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REVIEW ARTICLE

Improving Solar Dryers' Performances Using Design and Thermal Heat Storage

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Abstract Solar drying is one of the most important processes used by the farmers and the agriculture producers especially in developing countries, at the same time as using free solar energy permits to reduce the cost of the operation. However, in order to face or to limit the intermittent character of solar energy, storage is proposed as a solution. It is found that two ways are used for the thermal energy storage: thermal and chemical ways. Nevertheless, thermal way is the most useful for solar drying. We present, in this paper, a classification of the common methods of thermal energy storage applied to solar drying with the presentation of the optimum design parameters for the studied dryers. It was found that the most frequent materials used for energy storage during solar drying are packed-bed storage with the use of rocks, sands, or gravels. The packed bed can be added to the drying chamber, to the solar collector, or both of them. Also, desiccants, such as a mixture of several chemical products or wheat, can find applications as storage material used for solar drying process. Water is the other proposed storage material; it is used according to its availability, cost, and some of its thermo-physical characteristics. Latent heat storage has found a little application for solar drying. In general manner and depending on the dried product, the insert of the thermal energy storage increases the efficiencies of the solar dryers and allows recovering the surplus of solar radiations during sunshine periods for a reuse during the off-sunshine periods. The study is ended by an economic analysis of some developed solar dryers.

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List of symbols

A	Surface (m^2)
C or Cp	Specific heat capacity (J kg^{-1} °C^{-1})
D	Diameter (m)
G	Air mass velocity through grain bed/rock bed (kg s^{-1} m^{-2})
g	Gravitational acceleration (m s^{-2})
H	Height (m)
h or h_c	Convective heat transfer coefficient (W m^{-2} °C^{-1})
h_{as}	Adiabatic saturation humidity of air entering the drying chamber (kg water kg^{-1} dry air)
h_i	Absolute humidity of air entering the drying chamber (kg water kg^{-1} dry air)
I	Hourly average solar radiation on inclined surface (W m^{-2})
L_c or L_g	Latent heat of vaporisation (J kg^{-1})
M or m	Mass (kg)
Mev	Hourly moisture evaporation (kg h^{-1})
m_w	Moisture evaporated in time (kg s^{-1})
m_a or $\dot{m}_a$	Mass flow rate (kg s^{-1})
P_d	Blower power (J)
Q_f	Amount of heat energy consumed by the fan (J)
Q_h	Amount of heat energy given by the heater (J)
Q_p	Amount of heat energy consumed by the pump (J)
T	Temperature (°C)
T_{fHS}	Final temperature of heat storage material (°C)
T_{iHS}	Initial temperature of heat storage material (°C)
T_i	Inlet air temperature (°C)
T	Time (s)
U_L	Overall heat loss coefficient from chimney (W m^{-2} °C^{-1})
W	Air humidity (kg kg^{-1})

X	Dimension (m)
Z	Height above drying bed (m)
ΔP	Pressure drop (N m^{-2})
ΔT	Difference between ambient and component air temperature (°C)

Greek symbols

β	Coefficient of thermal expansion (°C^{-1})
ε	Porosity or emissivity
η	Thermal efficiency
ρ	Density (kg/m^3)

Subscripts

a	Air or ambient
b	Packed bed
c	Crop or collector
ch	Chamber
d	Day
E_0	Inlet exchange-storage unit
E_1	Outlet exchange-storage unit
f	Fluid in grain
g	Global
i	Number of side wall of dryer or the number of reflector or inlet
n	Night
o	Outlet
R	Rock
p	Absorber plate or pickup
RB	Rock bed
s	Storage material
t	Time
th	Thermal
w	Water
0	Initial

Introduction

Growth of the world population and the constant seek of life comfort play important roles on the increase in the energy demand and in consequence on its production (in all possible forms). Some of the exploited energies have conducted to serious environmental nuisance. Consequently and due to the anxious spirit and the challenge of environment preservation, a tendency of integration of renewable energies in the daily human habits, in particular solar energy, is noted. It is the most useful source that finds simple life applications, such as using it to heat water or air and for having electricity. Solar drying is one of the familiar applications used by the farmers and the agriculture producers, especially in developing countries. Using free solar energy allows reducing considerably the cost of the drying process, which is known to be an intensive operation with high energy consumption.

According to their functioning mode, we can find essentially two types of solar dryers—passive and active [12, 19, 22, 25]—both of them present intermittent character, as usually they work only during sunshine periods and present limitations in their utilisation in unfavourable climatic conditions, such as during cloudy days or in the night. To find a solution to this unconstructive property, auxiliary sources or energy storage systems or both of them are added to the drying system. The use of auxiliary sources is not useful as the solar dryer is kept dependent on a second source of energy in addition to solar energy. Storage, in particular thermal energy storage, of surplus of energy during important radiation periods, in order to use it throughout unfavourable conditions, is proposed as a key issue. It permits, in one hand, extending drying periods and accordingly increasing efficiency of the solar dryer. On the other hand, it avoids damage or an over-drying of the material by having temperature control [32].

As reported by Bal et al. [8, 9], thermal energy storage can be obtained by two ways: chemical or thermal methods. For the chemical method, thermal chemical pipe lines, heat of reaction, or a heat pump are used, as illustrated in Fig. 1. Nevertheless, thermal way is the preferable approach applied for solar drying. In this way, we can use sensible heat storage. It consists of increasing the temperature of a liquid or a solid or in other words increasing their internal energy during high radiations periods for discharged during the low radiation periods. The quantity of stored energy depends on the properties of the storage material and the variations of the radiations. Generally, water is used as the best liquid storage material because of its cost, its specific heat properties, and the temperature range of its use [50]. Rocks, bricks, and concrete materials can also be used for air heating applications [8, 50]. Furthermore, thermal energy can be stored by manipulating the latent heat of a material. The storage material absorbs the surplus of energy during high radiation periods leading to the phase change such as from solid to liquid or from liquid to gas. This absorption is done at almost constant temperature. As the chemical reaction is totally reversible, during low radiation period, the obtained energy is discharged and the material used for storage finds again its initial form. Latent heat storage with solid–liquid phase change has received special attraction. In this case, the used phase change materials present high latent heat storage; moreover, the melt and solidification are done in nearly constant temperature and a small volume is required. Reports by Bal et al. [8] and Sharma et al. [50] have presented an exhaustive work dealing with the classification of different phase change materials classified as organic (paraffins, non-paraffins, inorganic (salt hydrates, metallics) and eutectics materials with the presentation of several

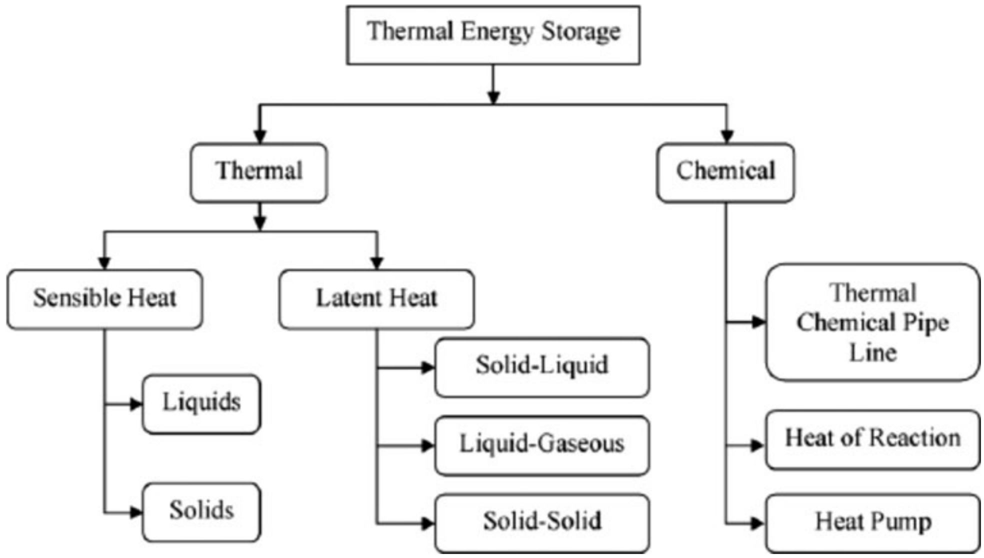


Fig. 1 Different types of thermal storage of solar energy [32]

physical properties such as melting point, latent heat, freezing point range, and heat of fusion.

This paper presents a review of the developed solar dryers dotted with storage systems for not especially food products with a particular care of the design of the dryer and the different storage materials used and their displacement with mathematical modelling description, efficiency calculus of the whole studied cases with presentation of economic analysis.

Presentation of Solar Dryers with Storage Materials

Solar dryers are classified according to the type of storage material and its position in the drying system. In view of that, solar drying systems that use sensible heat storage, such as rock bed, desiccants, and water systems, are firstly presented and then the solar dryers are dotted with latent heat storage.

Packed-bed Storage

Rock is commonly used as storage material for solar drying using air collector. However, several designs are proposed, while the packed bed can be used as a part of the collector, of the drying chamber or both of them. In this section, the different designs are detailed with the presentation of the mathematical modelling procedure.

Storage Material Part of the Drying Chamber

Chauhan et al. [18] present the performances of a solar dryer coupled to an air-heater-cum-rock-bed storage with comparison of the performances when a simple solar air heater is used. The study was applied for coriander food

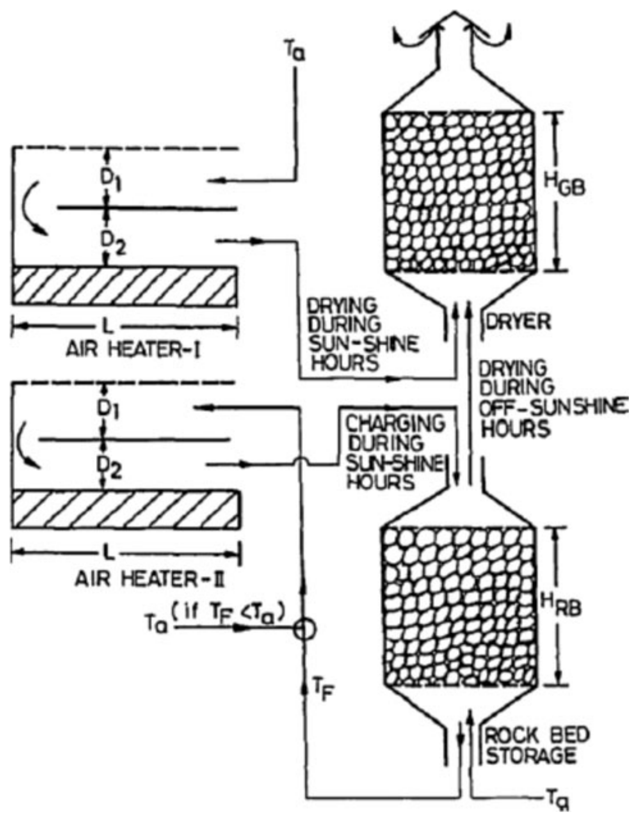


Fig. 2 Simplified schematic view of the solar dryer coupled to solar air-heater-cum-rock-bed storage [18]

product. The components of the solar dryer are as follows: the drying chamber, the rock-bed storage unit directly connected to the drying chamber, and two similar double pass with single cover solar air heaters. One of the collectors is coupled to the drying chamber and the second to the rock-bed storage unit, as shown in Fig. 2. The different characteristics of the dryer components are presented in

Table 1 Design parameters of the studied solar dryer [18]

Parameters	Value
(a) Air heaters	
Duct length (L)	3 m
Duct width (W)	1 m
Duct depth	
Above the absorber (D1)	3 cm
Below the absorber (D2)	3 cm
(b) Rock-bed energy storage	
Breadth of bed (B_{RB})	2.5 m
Width of bed (W_{RB})	2.5 m
Height of bed (H_{RB})	1 m
Porosity of bed (ε_{RB})	0.35
Rock diameter (D_R)	4 cm
(c) Coriander bed	
Size of grain (D_{GR})	4 mm
Shape of grain	Sphere
Drying constant (k)	0.04245 l/h
Width (W_{GB})	1.45 m
Breadth (B_{GB})	1.45 m
Height (H_{GB})	0.75 m
Porosity of the bed (ε_{GB})	0.45

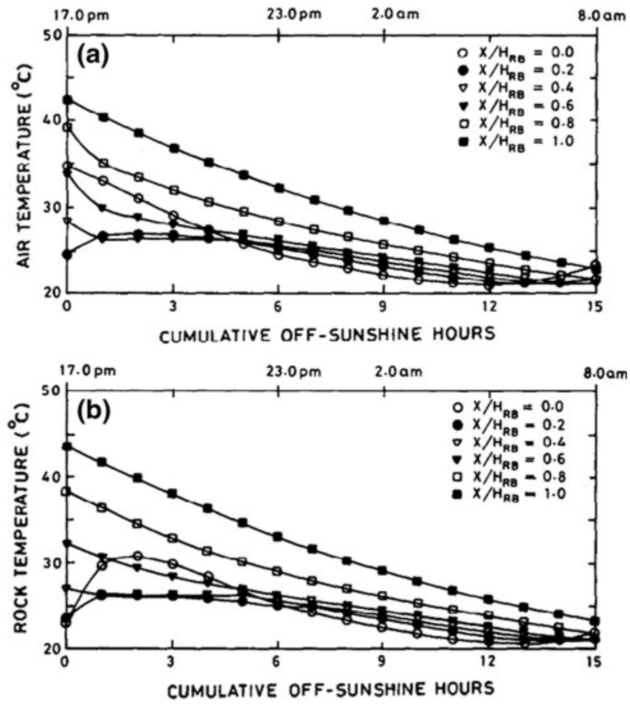


Fig. 3 Variation of the air and the rock-bed temperatures during off-sunshine hours [18]

Table 1. The capacity of the solar dryer is estimated as 0.5 ton per batch with product filled in thick layers. The inlet air temperature varies with changes in the ambient conditions and the received radiations. Two cases such as with and without storage systems are presented in this study. The results have shown that to reduce moisture content of the product from 28.2 % (dry basis) to 11.4 % (dry basis), about 27 cumulative sunshine hours or 3 sunshine days were necessary when a simple solar collector is used. However, only 2 days and 2 nights, or 18 sunshine and 13 off-sunshine hours, using rock-bed storage system, were needed. It is important to note that the results have shown that through thick layer drying, the process is effectuated with a non-homogeneous manner, as confirmed by other results dealing with thick layers drying [3, 4, 14, 15]. Therefore, when the moisture content of bottom layer, at the end of the process, is 11.4 % (dry basis), top layer moisture content is around 15 % (dry basis).

The mathematical modelling of the solar dryer passes through the establishment of heat and mass balances applied to the two air heaters, to the drying chamber and the storage unit. Along these lines, cover glasses of the air heaters, which receive a fraction of the solar radiations, exchange heat by radiation, by convection with heated air, and by convection with ambient air. Fluid circulated above and below the absorbers exchanges heat by convection, with the absorber, the glass, and the insulator. However, the absorbers receive the transmitted fraction of radiations and make exchanges by radiations with the glass and the insulation and by convection with the two fluids [18] The drying chamber is treated as a porous media [5, 14, 15, 31, 43, 46, 55], leading to four differential equations with some simplification hypothesis. These equations allow following the temperature of the fluid inside the chamber and the grain bed, but also following humidity changes for the dried product and the heated air. On the other hand, energy balance on the storage unit leads to the following two equations:

Air in packed bed

$$\rho_f C_f \varepsilon_{RB} \frac{dT_f}{dt} + G_{RB} C_f \frac{dT_f}{dx} = h_{cfR}\left(T_R - T_f\right) \quad (1)$$

Rocks in packed bed

$$\rho_R C_R (1 - \varepsilon_{RB}) \frac{dT_R}{dt} = h_{cfR}\left(T_f - T_R\right) \quad (2)$$

As the rock bed is not directly exposed to the sun lights and was indirectly heated by the circulating air (Fig. 2), the two equations show exchange by only convection between the rock bed and the fluid. Figure 3 shows the variation of the air and rock-bed temperatures of the storage system with a general form similar to the ambient temperature and solar radiation variations. At the beginning of the off-sunshine period, the reached temperatures were higher than 40 °C with a decease tendency until reaching the ambient temperature at the beginning of the next drying day. By this mean, it was possible to keep the product and drying air temperatures higher between 25° at the beginning of the off-sunshine period and 10 degrees at the end of the period, from ambient temperature. Also, the authors have shown that increasing the height of the rock bed could increase storage system temperature and consequently increase the drying air and product temperatures.

Jain [34] studied a solar crop dryer dotted with packed-bed storage systems. As shown in Fig. 4, the solar dryer is constituted of two absorbers, reflectors constituting a polygonal shape, two storage systems and a drying chamber that contains two perforated trays. The ambient air is heated by the first absorber noted as absorber plate-I, which is horizontal and receives a fraction of the reflected radiations from the reflectors. The heated air passes through a packed bed of pebbles, before reaching the trays. On the other side, the second absorber, noted as absorber plate-II, is situated above the trays, inclined by 30° and before the outlet air. We can find a triangular cavity below the absorber filled with granite grits, used as a second storage material and heated during sunshine periods by the absorber plate-II. During sunshine hours, the absorber-I absorbs energy and a part of this energy is delivered to the rock-bed pebbles and another part to the drying air. The absorber-II delivers his energy essentially to the second storage material but a part to the air is going out the collector. During off-sunshine hours, the ambient air at a mean temperature of 20 °C is heated by the energy delivered by the two storage systems. The mean temperatures of the second storage material, the trays, and the air passing through the absorber plate-II were kept between 52 and 45 °C, 7 h after the beginning of the off-sunshine period. The optimised design parameters of the solar dryer are presented in Table 2. In general manner, the solar dryer has shown good results as in 24 h, 95 kg of onions is dried from 6.14 (dry basis) to 0.27 kg/kg (dry basis).

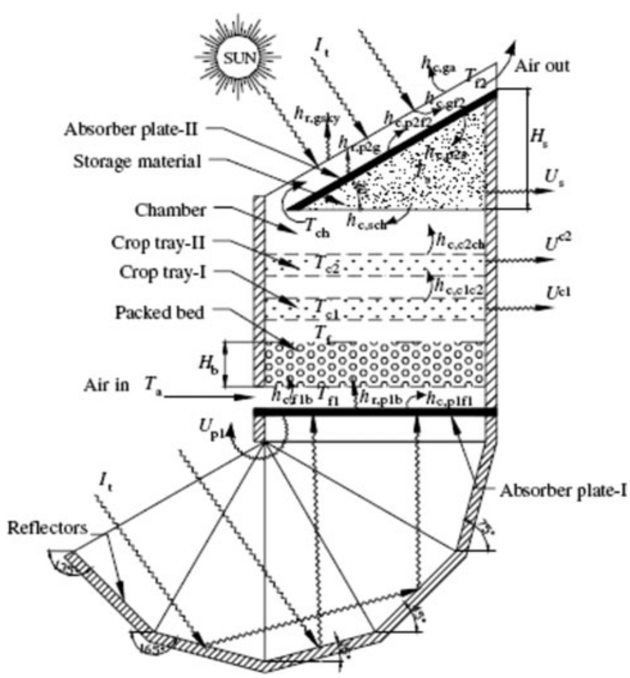


Fig. 4 Reversed absorber with thermal storage natural convective solar crop dryer [34]

The thermal analysis is based on the energy and mass balances applied for the different components of the dryer, which has the reversed absorber plate-I, the packed bed, the drying chamber with trays, the components of the natural convection collector with storage, and the dried product. However, the authors consider some simplification hypothesis such as the heat flows in one dimension and there are quasi-steady state conditions, the system is perfectly insulated, storage material has an average temperature (T_s) at a time (t) and the dryer is facing the sun.

A part of the energy obtained by the absorber plate-I is given up to the air and the rest to the pebbles. For the packed bed, equations similar to (1) and (2) are used.

The two trays and the chamber present exchanges between themselves, the fluid, and the dryer walls represented by different convective heat transfer coefficients and overall heat loss coefficient from sides of the dryer. Also for the second solar collector represented by the absorber plate-II, energy balance done to the glass cover gives exchange by convection and radiation with the ambient media and convective exchange with the fluid. As well, the absorbed plate-II absorbs a part of received radiations and exchanges heat by convection with the fluid and the material storage and by radiation with the glass cover. In addition, the fluid exchanges heat by convection with the absorber plate-II and the glass cover. The energy balance on the second storage material which is written in the following form shows heat exchanges with the dryer wall, the absorber, and the air in the chamber.

Table 2 Optimised design parameters of the solar dryer [34]

Parameters	Value
Length of the dryer and the absorber plate-I(L)	1 m
Breath of the dryer and the absorber plate-I (b)	1 m
Surface of the absorber plate-I (A_{p1})	L × b m^2
Duct width of air flow channel (d)	0.12 m
Diameter of pebbles (D_b)	0.025 m
Height of the packed bed (H_b)	0.15 m
Surface of the absorber plate-II (A_{p2})	b(L–d)/cos(30) m^2
Height of the second storage material (H_s)	A_{p2} × sin(30) m
Thickness of the dryer wall (l_w)	0.025 m
Thickness of the absorber plate-II (l_{p2})	0.002 m

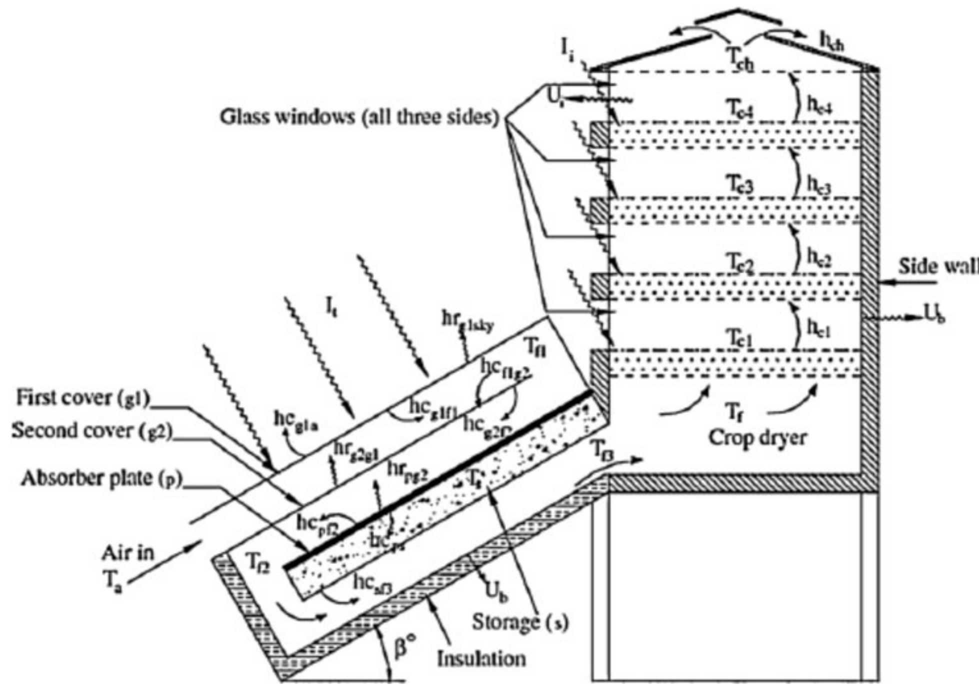


Fig. 5 Diagram of the multi-tray dryer with multi-pass solar air heater *dotted* with storage system [33]

Table 3 Optimum parameters of the multi-tray multi-pass solar air heater with storage [33]

Parameters	Value
Breadth of the collector plate (b)	1 m
Duct width (d)	0.1 m
Length of the collector plate (L)	4 m
Thickness of the bottom and side insulation of the collector and dryer (l_b)	0.05 m
Thickness of the absorber plate (l_p)	0.002 m
Thickness of the storage material (l_s)	0.1 m
Mass flow rate	(0.028 kg/s)
Collector inclination angle (β)	30°
Area of the drying chamber (A_{ch})	1.2 m^2
Area of each window	0.2 × 1 m^2
Crop Area	1 × 1 m^2

Storage Material Part of the Collector

Jain [33] has developed a multi-tray dryer coupled with solar air heater. This last is dotted with thermal storage material. The chart of the solar dryer is shown in Fig. 5. The drying chamber contains four trays distanced by equal vertical spacing. The east, south, and west walls of the drying chamber are made with glasses in order to increase the received radiations. The rear north side is an insulated wall. The received energy from the solar air heater is used to dry the product of the first tray and then the rest of energy is given up to the second tray then to the third and to the fourth tray. Radiations absorbed from the glass walls heat up the crop and accelerate the drying rate. As confirmed by other authors [13, 16], drying starts with the product of the first tray, then the second, the third, and the forth, respectively. Paddy crop product is tested in this study. The optimum design parameters of the solar dryer are given in Table 3.

The first glass cover receives a part of the radiations and gives it to the second glass cover with exchanges, and by convection with the fluid and the ambient environment, there is exchange with sky by radiation. The second glass cover receives another part of the radiations and exchanges energy by radiation with the first glass cover and the absorber and by the convection with the circulating fluid above and below the cover. However, the absorber exchanges by radiation with the second cover and by radiation with the fluid and storage material. The energy balance on the fluid gives exchanges by convection with the glass covers and the fluid. A part of the energy is given up to the dryer wall and to the storage material. The energy balance effectuated on the storage material is written in the form:

$$h_{c,ps}\left[T_p - T_s\right]A_p = m_s C_s \frac{\mathrm{d}T_s}{\mathrm{d}t} + A_p h_{c,sf}\left[T_s - T_f\right] \quad (3)$$

The mathematical treatment of the drying chamber was similar than one done by Jain [34] with adding a term representing the radiations received by the windows.

The overall thermal efficiency was given by the following equation:

$$\eta = \frac{L_c \sum_{t=1}^{t=24} \sum_{j=1}^{j=4} Mev_{t,j}}{3{,}600(A_p + A_c) \sum_{t=1}^{t=24} I_t} \quad (4)$$

t represents the time interval.

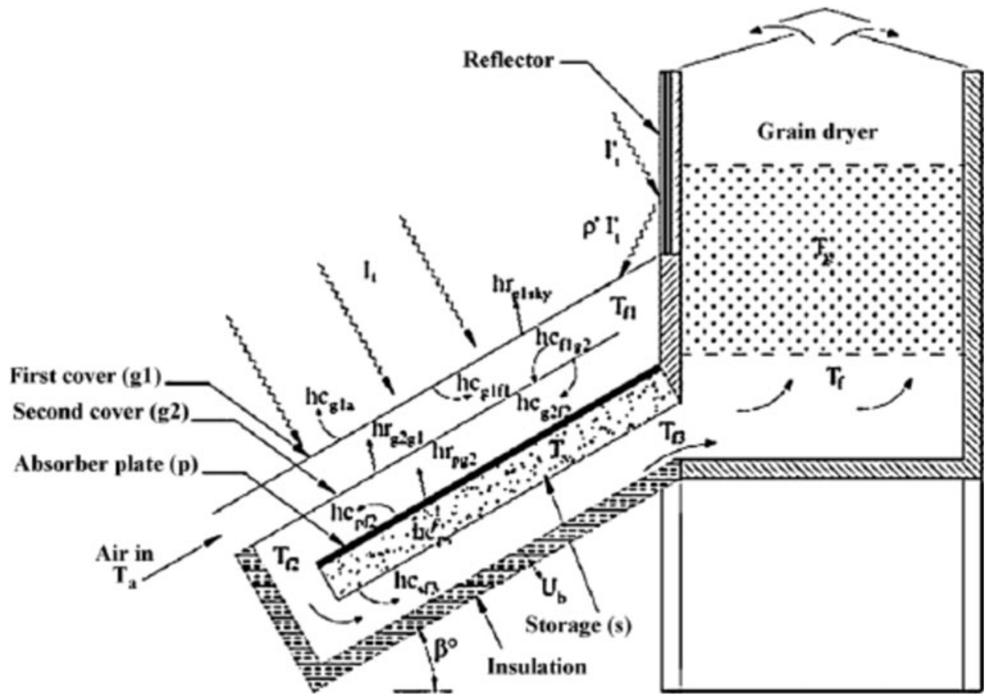


Fig. 6 Diagram of the packed-bed dryer with multi-pass solar air heater with storage system [35]

It was found that the efficiency increases linearly with the crop mass increasing from 5 % for 20 kg to more than 30 % for 100 kg. As reported by the author, for the same received solar energy, more water is available for evaporation at the crop mass increase.

Jain and Jain [35] have studied the same solar dryer using the same design characteristics but filled with thick layers with grain, and the windows were replaced by a reflector, as shown in Fig. 6. Comparing to the first solar drying system, the same equations describing the air heater are obtained. However, the drying chamber is presented as a porous media with four differential equations permitting to follow both temperatures and humidity of the grain and air. In this case, the variation of the efficiency linearly increases with the mass of the dried product, too, with efficiency around 8 % for a mass of 12 kg and increases to 40 % for 60 kg. As the authors have studied the influence of several parameters, such as the bed depth, the mass flow rate, and the length of the solar collector, on the drying results, no more information has been given on the influence of these parameters on the overall thermal efficiency of the presented drying system.

El-Sebai et al. [23] developed a natural convection solar dryer with a storage system added in the solar collector. As reported by Fudholi et al. [25], sand is used as storage material. The proposed solar dryer and the design characteristics are shown in Fig. 7. Several fruits and vegetables such as grapes, figs, apples, peas, onions, and tomatoes are tested in this dryer, and the drying constant of each product is a presented function of the temperature of the dried product. Deduced equations with experimental data are used in order to calculate the variations of the temperature of the heated air and the dried product. Also, the moisture content of the product is presented as a function of the drying coefficient. Several results with and without using storage material are presented in this paper, but without giving a comparison for some dried products.

Mohanraj and Chandrasekar [40] present a similar solar dryer with gravels added as storage material at the solar collector. The general view of the solar dryer is illustrated in Fig. 8 and its design parameters are presented in Table 4. The solar drier is consisted of flat plate solar air heater connected to the drying chamber. It is constituted of copper absorber plate-coated paint in black in order to absorb maximum of radiations, and it is covered with a transparent glass. The air to be heated flows between the absorber and the cover with a maintained distance of 25 mm. The collector is connected to a blower from one side. The 100-mm gap between the absorber and the insulation was filled with sand mixed with aluminium scraps to store heat during sunshine hours, to reuse it for heating the air during off-sunshine hours. The drying chamber is made of mild steel sheet of 2-mm thickness and was insulated with 10-mm thick of glass wool. It was found that the temperature of the heated air varies during off-sunshine hours between 68 °C as a maximum value and 43 °C as minimum obtained value. Twenty-four hours were sufficient to dry 40 kg of fresh chillies from about 72.8–9.1 % (wet basis). The drying time was extended to 4 h during off-sunshine period with the use of storage

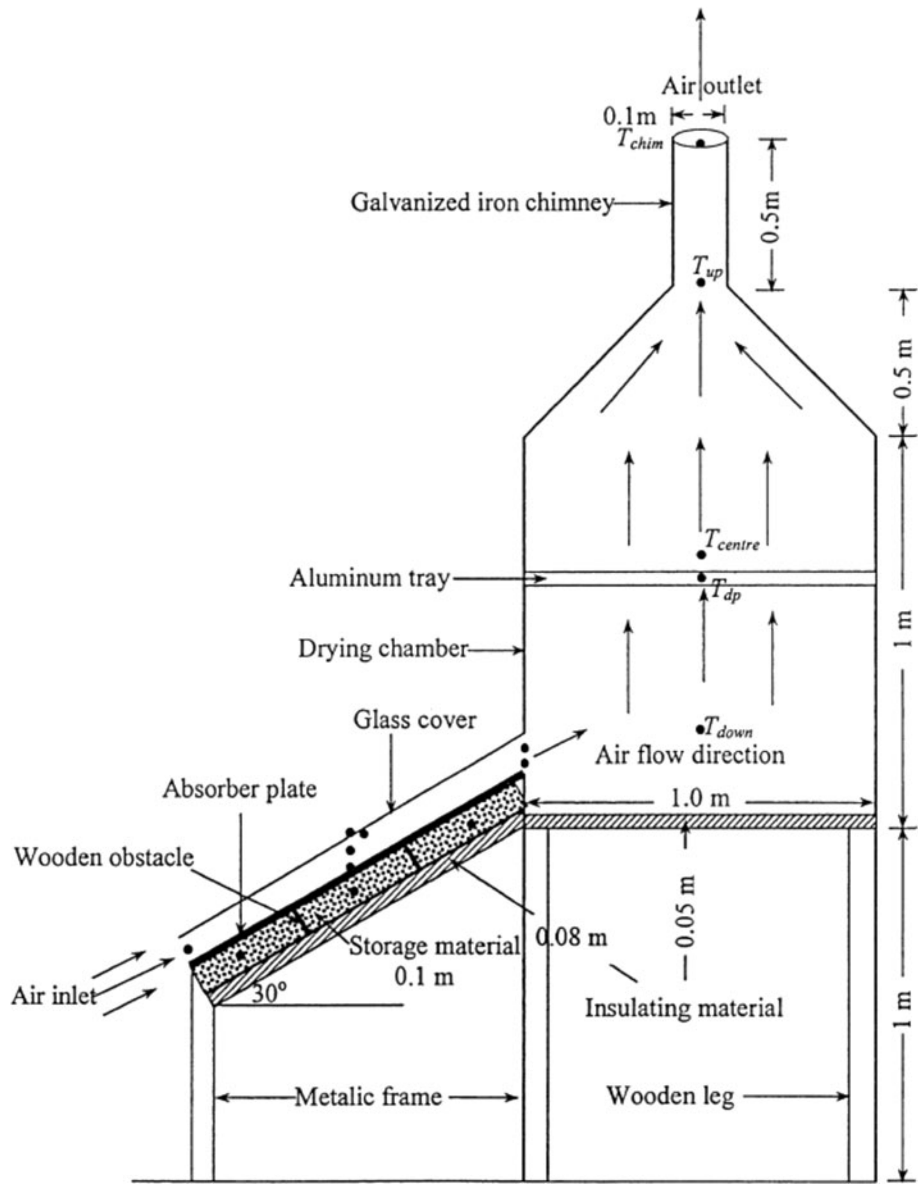


Fig. 7 Natural convection solar dryer with solar collector *dotted* with storage system [23]

material. The authors were interested by calculating the efficiency of the solar dryer, which was written in the following form:

$$\eta_{th} = \frac{m_w L_G}{m_a Cp_a[T_0 - T_i] + P_d + m_a Cp_a\left[T_{iHS} - T_{fHS}\right]} \quad (5)$$

And the average drier thermal efficiency was calculated to be about 21 %.

Storage Material Part of Both the Drying Chamber and the Solar Collector

Ayensu and Asiedu-Bondzie [6] have developed a solar dryer with convective self-flow and rock used as storage material. The chart of the solar dryer is shown in Fig. 9. It is constituted of three main parts that are the solar air heater, the drying chamber, and the chimney. A single-layer glass is used for covering the absorber with 10 cm air channel between the cover and the absorber. The glass cover is inclined with an angle of 15°. A pile of granite rocks of 3 cm in length is used as medium for heat storage. A 5-cm-depth layer of straw is used to insulate the absorber from the base ground. The authors made parametric design study and found that the surface of the collector must be around 3.3 m^2 to reach the required efficiency, which ought to be around 30 %. The drying chamber contains three trays, each made of a double layer of wire mesh (1 × 1 cm^2) and a depth of 2.54 cm. Access to the food was by three removal wooden panels made of plywood.

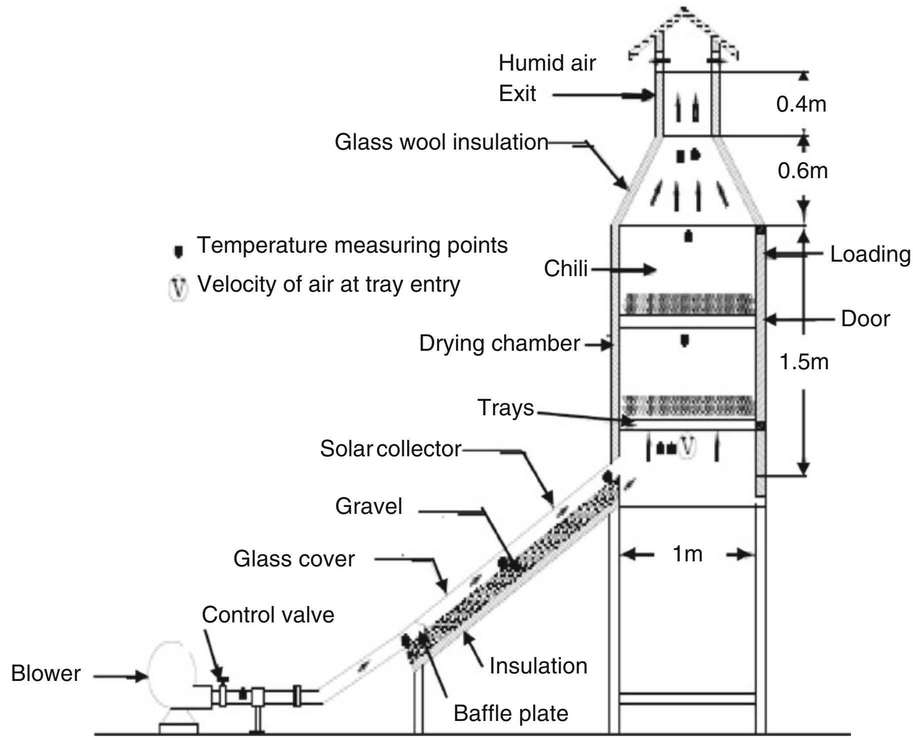


Fig. 8 General view of the solar dryer with storage system [40]

Table 4 Design parameters of the solar dryer developed by Mohanraj and Chandrasekar [40]

Parameters	Value
(a) Solar air heater	
Surface	$2 \times 1\ m^2$
Thickness of the absorber	2 mm
Thickness of the glass cover	5 mm
Angle inclination	25°
(b) Drying chamber	
Width	1 m
Depth	1 m
Height	1.5 m
Capacity	50 kg

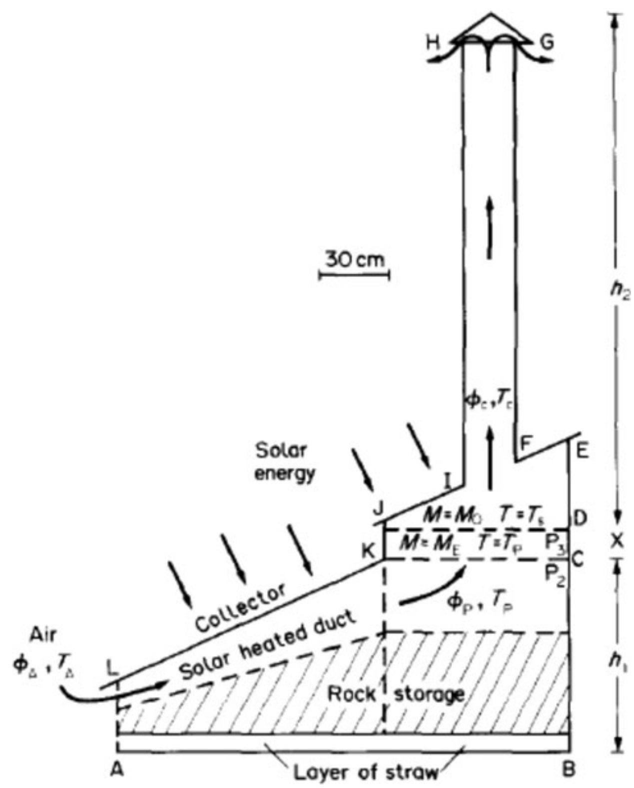


Fig. 9 Solar dryer with convective self-flow with rock storage [6]

The top of the drying chamber is made with glass in order to increase the picked-up radiations. Rock bed represents the bottom of the drying chamber. The chimney has a height of 1.9 m and 30 cm diameter hollow cylinder, made in galvanised iron. It was firmly fixed onto a slopping wooden based and mounted on the drying chamber. A metal cap is fixed at the top of the chimney to keep it out of rain. Also, it was paint in black to increase the temperature and in consequence the air flow. The objective is to dry 50 kg of cassava or similar crop from initial moisture of 70 % (Wet basis) to equilibrium moisture of 14 % or less, with an ambient air temperature of 32 °C and 80 % relative humidity. The objective was not totally attained as the heating efficiency of the dryer has attained only 22 %. It was calculated using the following equation:

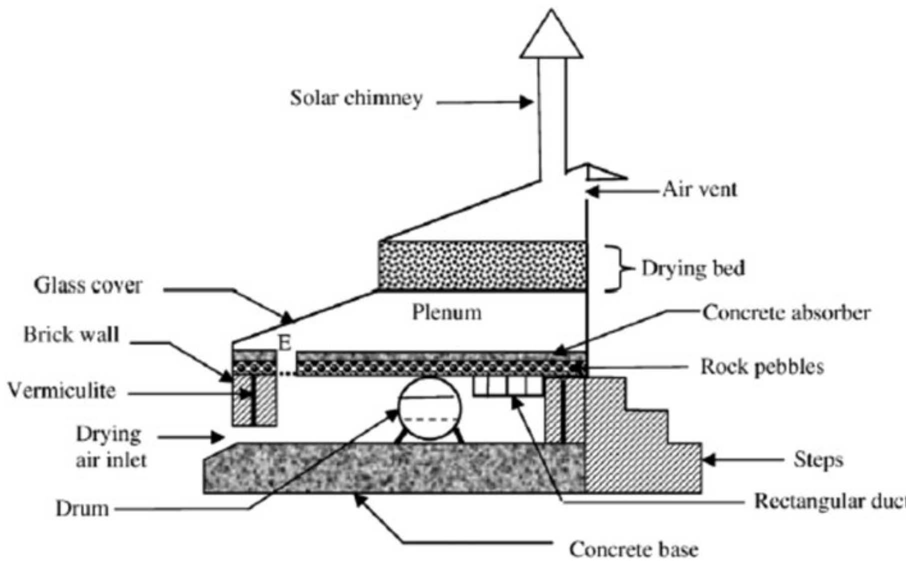


Fig. 10 Solar dryer equipped with thermal storage and biomass heater [39]

$$\eta = \frac{\dot{m}_a Cp_a \left[T_p - T_a\right]}{A_c F_i} \quad (6)$$

where F_i is the solar flux intercepted by the collector.

However, the rock storage system was benefit and stores 1.1 kW.h^{-1} used to enhance drying.

Using Storage with Mixed Sources of Energy

Madhlopa and Ngwalo [39] have designed, constructed, and evaluated the performances of an indirect natural convection solar dryer with integrated solar collector and a storage system but also biomass backup heaters (Fig. 10). Before the construction, the authors have evaluated the optimum design parameters resumed in Table 5. The collector of the dryer has a horizontal concrete absorber that is painted in black on its top part and integrated to the rock pebbles pile. It is enclosed in a wooden frame mounted on the top part of the brick wall that contains the burner. The exterior part of the vertical faces of the collector was covered with a painted galvanised iron sheet to protect the wood from weathering. The standard storage capacity of the solar air heater is 0.25 m^3 of pebbles per unit area of the collector, reported by Duffie and Beckman [21]. As application for this study, 0.55 m^3 of pebbles with 0.14 m depth is needed. The ambient air is first heated by the burner and then the heated air penetrates to the drying chamber via a rectangular hole (noted E in the Fig. 10). This flow of hot air would enable a reasonable amount of heat from the biomass burner to be transferred to the drying product. It is also important to note that during solar collection, heat is mainly transferred from the absorber plate to the rock bed by conduction. The drying chamber is managed to support three trays, and a quantity of about 20 kg of fresh pineapples can be dried. The top surface of the drying chamber is inclined at 16° to the horizontal to facilitate the evacuation of rain water. Furthermore, it facilitates the flow of the air from the plenum through the drying bed to the venting system. Two doors are situated in the back of the drying chamber to give access to the trays. A solar chimney is fitted in the top of the drying chamber to increase the natural convection of the drying air. It is also made with galvanised iron sheet and painted in black.

Air flow is induced by the difference between the temperatures of the air in the system components and ambient

Table 5 Optimum design parameters of the solar dryer dotted with thermal storage—biomass burner systems [39]

Parameters	Value
(a) Solar collector	
Aperture	2.2 m^2
Thickness of the absorber: concrete slab	0.025 m (Thick)
Glass cover	0.003 m (thick)
Angle inclination	16°
Granite rock	360 kg
Diameter of the rock	0.025 m
(b) Drying chamber	
Effective tray area	4.1 m^2
Solar chimney height	1.2 m
(C) Biomass burner	
Drum	
Length	0.89 m
Diameter	0.58 m
Door	0.55 × 0.54 m^2
Flue gas chimney	
Height	2.12 m
Diameter	0.12 m

air. The thermal buoyancy in the system components is given by the following equations (as given by Bala and Woods [10]):

$$\Delta P = \beta \rho_a g H(\Delta T) \quad (7)$$

$$T_{ch} = T_a + [T_c - T_a][1 - exp[-R]]/R \quad (8)$$

$$R = \pi D_{sc} U_L Z/(\dot{m}_a C_a) \quad (9)$$

The total thermal buoyancy of the drying air was found by summing the contribution from the burner, the enclosure, the collector, the drying bed, and the solar chimney.

A comparison of different results, with and without the combination of solar and biomass modes, was presented by the authors. The moisture content of a batch of fresh pineapple was reduced from 669 ± 24 to 16 ± 0 % (dry basis), using only solar energy and it takes between 96 h and 120 h. Other essays are effectuated using only biomass mode, without using the solar collector, and 72 h was sufficient to reduce the moisture content of the fresh pineapple from 614 ± 14 to 13 ± 0 % (dry basis). Almost the same time as biomass mode was registered at the combination of solar and biomass with a decrease in the moisture content of the pineapple batch from 669 ± 24 to 11 ± 0 % (dry basis). In general manner, the pickup efficiency of the solar dryer varies from 20 to 15 % for solar mode, from 15 to 11 % for biomass mode, and from 17 to 13 % for the mixed solar–biomass mode.

Use of Desiccant

Shanmugam and Natarajan [48] integrated desiccant as a solid storage material. The choice of the desiccant was based on the work done by Thoruwa et al. [54]. It was composed of mixture of 60 % bentonite, 10 % calcium chloride, 20 % vermiculite, and 10 % cement. The proposed solar dryer is revealed in Fig. 11. It is constituted essentially of a solar collector, drying chamber, and desiccant bed. An 18-gauge copper sheet painted in black is used as an absorber plate of the collector, which has a surface of about 1.2 × 2.4 m^2 and inclined at an angle of 30°. The collector is covered with 6-mm plain window glass and made with thick wood, and at the bottom 19-mm plywood is provided to support the absorber plate. About 20 mm is left between the absorber and cover for the air circulation. The collector is insulated using a 50-mm-thick wood. The drying chamber has the following dimensions: 1.2 × 1.2 × 1.0 m^3 fabricated using the 19-mm plywood. Double glazing, inclined at 30°, is provided at the top of the drying chamber with an air gap of 50 mm. A perforated sheet is provided to hold 75 kg of solid desiccant bed below the double glazing. The space between the bottom glass cover and the desiccant bed is 50 mm. The depth of the desiccant is 75 mm. During sunshine hours, a plate of plywood is placed at the bottom of the desiccant bed in order to facilitate the exit of the air and permits the desiccant to receive radiations. However, during off-sunshine hours, the plate is placed above the desiccant bed to avoid heat losses at the top. The trays are made using wire mesh fixed on wooden frame, it has a surface of about 1 × 1 m^2 and they can be easily removed from the drying chamber. The authors presented the performances of the dryer by calculating the pickup efficiency of the dryer, written by the following equation:

$$\eta_p = \frac{W_0 - W_t}{m_a A t [h_{as} - h_i]} \quad (10)$$

The pickup efficiency describes the efficiency of moisture removal by the drying air from the product. For this solar dryer, the green pea product is drier in around 21 h, 70 % is achieved through solar energy and the remaining is supported by the desiccant material. The pickup efficiency of the solar dryer varies from 63 to 20 % for different air flow rate.

Ziegler et al. [56] simulated the behaviour of a solar dryer with the use of wheat as desiccant. It has given better results than using chemical products such as silica gel. The simulated solar dryer can be used to dry bulk materials such as grain, hay or wood chips without combustible or fossil fuels. The relative humidity of the drying air of 65 % was maintained constant day and night at the exception when the relative humidity of the air is below 65 %. In order to avoid economic losses due to the over-drying of the product, a collector surface of 5 m^2 per m^2 ventilated area was sufficient. The holding container of the desiccant grain may be constructed similar to conventional mixed-flow dryers and alternatively be operated in continuous flow. As the product was placed in deep bed layers, the mathematical modelling can be studied as a porous media [5, 14, 15, 31, 43, 46, 55]) with 4 differential equations, which permit following variations of the temperature and humidity of both the heated air and the dried product.

Use of Water as Liquid Storage Material

Water is the most useful material that can be used for heat storage due to its availability, cost, and thermo-physical characteristics.

A solar kiln for drying boards of pine wood with energy storage by sensible heat, using water as storage material, is developed and studied by Luna et al. [38]. The system is composed of four main parts: the drying chamber, an air solar collector, a water solar collector, and the storage unit. The energy storage unit was made of two components—the exchange-storage unit and the heating unit—as it is illustrated in Fig. 12 and Table 6. It uses water as the storage

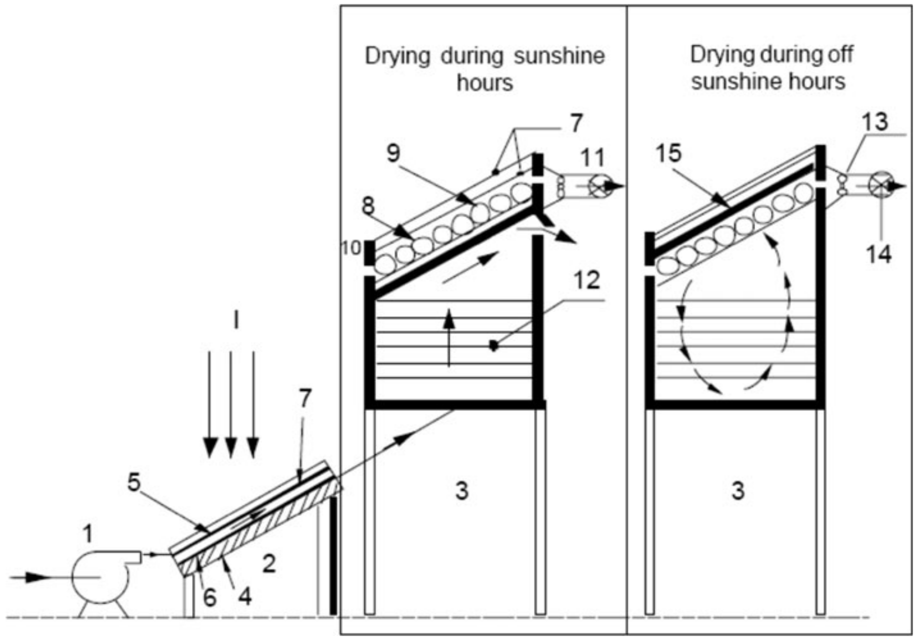


Fig. 11 Schematic view of a desiccant integrated solar dryer ([48]): *1* blower, *2* flat plate collector, *3* drying chamber, *4* insulation, *5* absorber plate, *6*bottom plate, *7* transparent cover, *8* desiccant bed, *9* plywood, *10* air inlet, *11* duct for air exit, *12* drying trays, *13* two-way fan, *14* valve, and *15* plywood

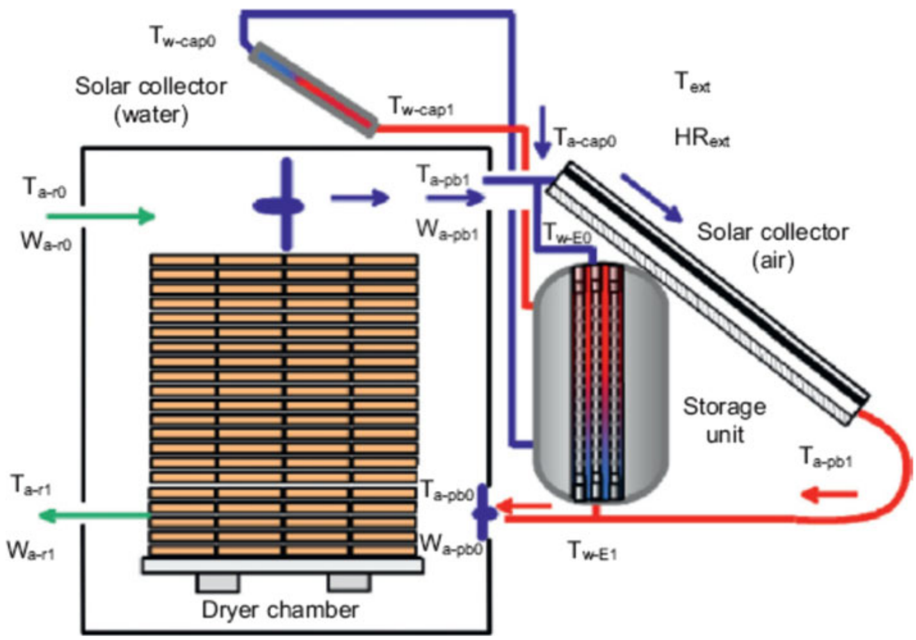
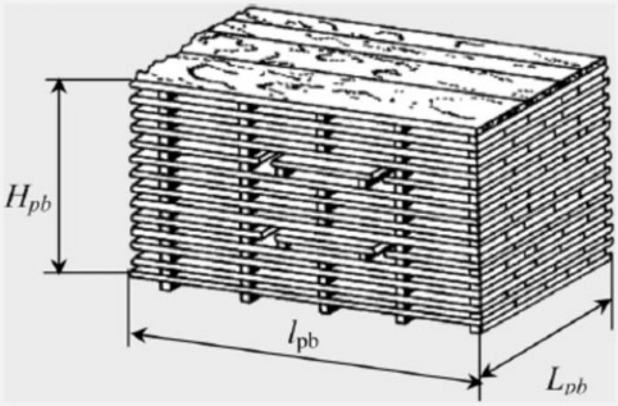
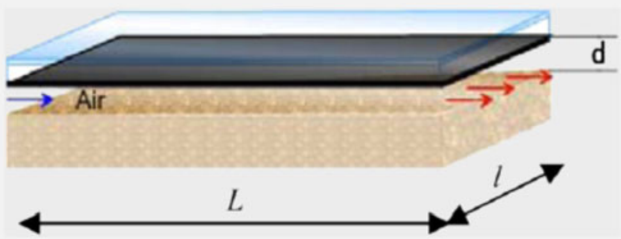
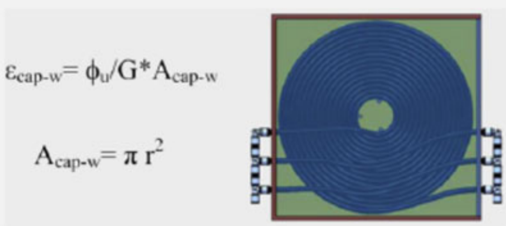
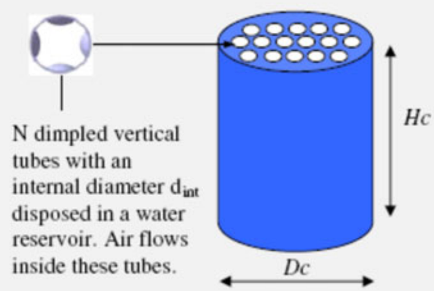


Fig. 12 Solar kiln dryer with energy storage [38]

fluid and air as the heat extraction fluid. It consists of a water reservoir that contains N vertical tubes where a part of the air (noted $T_{a\text{-cap0}}$ in Fig. 12) is heated. The storage unit is connected to a solar water collector defined by its area, and its 50 % global efficiency is used to heat water of the unit. On the other hand, there is a recycling system of the humidified used air. This air noted in Fig. 12 as $T_{a\text{-pb1}}$ is recovered and reheated by the solar air collector and then re-injected in the down part of the drying chamber. The solar air collector heats also another part of the air noted $T_{a\text{-cap0}}$. A comparison between two results, one with using storage and the other without, has given an idea on the importance of the used storage system. As a result, using storage system gives a gain in drying time of 50 h during the month of April, this gain increases to 62 h during August and 65 h during December, which gives around 30 % as an average save in drying time.

Heat and mass balance applied for wood product and heated air lead to four differential equations. Mass conservation of wood is expressed as the mass leaved is directly proportional to the gradient of product humidity. The humidity that leaves the product is totally recovered by the air representing the mass conservation for air. For the energy conservation of both the wood product and the air,

Table 6 Design variables associated with each operational unit [38]

Unit	Figure	DeV	OpV	Cr
Dryer unit		L_{pb}, l_{pb}, H_{pb}	τ_r, τ_m	
Solar air collector		L, l	τ_m	Drying quality, Q, Drying time, tS
Solar water collector		A_{Capw}, ε_{Capw}		
Storage unit		H_c, D_c, N, d_{int}, e_t		

they are similar to porous media [5, 14, 15, 31, 43, 46, 55]. However, the storage unit is represented by the following equation:

$$-M_w Cp_w \frac{dT_w}{dt} + m_a Cp_a [T_{a-E_1} - T_{a-E_0}] = 0 \quad (11)$$

Amer et al. [2] present a design and performances of hybrid solar dryer for banana shown in Fig. 13. The solar dryer is composed basically of solar collector, drying chamber heat exchanger, and heat storage. The design and parameters of the different parts are presented in Table 7. The solar collector contains a 4-mm-thick glass used for covering the absorber that is fixed 200 mm below the glass. The absorber plate is 2-mm-thick corrugated sheet painted in black. Received solar radiations are increased using three solar reflectors made of aluminium (1.8 m × 1.8 m × 2 mm thick). The collector had variable angles according to the sun direction. The metal reflectors were closed in unfavourable conditions to prevent heat loss through the glass during drying process. The solar drying unit was insulated by 50-mm-thick polystyrene. The entrance of the air is controlled and can be adjusted manually. The drying chamber has the same surface as the solar collector and it is located 200 mm under the absorber plate. It allows the usage of 16 trays. The heated air passes across the fruits placed in the trays made of wooden frame and plastic net. The drying air was heated in the solar collector and passes through a curved metal to the drying chamber. The direction of the air could be changed inside the solar drying unit. To increase the efficiency of the solar drying unit, some parts of the hot air were mixed with the fresh air at the end of the solar dryer and flew through the collector again to the solar drying unit. The heat exchanger is consisted of a 15-mm-diameter copper tube placed inside the solar collector, 100 mm below the glass and 100 mm above the absorber plate. It is constituted of 70 tubes covered the whole area of the drying collector. Two ends of the copper tubes were connected to the water storage tank that had a capacity of 500 l. Water was circulated from water tank through the tubes by the help of a water pump of capacity 20 $l.h^{-1}$. The heat exchanger gave a part of the collected heat during sunshine hours to the water inside the copper tubes. This water is stored in the tank insulated by 50-mm fibreglass. The heat stored during the day in the water tank was used in the night. However, the temperature of this water could be raised by using 6-kW water heaters located inside the tank to attain the desired temperature in the night or in unfavourable drying conditions. The solar dryer was able to decrease the moisture content from around 3 $kg.kg^{-1}$ (dry basis) to around 0.2 $kg.kg^{-1}$ (dry basis) of 30–32 kg of banana slices in around 8 h in favourable conditions and in 26 h in bad climatic conditions. The comparison between the different drying combinations was effectuated, and it was found that solar drying without water heating has shown best efficiency with a value of 37.4 %. Heating water before beginning drying process gave an efficiency of 31.7 %. It decreases to 25.3 % at the use of the auxiliary heating source.

The authors were interested by the calculus of the efficiency of the solar dryer and have used the following equations:

Collector efficiency when radiation was available:

$$\eta = \frac{\dot{m}_a Cp_a [T_i - T_o]}{A_c I_g} \tag{12}$$

Collector efficiency during night-time:

$$\eta = \frac{\dot{m}_a Cp_a (T_i - T_o)}{\dot{m}_W Cp_W (T_W - T_i)} \tag{13}$$

Solar dryer efficiency in daytime:

$$\eta_{dd} = \frac{m_W L_C}{A_c I_t t + Q_f + Q_p} \tag{14}$$

Solar dryer efficiency in night-time with hot water flow and without using water heater:

$$\eta_{nd} = \frac{m_W L_C}{Q_f + Q_p} \tag{15}$$

Solar dryer efficiency in night-time with hot water flow and with using water heater:

$$\eta_{nd} = \frac{m_W L_C}{Q_h + Q_f + Q_p} \tag{16}$$

Puiggali and Penot [44] built a solar dryer functioning with natural convection constituted of a drying chamber, a simple solar air collector, a chimney, and a storage system using water as storage material. The solar collector is not directly connected to the drying chamber but via the storage unit, where we can find containers with full water. This unit contains also tubes where the air flows during the day hours. Along these lines, the functioning mode of the solar dryer is as follows: during sunshine hours, the solar collector is used to heat inlet ambient air. This air passes through the tubes in the storage unit and goes to the drying chamber. After the flow in the course of the trays, the air goes out by means of the chimney. It is important to note that also, during this period, water is heated using solar energy. In the off-sunshine hours, the function of the solar collector is eliminated and the air enters by the bottom side of the drying chamber and passes through the water containers, where energy is recovered to the ambient air then heated air flows through the drying chamber and the chimney. The objective of this work was essentially finding the appropriate height of the chimney by calculating its efficiency. Also, it was found that this type of dryers is not appropriate to food product dotted with skins such as grapes and plums. But it was useful for other products like apples, mushrooms, peaches, and apricots. The results have shown that coupling the solar collector to the chimney conducts to increase the efficiency of the collector from around 24–44 %. The total efficiency of the solar dryer was around 45 %. As well, 50 % of the stored energy is directly lost to the ambient environment during the night. Nevertheless, 21 % of the stored energy in the day is recovered during the night with only 4 % used for drying.

Latent Heat Storage

Studies dealing with latent heat storage were focused on the system development and the understanding of the heat exchanger and thermal storage material behaviour [1, 24, 37, 49] Other studies were directed to the investigation of heat transfer characteristics of phase change materials in latent heat storage during melting and solidification [26–29, 36]. However, we cannot find much studies dealing with the application of the latent heat storage to solar

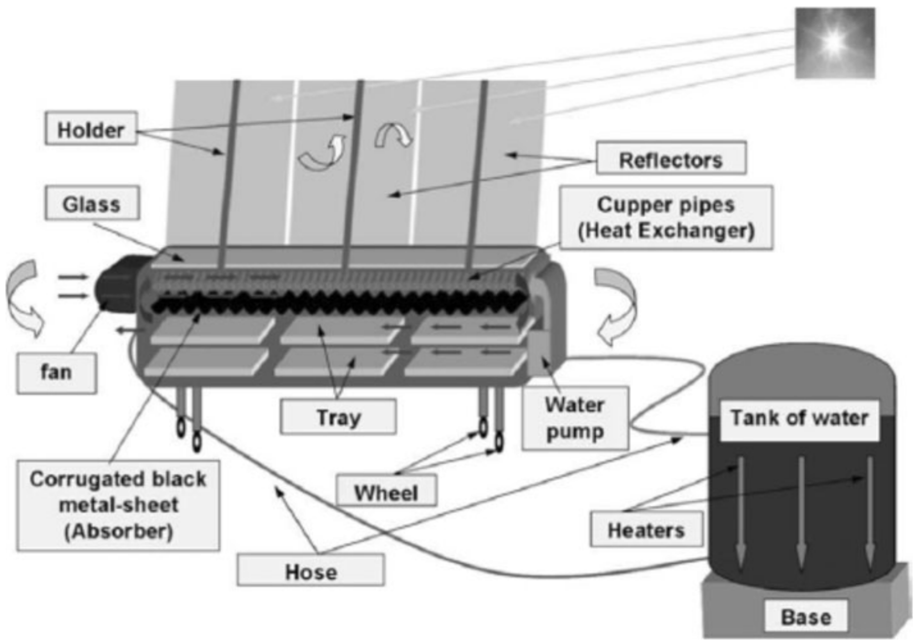


Fig. 13 Hybrid solar dryer with water used as material storage [2]

drying process. Devahastin and Pitaksuriyarat [20] explored the use of latent heat storage using paraffin wax as a phase change material, to store surplus of solar energy during drying and release it during unfavourable conditions. The proposed set-up is schematised in Fig. 14a. The set-up consists of an air compressor, a temperature controller, a heater, and a latent heat storage vessel. The latent heat storage consists of vessel itself, which is a cylindrical acrylic vessel with a diameter of 0.1 m and a height of 0.2 m. A tube through which flows the fluid is a copper tube and is attached with 18 copper fins. There is a space of 0.02 m between the cover and the vessel body in order to allow the air to be released from the vessel during the volume expansion of the phase change material during the change of its phase from solid to liquid. The temperature profiles of phase change material were determined in 16 positions, as shown in Fig. 14b, during the charge and discharge periods. The vessel was not insulated to permit visualisation of the melting freezing processes. The latent heat storage was attached to the drying chamber, fabricated with galvanised steel, and insulated with fibreglass, to study the effect of its use to conserve energy during drying and also on the drying kinetics of sweet potato food. The results have shown that using latent heat storage has permitted an energy saving varying from 40 to 34 % comparing with an ordinary drying process.

Bal et al. [9] have reported that recent study treating the development of solar dryer with latent heat storage and using paraffin wax as a phase change material, which stores during the day the excess of energy, was carried out by Bal et al. [7]. The work implies the possibility of reducing the amount of supplementary energy required in the drying process. The products were dried at the moderate temperature of 40–75 °C. Good thermal insulation and the low cost of half split bamboo permitted its used in the solar dryer. The desired outlet temperature has been achieved for drying of food.

Economic Analysis Aspect of Some Developed Solar Dryers

In general way, the studies dealing with solar drying are oriented to the calculus of their total performances represented by the efficiency and few of them treated the economical aspect by studying the cost of the dryer or the payback period. Boughali et al. [17], Rathore and Panwar [47] effectuated a payback analysis of their, respectively, indirect solar–electrical dryer and greenhouse dryer. The payback period was given as a function of the initial investment and the annual net undiscounted benefits.

$$\text{Payback period} = \frac{\text{Initial investment}}{\text{Annual net undiscounted benefits}} \quad (17)$$

They have found that, for their solar dryer, a period of, respectively, 1.27 year and 79 working days was necessary to get the payback. However, it was depending on several parameters such as the cost of the electrical consumption, the cost of the product, the climatic conditions, and the geographical situation where the dryer is tested.

Singh [51] affirms that the net present value (NPV) is the most important criteria in cost-economics analysis. It represents, as reported by the author, as an absolute index

Table 7 Design parameters of the hybrid solar dryer with storage unit [2]

Component	Specifications
1. Solar collector	
a. Type	Flat plate
b. Area	5.04 m^2
c. Transparent surface	Glass, 4 mm thick
d. Absorber plate	Corrugate sheet t-metal (280 × 180 cm), 2 mm thick
f. Collector tilt	0 (horizontal)
g. Reflectors	Brilliant aluminium (280 × 180 cm), 2 mm thickness
h. Insulation	Polystyrene 50 mm thick
2. Water tank	
a. Size	5001
b. Insulation	Made of fibreglass, 50 mm thick
3. Water pump capacity	20 l/h
4. Counter heat exchanger	
a. Type of tube	Copper (70 tubes)
b. Dimensions	180 cm length and 15 mm thick
5. Drying chamber	
a. Area	5.04 m^2
b. Height	20 cm
c. Insulation	Polystyrene 50 mm thick
d. Tray	16 try made of aluminium meshed, (90 × 70 cm)
6. Blower	
a. Type	Axial
b. Capacity	0.75 kw
7. Auxiliary heater capacity	6 kw

for the net contribution of a programme to economy. It is the sum of the net benefit in every year by the end of the programme in terms of the present value. The programmes with net benefits greater than zero are the feasible programmes. The index is given under the following form:

$$NPV = \sum_{n=0}^{N} \frac{(B_n - C_n)}{(1+r)^n} - I_c \quad (18)$$

where I_C represents the initial cost, B_n is the revenue received in the nth year during the project period, C_n is the expenditure cost in the nth year during the project period, r is the discount rate.

Mumba [41, 42] has given deeper information about an economical study of a solar dryer equipped with a solar collector and photovoltaic cells. The study has given information about the dryer life cycle cost given as a linear function of the difference between the total annual demand for delivered solar energy and the annual useful solar

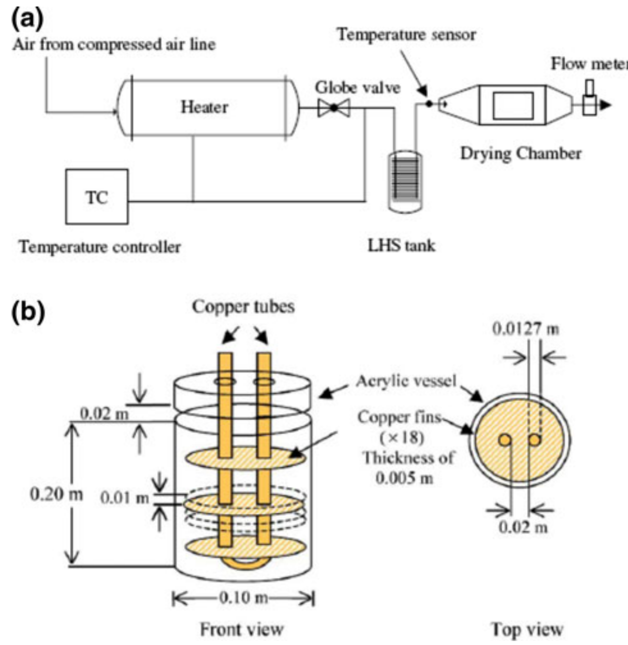


Fig. 14 **a** Diagram of the experiment set-up with attached drying chamber [20]. **b** Sketch of the latent heat storage vessel [20]

energy. It was found that the payback period of the solar dryer was depending on the surface of the photovoltaic cells used in the solar collector. The optimum parameters obtained were a payback period less than one year for 20 % of the collector surface covered with photovoltaic cells.

Sreekumar [52] and Sreekumar et al. [53] have developed a solar dryer dotted with a total collector surface of 46 m^2. It was able to dry in this solar dryer 200 kg of fresh pineapple to moisture content under 10 % within only 8 h. The techno-economic analysis developed by the authors was based on the study of the annualised cost method, the life cycle savings, and the payback period.

The annualised cost method was calculated using the following equation:

$$C_a = C_{ac} + C_m - V_a + C_{rf} + C_{re} \quad (19)$$

where C_a is the annualised capital cost, V_a the annualised salvage value, C_m the annualised maintenance cost calculated as fixed percentage of the annualised capital cost. C_{re} represents the annual running cost for fan use. C_{rf} is calculated at the use of an electrical dryer, and it is the annual running fuel cost.

C_{ac}, V_a, C_{rf}, and C_{re} are, respectively, written:

$$C_{ac} = C_{cc} \frac{d(1+d)^n}{(1+d)^n - 1} \quad (20)$$

$$V_a = V \frac{d}{(1+d)^n - 1} \quad (21)$$

$$C_{rf} = M_y \left[\left(\frac{m}{100} \right) \frac{LC_e}{e3600} \right] \quad (22)$$

$$C_{re} = R \times W \times C_e \quad (23)$$

C_{cc} is the capital cost of the dryer, d the rate of interest on long-term investment, n the life of solar dryer given in year, V the salvage value. M_y represents the mass of product dried in the solar dryer par year, m the moisture content calculated in dry basis, L the latent heat of water. R, W, C_e, and η_e are, respectively, the annual running hours of blower and fans, rated power of electrical blower and fans, cost per kW h of electrical energy, and efficiency of the electric dryer. Two ways were presented by the authors for the calculus of the life cycle savings, savings par day, and present worth of annual savings. The first parameter was written under the following form:

$$S_d = \frac{S_b}{D_b} \quad (24)$$

S_b is the saving par batch for the solar dryer and D_b is the number of drying days per batch.

And

$$S_b = M_d\left[C_b - \left(C_{dp} + C_s\right)\right] \quad (25)$$

M_d is the mass of dried product removed from the solar dryer per batch. C_b, C_{dp}, and C_s are, respectively, the selling price of branded dried product, the cost of the fresh product per kg, and the cost of the drying per kg of dried product in dryer.

The present worth of annual savings is written as:

$$P_j = S_d \times D \times (1+i)^{j-1} \times \frac{1}{(1+d)^j} \quad (26)$$

D is the number of days of use of the solar dryer per year and j represents the jth year.

Finally, the authors wrote the payback period under the following form:

$$N = \frac{ln\left(1 - \frac{C_{cc}}{S}(d-i)\right)}{ln\left(\frac{1+i}{1+d}\right)} \quad (27)$$

Sreekumar [52] and Sreekumar et al. [53] found that the payback period of their developed dryer is, respectively, 0.54 and 3.26 years with an assumed dryer life of 20 years. Hossain et al. [30] presented optimisation work of solar tunnel dryer for drying chilli. Three designs were tested; for the three cases, the collector surface was equal to the surface of the drying unit and was 26.6, 26, and 18 m^2. In their optimisation work, an economical model was presented. The annual cost C_a of drying was described as:

$$C_a = \frac{\left(C_T + \sum_i^N C_{rm} w^i\right)(w-1)}{w(w^i - 1)} \quad (28)$$

with C_T is the total cost of the solar dryer and is equal to the sum of the different dryer components such as the cost of the product to be dried, DC fans, PV cells, glass wool, polyethylene cover, rubber, drying tunnel, angle bar, rope, U-channel, paints, and fabrication charges.

C_{rm} is the repair and maintenance cost assumed to be 2.5 % of the capital cost.

w is the equal to [11]:

$$w = \frac{100 + \text{inflationrate}(\%)}{100 + \text{interst rate } (\%)} \quad (29)$$

and N is the project life expressed in years.

The authors indicated that the payback period was 3.99 years for the dryer dotted with 18 m^2 and 3.22 and 3.23 years for, respectively, the dryers with 26.6 and 26 m^2.

Puurohit and Kandpal [45] added in their economic analysis and during the valuation of benefits the effect of the CO_2 emission. Subsequently, the monetary worth of CO_2 emissions mitigation B_{cem} was expressed:

$$B_{cem} = \left(\text{GCE} - \frac{\text{CE}_{emb}}{t}\right)p_{cem} \quad (30)$$

GCE is the gross annual CO_2 emission and is given as function of the carbon emission factor of the used fuel, the fraction of carbon oxidised during the combustion of the fuel, and the annual amount of fuel saved by the solar dryer. CE_{emb} represents the amount of life cycle CO_2 embodied in the manufacturing, repair, and maintenance of the solar dryer, and P_{cem} id the cost of CO_2 emissions mitigation.

As it can be deduced, for the moment, there are no developed economical studies that give information about the influence of adding a storage system on the payback of a solar dryer, all the published works are limited to solar dryers with or without auxiliary source of energy but without using a storage system. However, the presented equations can be adapted to our situation by adding the effect of storage material on the total cost of the solar dryer and its effect on the final moisture content of the dried product.

Conclusion

For the majority of the studied cases, efficiency of solar dryer can be improved when thermal energy storage is added to the drying system. Besides several used storage materials, different designs of the solar dryers were proposed. Thermal energy storage uses two common ways but the most applied for solar drying is the thermal way with utilisation in particular of sensible heat against latent heat, which finds little application for the process. The most storage materials used in sensible heat are rocks, gravels, desiccants, and water.

Generally, the solar dryer is constituted of a solar collector, drying chamber, and a storage unit. At the use of solid storage material, this last can be added to the solar collector, to the drying chamber or both of them. However, the use of liquid storage material necessitates the utilisation of a separate tank full of water used as a storage unit. Several designs of the main parts of the solar dryers are anticipated. The proposed designs of the solar collector are a simple solar air collector constituted by glass cover, absorber, and insulation, and in some case reflectors are used to increase the received radiations. Double air pass by adding a second glass or multiple air pass by adding a second glass and storage unit are also projected. The drying chamber can hold multiple trays to support the product but also this last can be placed in thick layers. Packed beds of solid storage materials are generally added at the bottom of the drying chamber. But in some studied cases, solid storage material is added on the top of the drying chamber or both above and below the trays. Mixture of 60 % bentonite, 10 % calcium chloride, 20 % vermiculite, and 10 % cement or wheat is proposed as desiccant used to store thermal energy. However, due to its thermo-physical properties, paraffin wax is used as phase change material for the latent heat storage. In some studies, auxiliary sources of energy such as electrical energy and biomass backup heater were eventually used but without a real amelioration of the efficiency of the solar dryers.

Some of the designed solar dryers are not really useful, in particular those used for food drying, since they cannot be easily manipulated and cannot be moved to other places. In addition, efficiency of the dryers is not the unique criteria and the cost of these proposed solar dryers could be studied in order to calculate the feedback of the investment. These are some of the perspectives that should be explored and taken into account in order to develop practical and useful solar dryers.

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