	Active	Tunisia	Radès	Ayadi et al. [7]	60	Medicinal plant
Indirect	Active	Tunisia	Sfax	Bahloul et al. [9]	–	Olive
Indirect	Active	Tunisia	Hammam-Lif	Fadhel et al. [46]	–	Grapes and pepper
Indirect	Active	Tunisia	–	Oueslati et al. [87]	36.7–45	Tomatoes

Table 5 Summary of some dryers developed in Egypt and the products dried

Type of solar dryer	Mode	Country	Location	Author(s)	Angle of tilt of collector (°)	Product dried
Direct	Passive	Egypt	Ismailia	Hassanain [56, 57]	–	Sage
Direct	Passive	Egypt	Ismailia	Hassanain [56, 57]	47.5 south side and 30 north side	Sage
Indirect	Passive	Egypt	Benha	Bahnasawy and Shenana [10]	–	Dairy products
Indirect	Active	Egypt	Aswan	Aissa et al. [4]	–	Sponge cotton
Direct	Passive	Egypt	Giza	Sallam et al. [93]	–	Mint
Indirect	Mixed mode	Egypt	Ismailia	Hassanain [58]	30	Banana

solar dryer for tropical crops. The dryer was developed at the National Centre for Energy Research and Development at the University of Nigeria, Nsukka. The dryer was made up of a galvanized semicylindrical steel drying chamber (6.67 m × 3.0 m × 2.3 m) terminating with a vertical cylindrical chimney (Ø = 1.64 m and 3 m high) on one end and wrapped with treated polyethylene sheet. A black absorbing curtain was hanged within the chimney. This dryer is very simple to construct and does not need elaborate structure or separated heating structure or conduit for heat into the drying chamber. However, it still faces the challenge of localized heating like most direct solar dryers [39, 40]. However, the addition of solar chimney can help to reduce this by increasing the buoyancy force on the air stream. This approach will increase the moisture removal speed by increasing the air velocity. This dryer does not have the problem of wood associated with most dryers found in Nigeria because of steel construction of the walls of the drying chamber. The authors ([39, 40]) determined the major design parameters affecting the drying process which were the size and position of the absorber curtain and the chimney height. The average radiation intensity values during the tests ranged between 330 and 460 W m^{-2} with maximum values of 650–990 W m^{-2}. The average temperature of the dryer was 35–45 °C with the ambient air temperature ranging from 27 to 33 °C. It was possible to dry cassava from a moisture content of 141 to 18% dry basis in 2 days which equal to about 16 sunshine hours. When the same dryer was evaluated over two seasons, rainy and dry, it was found that solar drying application is better for drying in the area during the dry season [39].

Correlation of the internal temperature difference over the energy balance between the crop and air was given as

$$T_{\mathrm{pr}}-T_{\mathrm{air}} = \frac{m_{\mathrm{air}}\mathrm{Cp}_{\mathrm{air}}}{\left(m_{\mathrm{pr}}\mathrm{Cp}_{\mathrm{pr}}-UA\right)}\left(T_{\mathrm{o}}-T_{\mathrm{air}}\right)-\frac{m_{\mathrm{w}}\mathrm{Lv}}{\left(m_{\mathrm{pr}}\mathrm{Cp}_{\mathrm{pr}}-UA\right)} \quad (21)$$

The drying rate of the dryer was found to correlate linearly with the dryer performance term G, defined as

$$G = I^{1/2}T_{\mathrm{air}}M_{\mathrm{i}}V_{\mathrm{d}} \quad (22)$$

Where V_{d} is the vapor pressure deficit given as

$$V_{\mathrm{d}} = e^{*}(1-\varnothing_{\mathrm{air}}) \quad (23)$$

The plot of drying rate versus G (Fig. 13) according to the authors can be used by farmers to determine whether passive solar drying will be suitable for a particular region within the tropics with optimum performance placed at line "B." Bolaji [23, 24] presented two direct solar cabinet dryers (Fig. 14a, b). The dimensions of the dryers are shown in the figures (Fig. 14a, b); however, few details and explanations were given. The dryer was designed to dry various food materials. Fagunwa et al. [48] developed an intermittent mixed-mode solar dryer (Fig. 15) for drying cocoa bean. The dryer was developed at a university of Ife southwestern Nigeria and operates under natural and forced convection mode. The dryer was made of wood mounted on a wheeled frame with angle iron. The flat solar collector measured 1.1 m × 1 m × 0.2 m and inclined at an angle 15° to the horizontal. The heated air is sucked into the drying chamber by a fan installed inside a

Table 6 Summary of dryers developed in Morocco and the products dried

Type of solar dryer	Mode	Country	location	Author(s)	Angle of tilt of collector (°)	Product dried
Indirect	Active	Morocco	–	GTZ [54]	Horizontal	Fruits, vegetables, and medicinal plants
Indirect	Active	Morocco	Marrakech	Lahsasni et al. [70] and Lamharrar et al. [71]	31	Prickly pear cladode and Artemisia (*herba-alba*)
–	–	Morocco	Northern Morocco	Chimi et al. [32]	–	Figs
Active	Active	Morocco	Rabat	Bekkioui et al. [13, 14]	25	Wood

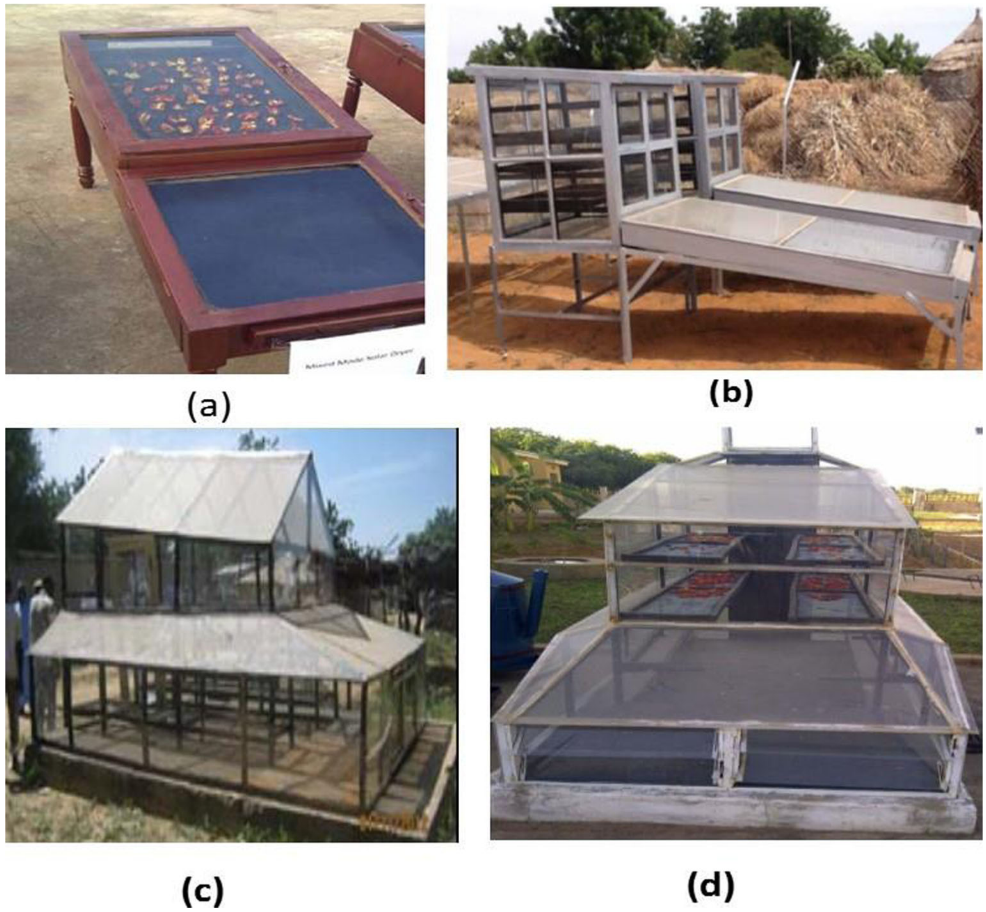


Fig. 12 Mixed-mode solar dryers developed at SERC. **a** Drying for food preservation. **b** One of the two strategically installed large-scale solar dryer for community use in Danjawa. **c** Solar meat dryer in Danjawa Village. **d** Solar crop dryers [11, 12]

short duct that links both chambers together. The solar dryer was designed to dry about 50 kg of cocoa. Result of the evaluation of the dryer showed that the dryer dried the cocoa bean from a moisture level of 53.4 to 3.6% (w.b.) in 72 h under intermittent drying process with ambient temperature and relative humidity at 25–30 °C and 58–98%. They found that good quality beans with pH of 6.35, acid value of 3.40 mg/g, and mildly bitter taste were gotten under passive drying, while beans dried under forced convection mode showed increase in moisture reabsorption and acidic flavor. Although the design material was sourced locally which reduced the initial cost, the authors [48] recommend treatment of the product to avoid its fast deterioration. Eke [37] investigated several mixed-mode solar dryers (Fig. 16a–d) for drying vegetables in rural areas of northern Nigeria. The developed dryers were made up of metal, wood, cement, and mud. All the four dryers had equal solar collector area of 0.61 m × 0.92 m and a drying chamber area of 1.53 m × 0.91 m with air plenum of 0.065 m. The dryers, similar in shape, were tilted 15° to the horizontal and southwards. Evaluation of drying in terms of time saving compared to open sun drying showed saving of 131.25, 131.25, 136.17, and 192.11% for metal, wood, cement, and mud at drying efficiencies of 7.38, 19.56, 20.25, 20.91, and 27.24%, respectively. This shows a better transient performance for the mud-casted dryer; however, quality assessments of the dried products were not done. The weakness of these designs is the durability of the used materials which might increase cost in the long run, despite its low initial cost. Iloeje et al. [61] presented a mixed-mode natural convection solar barn for drying wet Ada rice in southeastern Nigeria equipped with biomass gasifier. A photovoltaic-powered solar cassava dryer was developed by Anyanwu et al. [6]. The dryer was able to dry about 50 kg of cassava from 74 to 12–6% in 20 h. They found out that trays at the topmost rack dried faster than the lower rack. The dryer temperature varied from 26 to 48 °C. Bolaji and Olalusi [22] investigated mixed-mode solar dryer (Fig. 17) at Ekiti southwestern Nigeria. The studied dryer was able to remove 85.4% d.b of moisture from yam chips with initial weight of 6.2 kg in 10 h, at a drying rate of 0.62 kg water/kg dm^{-1} h^{-1}. For this proposed drying system, the collector efficiency was about 57.5%.

Although the average solar insolation in Nigeria averaged 5.25–6.0 kWh m^{-2} day^{-1} [12], the southern and central parts to some extent receive less with an average of 3.50 kWh m^{-2} day^{-1}. The reason is because of the weather pattern in the south which is dominated by southward oscillatory movement of the intertropical discontinuity [77]. Even in the afternoon, there is occasional intrusion of fast, moist wind from the southern Atlantic Ocean

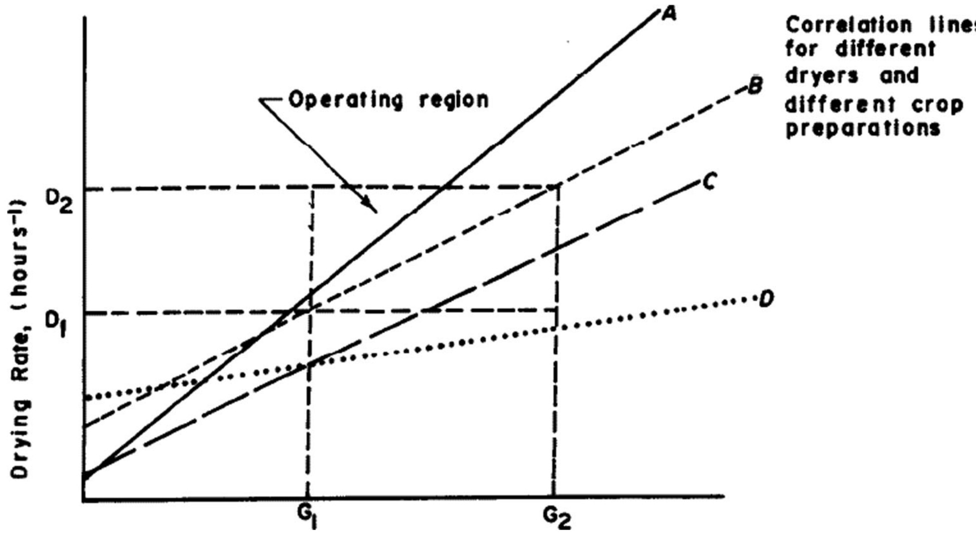


Fig. 13 The drying rate versus G-factor correlation as the basis for a design chart via which the optimal natural circulation solar energy tropical crop dryer can be determined [40]

which dilutes the weather [77]. Therefore, solar drying periods are more dominated by off-sunshine hours than sunshine periods. Based on this information, hybrid solar dryers equipped with supplementary heat source or storage system had been investigated in Nigeria to assist and increase the efficiency of the drying process. Okonkwo and Okoye [84] developed a solar dryer with rock pebble as thermal storage material. The solar dryer is made up of a solar collector (0. 67 m × 1.10 m × 0. 21 m) imbedded with pebble bed solar heat storage unit. The collector is covered with Perspex glass and tilted to 22° southwards. The drying chamber measures 50 cm × 50 cm × 90 cm with wire gauze as the trays, while the roof is made of transparent glazing. Evaluation of the dryer showed that maximum absorber temperature reached 72 °C, with the pebble bed temperature at 58 °C and average drying chamber temperature of 57 °C at a maximum ambient temperature of 34 °C. It was possible to reduce the moisture level of cassava from 73 to 10.2% after 3 days of drying. The addition of rock pebbles removed the problem of electricity to power the supplementary heater as encountered in the literature [15] and therefore can easily be adopted by the rural farmers. Ibrahim et al. [60] presented a hybrid solar (Fig. 18) dryer equipped with biomass incinerator in order to dry chili pepper. The dryer was tested in Markurdi central Nigeria under humid climate. The dryer is made of a solar flat collector, drying chamber, and incinerator. The incinerators were linked to two reservoirs from which the heated supplementary air was circulating during off-sunshine hours. However, this dryer might require constant attention during the off-sunshine hours as there is no device to monitor the overheating of the dryer when the biomass incinerator is applied. Again, due to nonapplication of electricity, it can still be useful in the rural area without electricity and the biomass utilization can help to convert

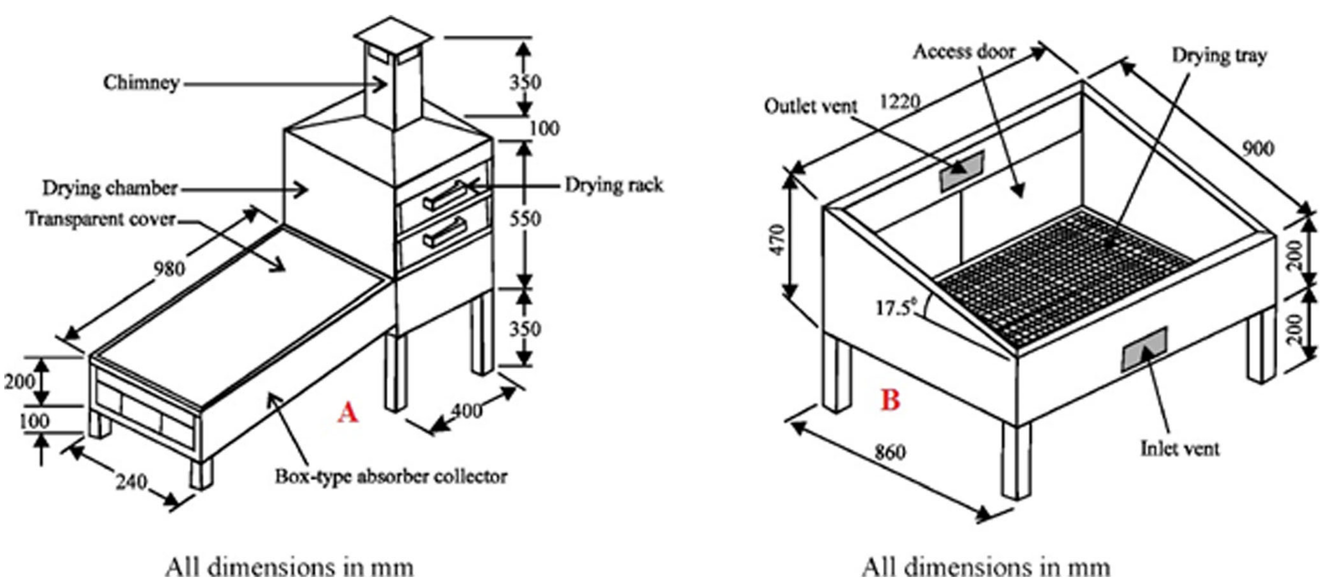


Fig. 14 **a**, **b** Solar dryer [23]

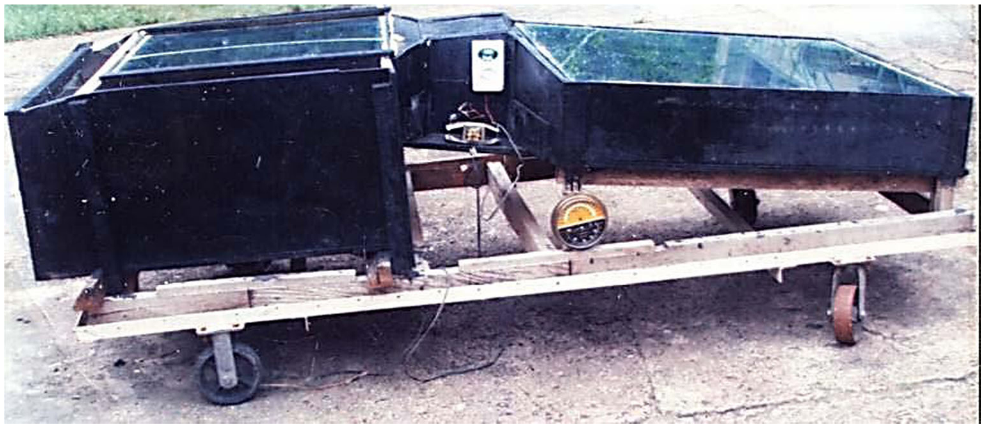


Fig. 15 Cocoa bean solar dryer [48]

some wastes from the farm into energy. The results of the drying process presented in Table 3 showed that the hybrid dryer can reduce the moisture content of 1 kg of chili from 86.6% dry basis to 0.46% in 34 active hours with a drying efficiency of 13%.

Okoroigwe et al. [85] described a hybrid solar biomass dryer for drying crops in Nsukka, Nigeria. The dryer is using biomass stove supplementary heater (maximum temperature − 70 °C) with the heat circulating through a heat exchanger made from aluminum. The collector (0.62 m × 0.03 m) is made from aluminum insulated with sawdust, while the drying chamber is covered with Perspex glass. The collector is tilted at 7° southwards to the horizontal. This dryer has similar components with the one presented by Ibrahim et al. [60] and, therefore, will face the same challenges. The efficiency of the dryer was 5.19–16.04, 0.23–3.34, and 1.636–8.96% for different modes of drying of okra, groundnut, and cassava chips, respectively, with collector efficiency of 61.42% during evaluation with all the tested products.

Exergy-Based Optimization Studies of Solar Dryers Investigated in West Africa

During solar drying, the convective air moving through the product is heated by solar radiation and the useful energy is given by Eke [37] as follows

$$Q_u = A_s F_R \left[I\tau - U\left(T_{o,s} - T_{amb} \right) \right] \quad (24)$$

However, the above equation does not take into account the quality of losses in the heat exchange process or energy moving across the thermal boundary. This is the major disadvantage in using energy-based parameters in the optimization process. Therefore, commonly, exergy is used to evaluate the performance and optimize thermal systems [89]. Exergy quantifies the actual useful energy irrespective of the amount of energy generated. It takes into account losses and recoverable and irrecoverable input energy and shows exactly the

Fig. 16 Low-cost solar dryer [37]

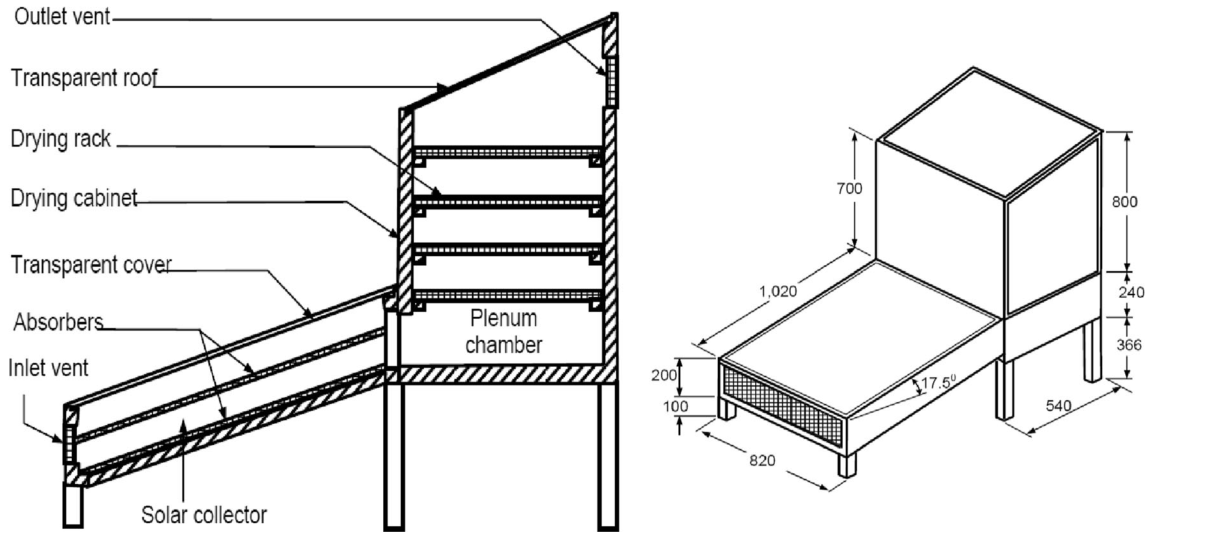


Fig. 17 Mixed-mode solar dryer [22]

level of degradation and the specific location it occurs in energy quality. Based on exergetic analysis, Nwosu [81] used pin fins for the design of an absorber in a solar air heater used in solar drying. According to the author [81], fins serve for the increase of heat transfer in the solar air heaters, but they raise the pressure drop in flow paths. The basic theory adopted in the optimization study is to minimize the entropy generated by the fins. The optimum nondimensional temperature obtained based on this analysis for a finned solar was given by:

$$\theta_z = 1 - \frac{\left(\theta_z{}^4 - 1\right)}{M[1 - N\varnothing(1-\eta_f)]} + \frac{\tau\alpha I\eta}{M\varepsilon\sigma T_\infty^4[1 - N\varnothing(1-\eta_f)]} \quad (25)$$

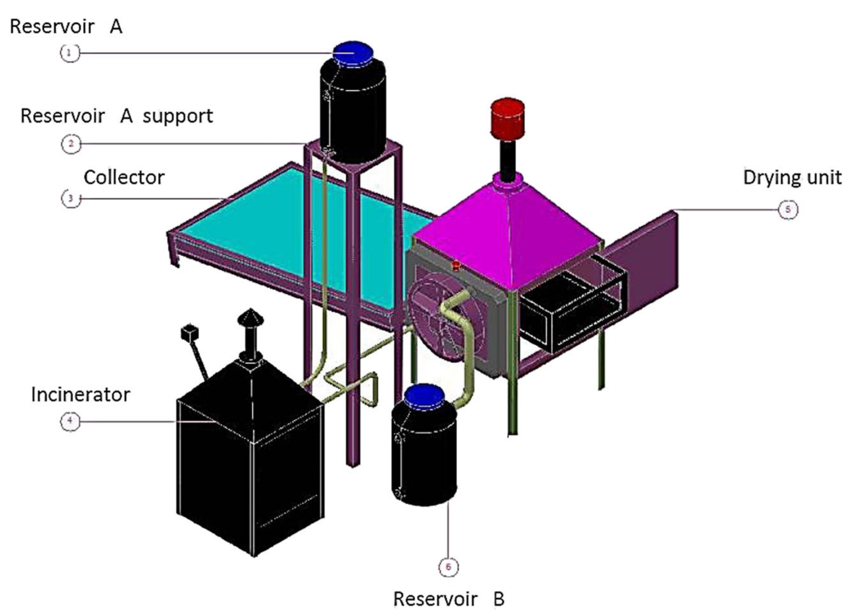
Where M and $\varnothing$ are nondimensional ratio defined in Nwuso [81]. This equation is applicable to an unfinned solar collector, and in case the fine component does not exist, we can assume that $N = 0$.

The results of the optimization showed improvement in the absorptivity of the absorber, heat absorption, and dissipation, and also the absorption increased when the ratio α/ε was increased.

Summary of Solar Dryer Investigated in West Africa

The review of solar drying experience in Nigeria revealed the existence of several solar dryers with different configurations but mainly operated in mixed mode (Table 7). Hybrid solar dryers had been developed by adding a supplementary heat source that operates during off-sunshine hours. Evaluation of the dryers cut across all the regions with different levels of solar radiation but almost peaking around 850–900 W m^{-2} at noontime. However, simulation and modeling are very scarce and most of the research is still elementary. Scale-up of the developed solar dryers to the industrial scale has not been

Fig. 18 Hybrid solar dryer integrated with incinerator [60]



explored, and this is probably due to the limited fund for the researchers. The quality of the esthetics of the dryers is poor and requires improvement, while the materials require treatments to withstand weather attack.

Southern Africa

Most Southern African countries have high solar insolation like those in North Africa, especially countries around the Kalahari and Namibian desert. Some of these countries which are situated in the sunny belt receive average solar irradiance of 5.5 kWh m^{-2} day^{-1} [63]. The average annual solar insolation is 4000 h of sunshine for Zimbabwe [63]. Much of this is channeled toward electricity generation rather than drying due to availability of abundant sun. This apathy is mostly common among African countries because of subsistence nature of the agricultural practice in the continent. This observation was also made by Jingura and Matengaifa [63] for Zimbabwe, and they recommended improved effort in research in the area of solar utilization for drying agricultural products.

Experience of Solar Drying in Southern Africa

Gwala and Padmavati [55] dried slices of pineapple in a laboratory cabinet indirect solar dryer in Harare, Zimbabwe, without indicating its specifications. The results showed that it took 20 h to reduce the moisture content of sliced pineapple from 90 to 7% w.b. Mathematical modeling of the drying curves showed that the Henderson and Pabis model had given the best fit with the experimental results. Madhlopa and Ngwalo [72] developed a hybrid indirect direct passive solar dryer (Fig. 19) in Blantyre Malawi (15° 48′ S, 35° 2′ E) for drying pineapple. The dryer had biomass as supplementary source of heat. The absorber was a horizontal concrete floor integrated with rock pebble storage mass, painted matt black, and enclosed within a wood board. The outer vertical part of the collector was covered with galvanized iron sheet to protect the wood. The cover was glass tilted 16° northwards. The drying chamber was made from bricks and the dimensions of the dryer are presented in Table 8. This dryer will require constant attention during off-sunshine hours as earlier reported for similar dryers. However, a temperature-automated shutter which can cut off the heat from the biomass can be used to solve this problem. This dryer can be very elaborated, but the material for the design which is mainly bricks can be affordable and durable. Therefore, the overall cost at the long run might be low although this was not reported in the study. The authors Madhlopa and Ngwalo [72] had performed a comparison between drying pineapple with and without the biomass heater. Consequently, the dryer efficiency increased from 11% without to 20% after using the heat supplement. Vitamin C retention level in the dried pineapple samples ranged from 26 to 44%.

Sunworks [97] presented two direct cabinet solar dryers developed in Zimbabwe and South Africa in which they did not present the results of their evaluation. Both were cabinet type and the product to be dried was placed directly on the absorber. The collector was built with wood, while the absorber was covered with transparent glass tilted southwards. Most of the dryers found in this region were using passive mode (Table 9). The reason can be attributed to the low cost and the easy construction, bearing in mind that this region is poor and most drying is at the subsistence level. However, they are wooden dryers and will face similar prospects like previously reported for similar dryers.

East Africa and Sudan

Daily solar insolation around East African states is among the highest in Africa. East African countries, such as Ethiopia, Kenya, and Djibouti, receive average daily insolation of 5.84, 5.62, and 6.37 kWh m^{-2} day^{-1} solar insolation, respectively. Most of the countries here are dry during the major part of the year with low rainfall. Several solar dryers have been tested in this region.

Table 7 Summary of dryers developed in Nigeria and the products dried

Type of solar dryer	Mode	Country	Location	Author(s)	Angle of tilt of collector (°)	Product dried
Direct	Passive	Nigeria	Nsukka	Ekechukwu and Norton [39, 40]	–	Cassava
Indirect	Active	Nigeria	Ife	Fagunwa et al. [48]	15	Cocoa
Indirect	Passive	Nigeria	Northern Nigeria	Eke [37]	15	Pepper
Direct	Mixed mode	Nigeria	Nsukka	Iloeje et al. [61]	7	Rice
Indirect	Active	Nigeria	Nsukka	Anyanwu et al. [6]	–	Cassava
Direct	Passive	Nigeria	Ogbomosho	Tunde-Akintunde [100]	11	Chili pepper
Indirect	Mixed mode	Nigeria	Ekiti	Bolaji and Olalusi [22]	17.5	Yam chips
Indirect	Mixed mode	Nigeria	Markudi	Ibrahim et al. [60]	–	Chili pepper
Indirect	Mixed mode	Nigeria	Nsukka	Okoroigwe et al. [85]	7	Okra, groundnut, and cassava chips

Sudanese capital Khartoum has the third highest daily insolation among the capitals of all the African countries (Table 1). The country in general is dry and very hot and has a lot of potential in solar energy applications. However, very little research was found in this country.

Experience of Solar Drying in Eastern Africa and Sudan

Almost all the solar dryers found in East Africa are wooden dryers for a similar reason to the solar experience in Southern Africa as previously reported. Therefore, they will face the same challenges in terms of operation, durability, efficiency, and cost. Tefera et al. [98] presented a direct box and pyramid solar dryer used to dry potato in Bahir Dar region of Ethiopia. The solar collector (1.17 m^2 for the box type and 3.28 m^2 for the pyramid type) was oriented southwards with an inclination of about 21.3° to the horizontal and covered with 4-mm-thick glazed transparent glass. The drying chamber of the box dryer was a wooden box that had the following dimensions: 1.81 m × 0.83 m × 0.82 m. The front and rear sides of the pyramid dryer were covered with a transparent plastic sheet. The results of the performance evaluation are shown in Table 10. The authors Tefera et al. [98] recommended pyramid dryer for drying that had a capacity of 10–15 kg of agricultural products which can serve the needs of most households. Tewolde-Berhan et al. [99] dried *Cordia africana* Lam in Tigray area of northern Ethiopia with a direct solar dryer which they did not describe nor show its diagram. However, they stated that the product was dried after 5 days in the solar dryer. Ayua et al. [8] presented a mixed-mode solar dryer for vegetables (Fig. 20) tested in Edoret region of Kenya. The dryer measures were 2.4 m × 1.2 m × 0.35 m. The absorber was made of plastic sheet painted in black. A chimney wrapped with black polythene sheet was attached at the top end. The authors did not give details of materials composing the drying chamber and solar collector. The dryer was used to dry amaranth nightshade, spider plant, and African bird's eye chilis. Evaluation showed that the system can dry these products to below 10% in 4.5–64.5 h. The maximum temperature for the mixed-mode dryer was 72.1 °C. Return cost for investment of the dryer was estimated to be 2.2 months by the authors. The Kenyan Agricultural Research Institute (KARI) in 2008 [65] presented a direct wooden solar dryer (Fig. 21) which was used for drying pyrethrum flowers. The listed benefits of using this dryer were lower drying time with cleaner and dry flower, minimal loss of flowers, minimum fermentation and improved flower quality, and cheap construction materials which are locally accessible and easy to build. Kiggundu et al. [67] in their review of solar fruit dryers in Uganda identified only five available dryers of which two are presented in Figs. 22 and 23. The solar dryers were the static bed box-type solar dryer model, Patience Pays Initiative (PPI) tunnel solar dryer model, the NRI Kawanda cabinet solar dryer, the hybrid tunnel solar dryer, and the UNIDO solar hybrid dryer model. They concluded that all the first four local dryers are not efficient, while the hybrid solar dryer built by UNIDO (Fig. 23) which used a supplementary source of heat was identified as adequate for Uganda. However, the various authors focused more on the drying aspect and not on economic aspect to draw their conclusions.

Kituu et al. [68] presented a solar tunnel dryer (Fig. 24) in order to dry fish in Kenya. The tunnel measured 2.24 m ×

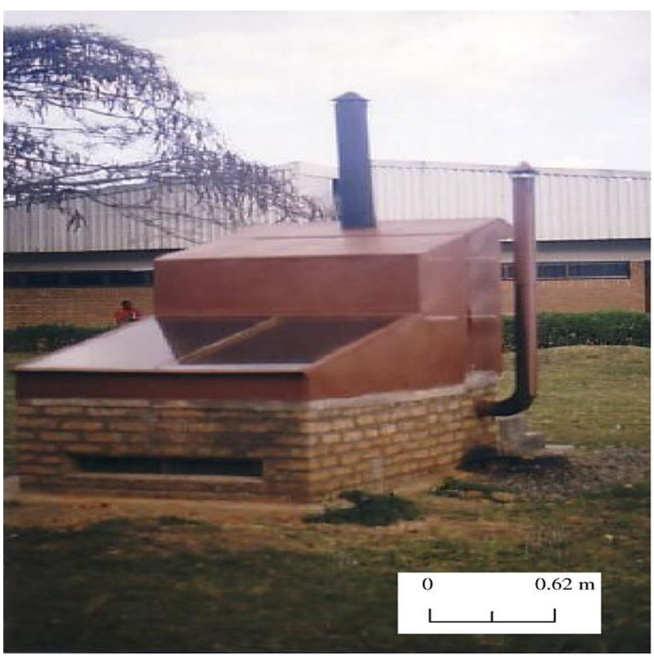


Fig. 19 Hybrid solar dryer [72]

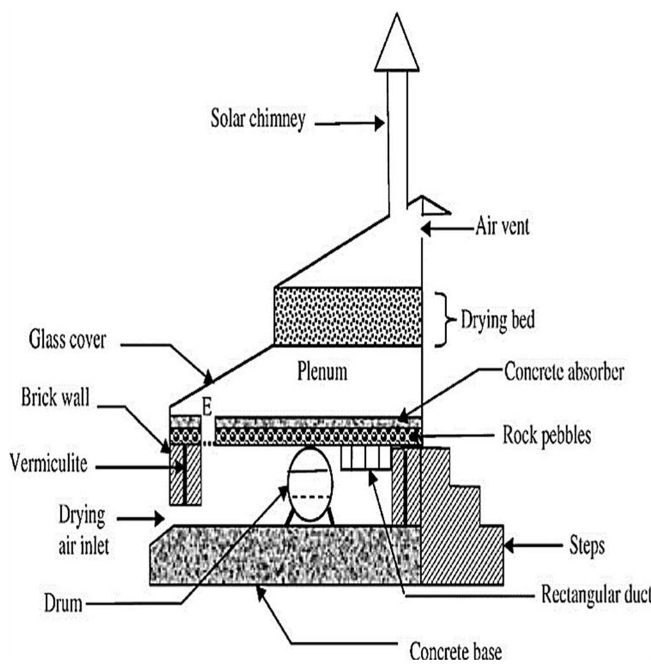


Table 8 Design parameters for the hybrid solar dryer [72]

Dryer	Drying load and meteorological conditions
Solar collector aperture, $A = 2.2\ m^2$	Drying product
Absorber: concrete slab (0.025 m thick)	Initial mass of load, m1 = 20.0 kg
Glass cover	Initial moisture, M1 = 85% (wet basis)
Thickness = 0.003 m (wet basis)	Final moisture, M2 = 10%
Tilt angle = 16	Meteorological conditions
Granite rock = 360 kg	Solar radiation, Hd = 6.30 × 107 J m^{-2}
Drying chamber	Inlet air temperature = 303 K
Effective tray area = 4.1 m^2	Inlet air temperature = 303 K
Solar chimney = 1.2 m height, Ø = 0.18 m	Plenum temperature = 313 K
Biomass burner	Relative humidity, / = 80%
Drum	
Length = 0.89 m	
Diameter = 0.58 m	
Door = 0.55 m × 0.54 m	
Flue gas chimney	
Height = 2.12 m	
Diameter = 0.12 m	

1.2 m × 0.54 m. The collector was made of galvanized iron painted black and was 9 mm thick. The bottom plate of the tunnel was built with aluminum for reflection of heat. The chimney was also built using galvanized iron, but the inside was coated with aluminum. The chimney was attached with an exhaust system made from acrylic glass for trapping solar energy. Below the exhaust pipe was a solar-driven fan, powered by photovoltaic cells, which was switched to reach the desired drying conditions. This dryer is very elaborate and requires high initial investment cost. Drying took about 35 h for tilapia fish. In the modeling part, the temperature of the plenum was determined by application of heat transfer balance and described by the following equation:

$$T_p = T_i + \frac{I}{U_l}\left\{1\text{-exp}\left(-\frac{A_c F' U_L}{\dot{m}_{air}\left(Cp_{air} + \varnothing Cp_{vap}\right)}\right)\right\} \quad (26)$$

T_p is the plenum chamber temperature and T_i is the inlet air temperature.

Oduor-Odote et al. [82] presented a modification of a solar tunnel dryer (Fig. 25) of Kituu et al. [68]. The authors Oduor-Odote et al. [82] dried fish in Giza south coast of Kenya and compared the quality with fish dried with traditional rack type dryer in terms of appearance, test, and texture. They found no significant difference in both drying time and quality attributes for the two drying methods.

Nasroun et al. [76] described two solar greenhouse dryers used to dry timber in Suki, Senna state, Sudan. Although they did not present the diagram of these two dryers, nevertheless, the authors described them. They stated that the dryers were made from wood with a corrugated zinc roofing and covered with transparent plastic sheet. In one of the dryers, the absorber plates were corrugated zinc painted black and placed on the floor with the timber in east-west orientation. For the other dryer, the absorber was placed below the roof but above the stack, while the timber was placed in north-south position. Their findings after 34 days showed that placing the collector up dried the timber faster than placing the collector on the floor. A natural convective cabinet solar dryer (Fig. 26) was designed by El-Amin et al. [41] for drying of mango in Khartoum. The solar dryer and the cabinet formed a single unit with the bottom forming a composite of mild steel, glass wool, and galvanized steel. Black-painted corrugated metal

Table 9 Summary of dryers developed in Southern Africa and the products dried

Type of solar dryer	Mode	Country	Location	Author(s)	Angle of tilt of collector (°)	Product dried
Indirect	Passive	Zimbabwe	Harare	Gwala and Padmavati [55]	–	Pineapple
Direct	Passive	Malawi	Blantyre	Madhlopa et al. [72]	16	Pineapple
Direct	Passive	Zimbabwe	–	Sunworks [97]	–	–
Direct	Passive	South Africa	–	Sunworks [97]	–	–

Table 10 Mean temperature in degree Celsius for the drying chamber for the two solar dryers [98]

	Box solar dryer		Pyramid solar dryer	
	Time 12:00–24:00	Time 00:00–12:00	Time 12:00–24:00	Time 00:00–12:00
Ambient	25.3	20.1	25.5	20.0
Tray 1	35.6	20.0	43.5	21.5
Tray 2	34.0	19.7	41.1	21.5
Tray 3	35.2	20.5	37.8	21.5
Tray 4	34.1	20.7	37.5	22.2

sheet served as the absorber. The inner three sides were made of Masonite sheets wrapped with aluminum foils for protection from moisture, while the fourth side served as the door made from steel. The top was a transparent glass tilted 15° south. The trays were wooden mesh supported with angle iron. The air inlet was an adjustable hole below the absorber, while the exit was at the rear. The dimensions of the dryer are shown in Fig. 26.

Figure 27 shows the schematic representation of a natural convective indirect flat plate solar dryer developed at the University of Khartoum, Sudan, by Ismail and Ibn Idriss [62]. The dryer was made using local materials and consisted of a prism-like solar collector measuring 1.05 m × 1.05 m × 3 m frame with a composite of 3 mm Masonite sheets, glass wool, and 2-mm-thick steel sheet. The metal sheet was painted in black to serve as the absorber. The collector was covered with 4-mm-thick transparent glass and tilted 15° south. The drying chamber was a double barrel cylindrical drum fitted coaxially with detachable inner barrel. The inner barrel was perforated and served as the drying tray for okra samples. The collector base was fixed with angle iron on a trapezoidal-shaped structure. The finishing of this dryer is poor and requires improvement. Result of the evaluation showed that the dryer achieved a maximum temperature difference of 41.9 °C between the ambient and the drying chamber. Mathematical modeling of thin layer drying curves of okra pod showed that the Page model can describe better the drying curves than the other models. Abdel Moneim et al. [2] presented an indirect solar dryer which they did not describe. The dryer was used to dry fish at the Food Research Center, Shambat, Sudan (32° 32′ E, 15° 45′ N), by placing it on top of a two-floor building. The dryer achieved a maximum drying air of 52.56 °C when the ambient air was around 38 °C, and it took 3 days to dry the fish from 78.67% (w.b.) moisture content to 11.41% (w.b.).

Summary of the Solar Dryers Investigated in East Africa and Sudan

Most of the dryers found in Eastern Africa were using mixed-mode and passive solar dryers as shown in Table 11. One of the eventual reasons could be that East Africa is windy in most times of the year with very low humidity, which helps to drive the air movement in the system if properly positioned.

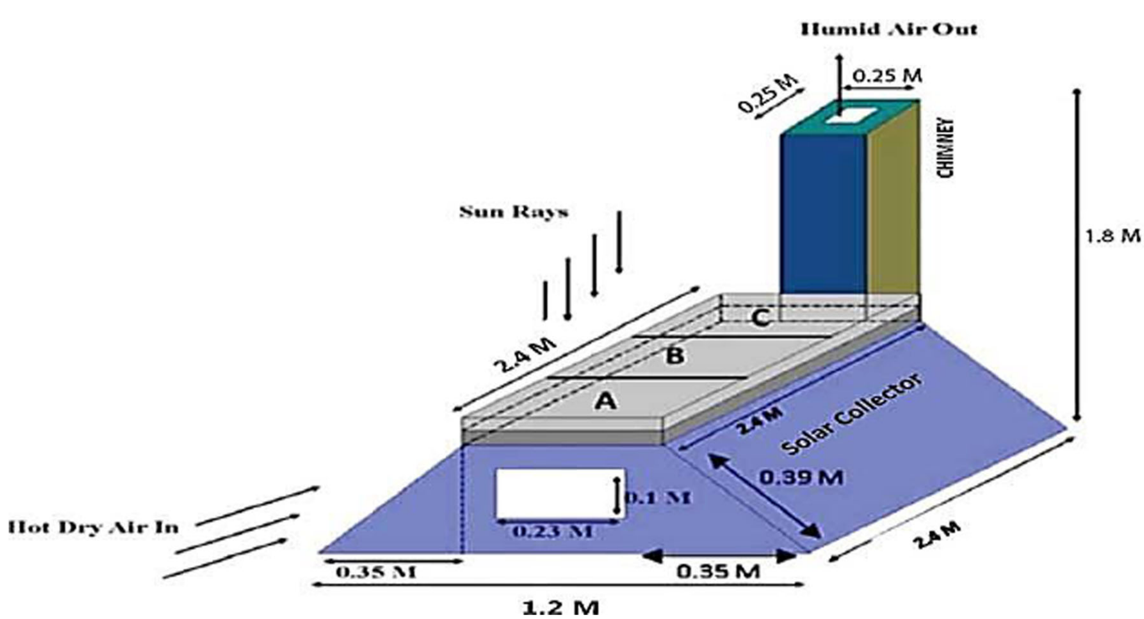


Fig. 20 Mixed-mode solar dryer (A, B, and C show the placement of the racks) [8]

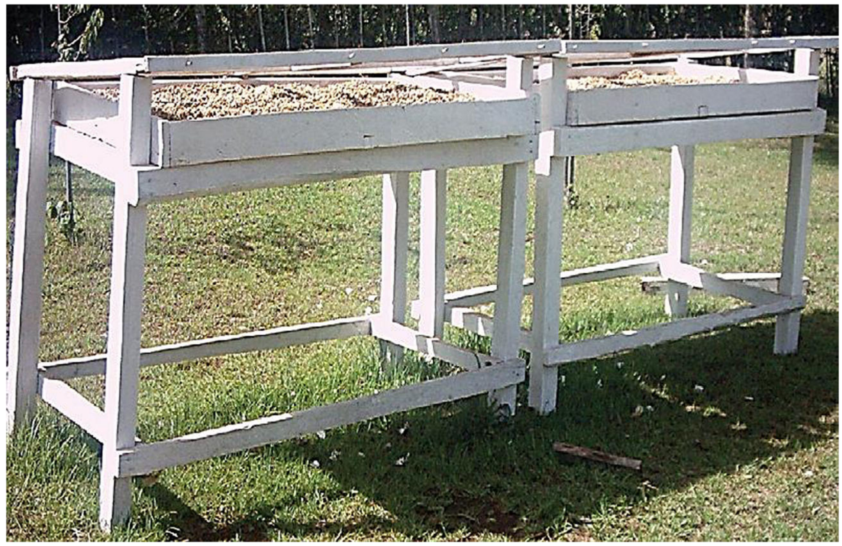


Fig. 21 Wooden solar dryer for pyrethrum flowers [65]

Another reason might border on the economic status of the countries around this region because adopting an active system will increase the construction and operating cost which will be transferred to the buyers. Most material used for construction was timber. We cannot find theoretical studies dealing with mathematical modeling and simulation of the tested dryers as well as the economical part the efficiency of the presented drying systems. The quality evaluation of the final product was not carried out.

Central Africa

Daily solar insolation around Central African states is among the lowest in Africa (Fig. 1). These countries are warm and humid in most times of the year with an average solar insolation hovering around 5.0 kWh m^{-2} day^{-1}. The region falls within the tropical rainforest zones which might be the reason for the lack of interest in conducting research in solar drying.

Experience of Solar Drying in Central Africa

Berinyuy et al. [20] presented an indirect solar tunnel dryer with thermal storage bed and a chimney (Fig. 28) for drying vegetables in Dschang region of Cameroon. The dryer was an adaptation of the tunnel dryer presented by Mühlbauer et al. [74]. The collector made of wood shavings sandwiched between plywood boards (double passed) had the following dimensions: 4 m × 1 m × 0.6 m and tilted 6° facing south. The absorber was made from corrugated aluminum sheet, painted in black, and loaded with black-painted stones for thermal storage. Air intake was from the underneath of the collector and double passed the absorber into the drying chamber. The

Fig. 22 Static bed box-type solar dryer mode [67]

Fig. 23 UNIDO solar hybrid dryer model [67]

drying trays were made from wood and plastic and measured 3.25 m^2. The utilization of plywood in a very high moisture environment like Central Africa where the equipment will be placed outdoor is not a good choice of material. This is because plywood absorbs moisture quickly and swells; therefore, we expect a fast deterioration of the dryer. However, economic factor may be necessary due to the extreme poverty level in this region. Evaluation of the dryer showed an overall dryer efficiency of 17.68% with an air flow rate of 9.68 m^3/h. This provided a moisture extraction efficiency of 79.15% from the initial value of 95% for cabbage in 5 days. Bokungu Efoto et al. [21] reported a solar dryer, called "Elouama 1" for drying cassava chips in the Democratic Republic of Congo. The drying chamber and the collector were fused together at a rectangular-like junction and both covered with transparent plastic roof with gap between the roof and the two sections for air circulation. The wall was a composite of transparent plastic sheet, sawdust, and plywood. The floor was made of agglomerated bricks and cement. The absorber was gravel placed on sawdust, while the trays were 1.0 × 1.5 m^2 separated by a 1-m-wide wall. The efficiency of this dryer was not stated; however, the dryer was used to reduce the moisture content of the cassava to 10%.

The Challenges of Filling the Solar Drying Energy Gap in Africa

The former United Nations Secretary General, Ban Ki Moon, began in 2011 to advocate the "Sustainable Energy for All by 2030" project, the goal of which is to ensure global pathway to sustainable energy services, doubling the rate of development in energy efficiency and conservation and also expand the portion of the integration of renewable energy in the global energy mix. Solar drying via solar energy features prominently among these three goals. Therefore, attaining the solar thermal drying potentials in Africa could be a potential solution, in particular for farmers, for partly achieving sustainable energy growth to fill the energy gap in the continent. The major challenge facing the adoption of solar dryers is the lack of

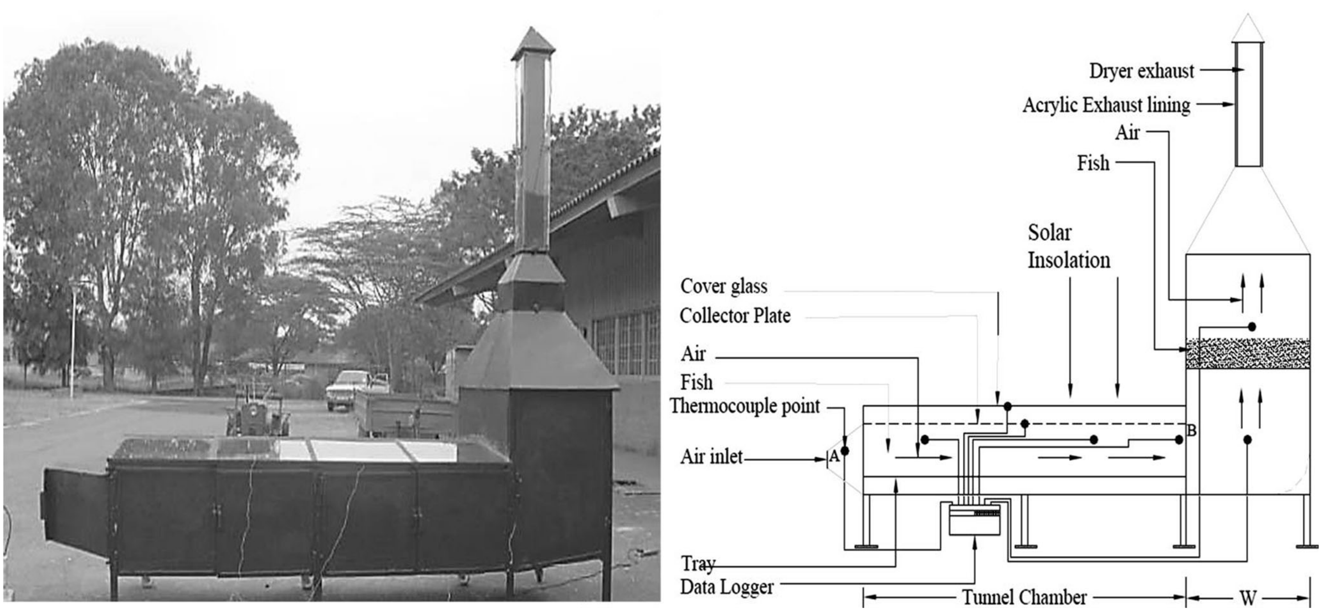


Fig. 24 Solar tunnel dryer [68, 69]

Fig. 25 Modified solar tunnel dryer [82]

advocacy and awareness targeted toward the end user. In the case of crop dryers on farms, exhibition is necessary to drive home the impact to the end users. Active and high-capacity dryers require high initial investment. Therefore, Africa with low per capita income, sourcing for fund, can pose a big challenge. This is where government can come in with financial incentives like power purchase agreements and feed-in tariff.

Conclusion and Future Area of Research

Solar drying in the entire Africa has evolved over the years with indirect or mixed-mode solar dryers dominating the designs. However, the level of research is still very low compared to other parts of the world. Therefore, investments in solar drying research in Africa are still required and can provide a good window for companies producing solar drying equipment. It was found that sun drying is still the dominant drying method due to high solar insolation across the continent which can explain the low level of solar drying research across the continent. This is because in Africa most comparison of solar drying with open sun drying is in terms of quick drying only, but comparison based on the quality of the final product is limited as shown from the data presented in most of the reviewed papers. Nevertheless, several products have been dried which include medicinal plants, fruits, flowers, vegetables, fish, dairy products, and woods. The angle of inclination of the solar collectors ranged from 0° to 60° toward the south with only one exception found inclined to the north. The design material is mostly locally sourced timber available in the

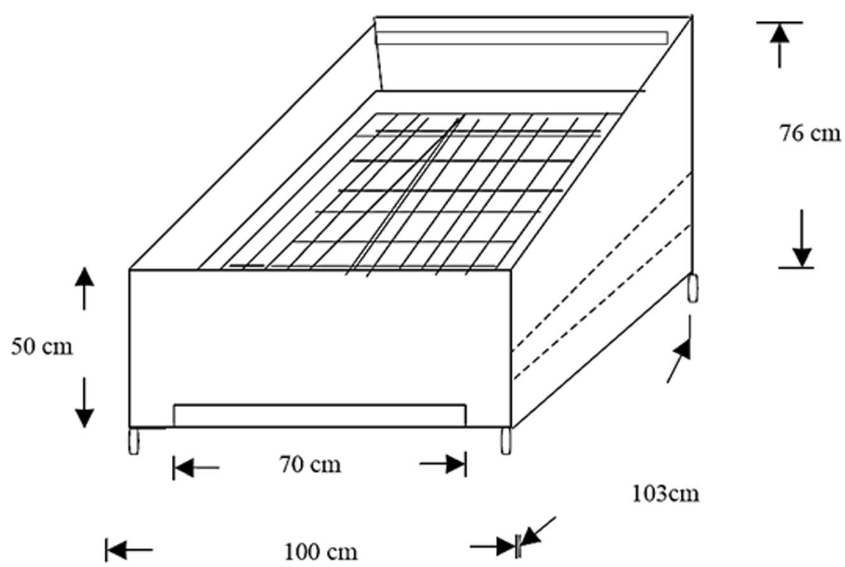


Fig. 26 Solar cabinet dryer for drying mango [41]

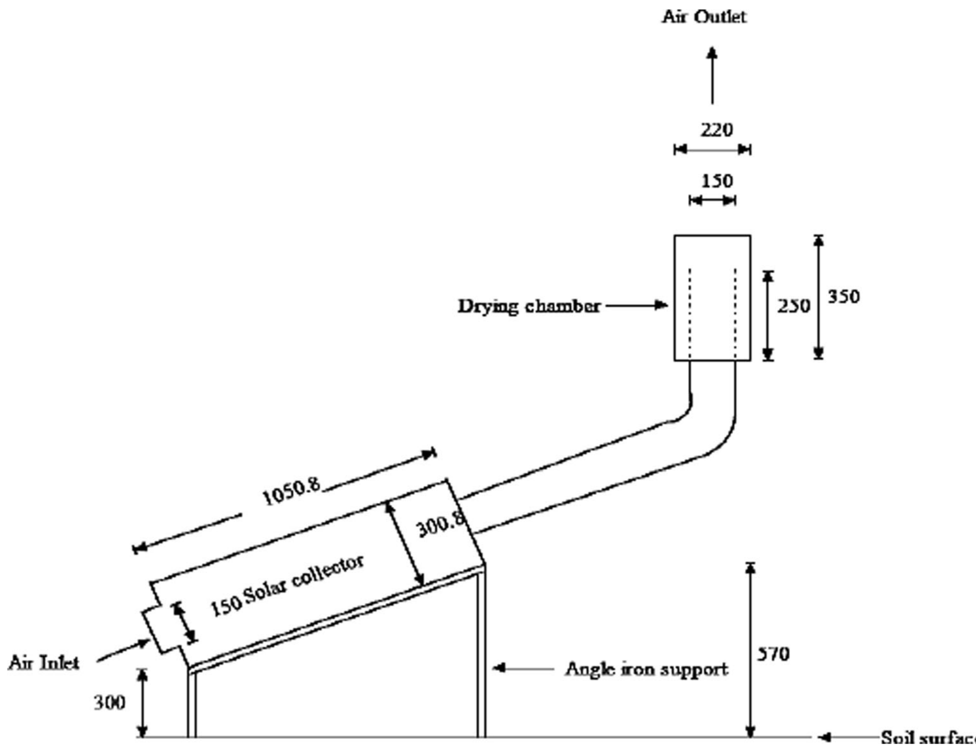


Fig. 27 Natural convective indirect flat plate solar dryer [62]

particular country. A good number of different modes of air circulation were found; however, every region has more dominant modes as shown in the summary tables. In one case, fins were introduced on the solar plate to drive the air which is innovative, and this line of research can be expanded. Hybrid dryers with auxiliary heat source are found more in Nigeria especially those powered by biomass; however, other countries are also keying in due to changing weather. In some countries, rock pebbles have been used as thermal storage, but exploring this aspect is not much found. Some areas like the Central African region with high humidity and lower investment in solar drying research should explore thermal storage to capture very short time of availability of the sun to aid drying during off-sunshine hours. Phase change material has not been used in thermal storage in Africa to the best of our knowledge. This should be explored especially areas like Central Africa and the coastal lines that has lower solar insolation. This is because phase change materials present special attraction due to high latent heat storage density with phase change taking place at a narrow temperature range and small required volume. Therefore, their application in solar dryer as thermal storage material forestalls the challenges posed by the vagaries of weather. Very few dryers at the industrial scale were found with most of the dryers for the subsistent type of agriculture. The esthetics of most designs are poor due to the fact that this research might be private funded with less money at the exception of those developed in the public research institutions. However, one good thing is that these dryers are cheap, flexible, replaceable, and adaptable for drying other crops. With the exception of Algeria, Nigeria, and Tunisia, other African countries are lacking behind in solar drying research, and in some cases, the solar drying research is pioneered by foreign organizations. As it can be seen, most of the theoretical studies were focusing on modeling the drying kinetics and few of them were directed

Table 11 Summary of dryers developed in Eastern Africa and the products dried

Type of solar dryer	Mode	Country	Location	Author(s)	Angle of tilt of collector (°)	Product dried
Direct	Passive	Ethiopia	Bahir Dar	Tefera et al. [98]	21.3	Potato
Direct	–	Ethiopia	Tigray	Tewolde-Berhan et al. [99]	–	*Cordia africana*
Direct	Mixed mode	Kenya	Edoret	Ayua et al. [8]	–	Amaranth nightshade
Indirect	Mixed mode	Kenya	–	Kituu et al. [68, 69]	Horizontal	Fish
Indirect	Mixed mode	Kenya	Giza	Oduor-Odote et al. [82]	Horizontal	Fish
Direct	Passive	Kenya	–	KARI [65]	–	Pyrethrum flowers

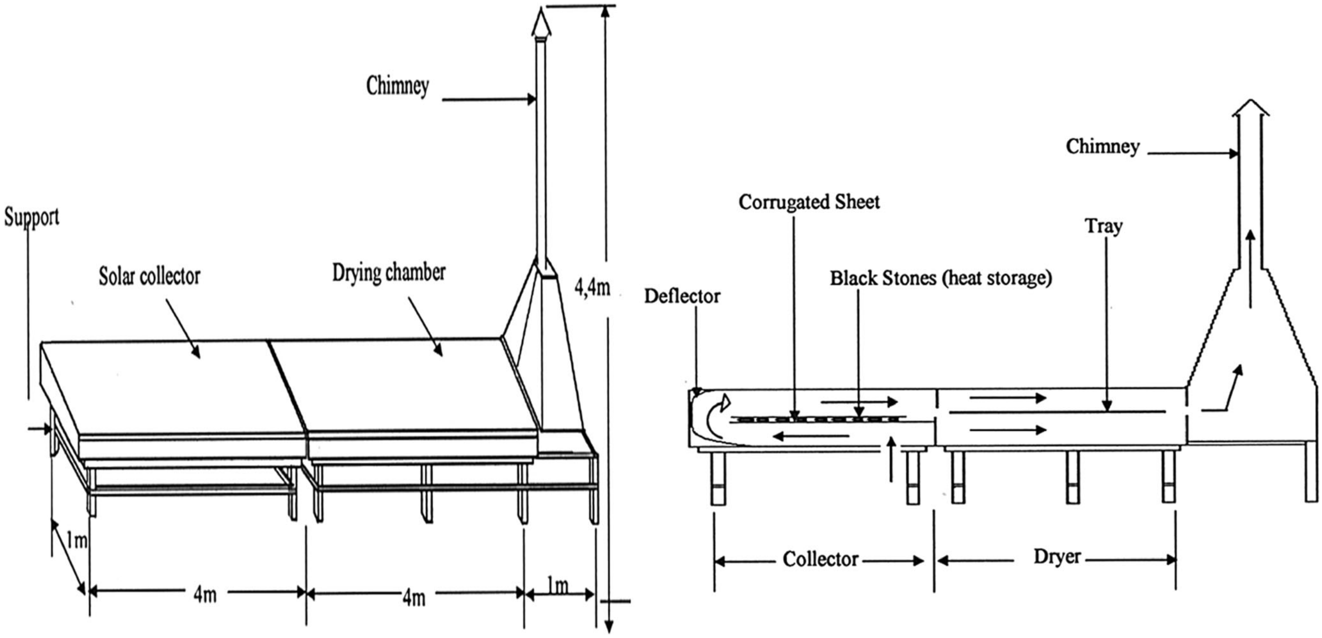


Fig. 28 Solar tunnel with stone as thermal storage [20]

to predict the behavior of the developed solar drying systems. Simulation mathematical modeling and optimization studies have not been substantially done within cities and countries based on our findings since climates and local demands modify solar dryer design. This is probably because in some countries like Algeria solar drying research is localized within the research centers; therefore, simulation and optimization should be rigorously pursued by bringing it to other climates. This will form a design pool for each country and reduce the cost of experiments. Simulations will cover the designing and the redesigning phase of the solar dryer out of the loop by relating the model previously proven in the design segment [3]. The other advantage that simulation will give is the quantum of details and data that will be made available for researchers and investors, knowing fully that most countries in Africa are large with diverse climate within the same country. It will also provide optional results that are difficult to determine experimentally due to instrument limitations [3].

Analysis based on the exergy has not been substantially connected to the study of the solar dryers. In fact, exergy could provide a better and more meaningful insight into the energy utilization. This is because exergy analysis in this case will take into account the reference temperature of every location which makes its analysis environmentally specific. Moreover, the economic sustainability value and thermodynamic process of the solar dryers could be properly mirrored, and the ability to design more effective solar dryers by reducing inadequacies could be really discovered through the exergy studies [36]. The research revealed the difficulties at the application of drying using solar energy because most of the products are dried with a nonhomogeneous manner. However, this line of research can still be pursued especially in countries such as Burkina Faso, Sudan, Egypt, and East African countries with very high solar radiation that are dry and windy during most parts of the year. The economic aspects of the developed solar dryers are usually neglected; however, we recommend that when developing research in this area of solar drying to make a calculation of the investment and the payback as well as introduction of the quality of the final product be included. This approach could provide useful arguments that may attract public or private investments. Regarding the calculation of the initial investment and the payback of the construction of a solar dryer, we do recommend the study published by Bennamoun [17]. Finally, African countries still has a long way to catch up with the rest of the world, but solar drying experience is improving based on the volume of current literature.

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