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Thermodynamic analysis of forced convective solar drying of cocoa with black coated sensible thermal storage material

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ABSTRACT

Thermodynamic analysis of a forced convective solar dryer integrated with black coated sensible (firebrick) thermal storage material (STSM) for cocoa was investigated. The intermittent nature of solar radiation and its consequence on thermal processes such as drying necessitates the introduction of materials for heat supplement to keep the cocoa beans at a raised temperature above the ambient. As a steady flow thermodynamic system, the analysis was carried out based on the first and second laws of thermodynamics to account for the energy involved in the solar drying of cocoa beans. The maximum drying chamber utilization energy during the first and second daytime drying process was 0.739 and 0.724 kJ/kg. The energy utilization (EU) decreased with the increase in time from 12:00 to 18:00 h respectively. Also, the energy utilization ratio (EUR) ranged from 0.190 to 0.577, and 0.222 to 0.931 during the first and second daytime experiments respectively. The collector efficiency varied between 4.2 and 61.2% while the minimum and maximum solar radiation for the two daytimes were 49.6 and 759.6 W/m^2 with an average mass flow rate of 0.032 kg/s. The maximum energy efficiencies for the two-day times obtained at 10:00 h were 28.0 and 58.2%. In the drying chamber, the maximum exergy (inflow and loss) for the two-day time drying process was 7.53 and 8.33 kJ/kg, and 4.83 and 8.175 kJ/kg respectively. The exergetic efficiency during the first daytime experiment varied between 1.52 and 65.81%, while it varied between 1.82 and 53.30% during the second daytime. Thus, the results obtained in this study will inform the choice of an appropriate solar dryer design by the relevant stakeholders in the cocoa industry.

1. Introduction

One of the major causes of the sudden disappearance of food items (agricultural products) immediately after harvest is the lack of proper postharvest techniques. Elimination of food insecurity in developing countries such as Nigeria is achievable if adequate postharvest measures such as drying are adopted. At harvest, the moisture content of all agricultural products such as cocoa is usually above the recommended storage level. The reduction of moisture content is usually accomplished by drying. One of the postharvest

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Abbreviations

A	area, m^2
C	specific heat, kJ/kg/K
E	exergy, kJ/kg
EUR	energy utilization ratio
g	acceleration due to gravity m/s^2
h	enthalpy, kJ/kg
IMP	exergetic improvement potentials, kJ/kg
P	pressure, kPa
$\dot{Q}$	net heat, kJ/hr
S	specific entropy, kg/kJ/K
STSM	sensible thermal storage materials
T	Teperature, K
U	specific internal energy, kJ/kg
v	specific volume, m^3/kg
V	velocity, m/s
W	humidity ratio
w	specific humidity, g/g
$\dot{W}$	energy utilization, kJ/kg
Z	coordinate of altitude, m

Subscripts

ain	air inlet
aout	air outlet
CHE	chemical
Coll	collector
Dra	dry air
dra	drying air
En	energy
in	inlet
KHE	kinetics
mpr	moisture of the product
NRC	non reactive
out	outlet
PHE	physical
r	radiation
RC	reactive
Satv	saturated vapour, kJ/kg
sy	system

Greek letter

η	efficiency, %
∞	ambient
ρ	density, kg/m^3

processes that play major roles in the formation of cocoa products of high quality is drying. Drying is a complex thermodynamics process in which unsteady heat and mass transfer occur simultaneously. It is one of the most effective post-harvest treatments used worldwide to reduce spoilage thus, improve the shelf-life of agricultural products [1]. It is also, a basic unit operation in numerous industrial applications that utilizes a large quantity of energy, thus making it one of the most energy-intensive processes. The input of high energy in thermal drying is caused by the high latent heat of water evaporation and relatively low dryer energy [2]. The major concern of engineers in designing and optimizing industrial thermal drying systems is to utilise as little energy as possible to achieve optimum removal of moisture for the desired final product conditions [3]. One of the key techniques for sustainable development is the conception of an energy-intensive network with lower costs and greater performance [4].

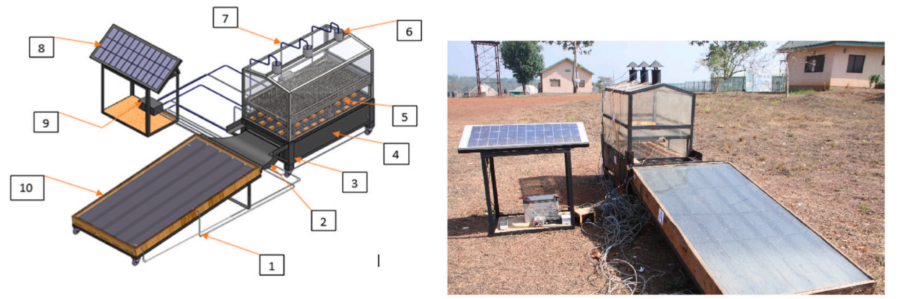
One of the drying industry's most critical problems is to reduce the energy costs to produce high-quality dried goods [5]. The importance of analysing the energy quantity and stream in contact with the material or by direct exposure to solar radiation (or both simultaneously) would have been a better alternative to open sun drying if not for its associated shortcomings such as climate dependence, quality of a drying procedure to give optimum energy efficiency and drying conditions [6]. According to Fudholi et al. [7], energy and exergy analyses need to be examined so that the energy interactions and thermodynamic activity of drying air within the drying chamber can be obtained [8]. The quantitative and qualitative analyses i.e (energy conservation) and (exergy consumption, exergy destruction, irreversibility, and lost work) during the drying process should, therefore, be examined based on thermodynamics first and second laws.

In the thermodynamic analysis of the first and second laws, the drying process is usually regarded as a steady flow process and the major condition for the analyses is the thermodynamic phenomenon of moist air [9]. Throughout the drying process, the air conditioning cycle involves heating, cooling, and humidification systems. The air conditioning cycle can be modelled as processes under steady flow using the principles of steady mass and energy conservation [3,9]. The conventional thermal system analysis methods are based on the first law of thermodynamics. These methods employ an energy balance on the system to assess the heat transfer between the system and its environment. Thermodynamics' first law presents the principle of energy conservation which states that energy entering a thermal system is stored and cannot be damaged by heat, electricity, moving streams of matter, etc. Thus, energy analysis is deficient in some areas. Energy balances in general usually do not include details on the standard or energy grades entering the boundaries of the thermal system boundaries and on the losses within [10]. Energy analysis also does not include details on the inability of any thermodynamic process to translate heat to mechanical work with optimal performance [11]. It neither provides knowledge on irreversibility aspects of thermodynamic processes nor distinguishes the various energy properties such as heat quality, which depends on the temperature of the source of heat [7].

Consequence upon the thermodynamics inadequacies of energy analysis, the introduction of exergy analysis seems to provide a more feasible instrument for quantifying energy operational efficiencies of the system and processes for optimum drying conditions. Exergy is the optimum quantity of work that is useful and achievable by a system communicating with an atmosphere at constant temperature and pressure [10]. This is a combination of a system's property with its surrounding. exergy is not liable to conservation law unlike energy, but, it is used or lost as a result of irreversibilities in real processes such as drying [6]. It should, therefore, be noted that exergy performance analysis not only identifies the extent, position, and triggers of system irreversibilities but often helps engineers to identify the efficiency of the system's components [12,13].

Traditionally, drying of cocoa in the open sun is common and considered cheap but requires a big space and longer duration. Not only that, the process is uncontrollable and susceptible to contamination from foreign materials as well as insects, bacterial, and fungal infestation. In term of energy saving cost, application of solar energy for the drying process, either by pre-heating the air stream in contact with the material or by direct exposure to solar radiation (or both simultaneously) is being adjudged as a better and promising alternative to open sun drying despite its associated shortcomings such as climate dependence, intermittency, and moisture reabsorption in the nighttime. The recent integration of solar drying systems with thermal storage materials toward eliminating the shortcomings of the solar dryer would not only increase the system's time of operation but further save the cost of energy. Three thermal storage materials have been presented in the form of sensible, latent heat, and thermochemical [14,15]. According to Komolafe et al. [14,15], several studies on the integration of solar drying system with thermal storage materials such as gravel, sand, bricks, phase change materials and desiccants for the drying of cocoa beans, cassava leaves, and chips, unshelled groundnut, and chilli, cocoa beans, pea, and pineapple have been reported. Considering the easy accessibility and cost of the three types of heat storage materials, the cocoa farmers who majorly reside in the local area would prefer the sensible heat storage material type [14]. Komolafe et al. [14] in their previous study, modelled the solar drying characteristics of cocoa using STSM (firebrick), however, analysis of energy utilised in the process was not accounted for. Thus, the need to investigate thermodynamic analysis (energy and exergy) of solar drying of cocoa using firebrick as thermal storage material.

Although, many researchers have reported thermodynamics analysis of the drying process of agricultural materials using various types of drying systems [3,6,7,10,16–29]. There are scanty studies on solar drying of cocoa with thermal storage materials [14,30–32]. However, the authors wish to state that no study on the thermodynamic analysis (energy and exergy) of solar drying systems integrated with firebrick thermal storage material for cocoa is available. Therefore, the major focus of this work was to investigate the thermodynamic analysis of forced convective solar drying of cocoa with a black coated sensible thermal storage material (firebrick).



1. One of the temperature cables 2. Connecting duct 3. Supporting frame 4. Plenum chamber 5. Drying chamber (comprising heat storage material platform, drying tray with stirrer) 6. Chimney 7. One of the relative humidity cables 8. Solar panel 9. Data acquisition system 10. Solar collector

Fig. 1. Schematic and pictorial view of the experimental set-up indicating all the major components.

2. Materials and methods

2.1. Cocoa beans sample preparation and the firebrick thermal storage material

2.1.1. Cocoa beans preparation

Samples of the ripe cocoa pod obtained from a Research Institute in Nigeria were prepared following the procedure of Komolafe et al. [14,33] and Hii et al. [34].

2.1.2. Preparation of firebrick thermal storage material

The soil sample used for moulding the STSM (firebrick) was collected from a termite mound in Omu Aran, Nigeria. Particle size analysis was also carried out before the moulding was done as presented recently by Komolafe et al. [14]. The firing operation of the bricks as reported by Komolafe et al. [14] was conducted based on the procedure of Karaman et al. [35].

2.2. The experimental set-up and drying procedure

Presented in Fig. 1 is the experimental set-up of the 10 kg capacity forced convective solar drying system for cocoa beans incorporated with STSM (firebrick). The drying experiment took place at Landmark University, Nigeria in November between 9:00 to 18:00 h as recently presented [14].

The drying process of cocoa with the developed dryer is a combination of convective heating of the hot air and the direct radiation through the Perspex glass cover. For the convective heating, after loading the clean cocoa beans into the tray inside the drying chamber, the thermal energy absorbed through solar radiation by the collector plate is transferred convectively to the working fluid (air) inside the copper chrome pipes underneath the black painted collector plate in the collector box. The solar PV-operated axial fan in front of the air duct sucks in hot air and forces it into the plenum chamber. Owing to the density difference, the hot air in the plenum chamber moves upward and is distributed through the perforated heat storage platform onto the beans inside the drying tray. The hot air picks up the moisture and moist air leaves the system through the exhausts/chimneys at the top of the dryer. The photovoltaic-controlled thermostat placed directly under the drying tray helps in the regulation of the drying air temperature. The thermostat and the fan were linked in such a way that once the recommended maximum drying air temperature for cocoa beans (60 °C) is reached within the drying chamber the thermostat trips off. That is, whenever the thermostat turns off, the fan stops automatically. Continuous moisture extraction by drying air leads to a decrease in the mass and moisture content of cocoa beans in the drying chamber. On a digital weighing balance (Control S.R.L Aosta 6. Cernusco, Italy), the mass of the sample was determined by removing the tray from the drying chamber at a 2-h interval. This occurs until a negligible product mass reduction is attained and it is presumed that equilibrium with the environment has been reached and the drying process is terminated.

Loading and unloading of the drying tray with or without beans are quite easy as this is simply done through a hinged door located on the Perspex glass cover.

In the nighttime (19:00 to 8:00 h of the next morning), the products were kept in the dryer without operating the fan, and the heat required to keep the beans at a higher temperature than the ambient was supplied by the firebrick (STSM). Also, to eliminate the influx of humid air, the air vents were closed during this period. This according to Fagunwa et al. (2009) will prevent moisture re-absorption that usually occurs during forced convective drying especially at night time when the relative humidity will be as high as 98%.

2.3. Thermodynamic analysis

2.3.1. Energy analysis

The obtained data from the forced convective thin layer drying process of cocoa were engaged in the analyses. This thermodynamic analysis was taken as a steady-state phenomenon that needs to be studied by introducing the concept of mass conservation and energy to a steady flow. The general equation of drying air mass, moisture, and conservation energy may be expressed as [3,9,27,36].

Mass conservation equation

$$\sum \dot{m}_{ain} = \sum \dot{m}_{aout} \tag{1}$$

where $\dot{m}_{ain}$ *and* $\dot{m}_{aout}$ is the inlet and outlet mass flows of drying air respectively.

Mass conservation of moisture

$$\sum \left(\dot{m}_{ain} + \dot{m}_{mpr} \right) \sum \dot{m}_{wout} \tag{2}$$

Or

$$\sum \left(\dot{m}_{ain\ win} + \dot{m}_{mpr} \right) = \sum \dot{m}_{ain\ wout} \tag{3}$$

$\dot{m}_{win}$ *and* $\dot{m}_{wout}$ represent specific humidity (g/g) at the inlet and outlet mass flows respectively; $\dot{m}_{mpr}$ is the moisture of the product mass flow; w_{ain} and w_{out} stand for the specific humidity inflow and outflow respectively.

Energy Conservation

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out}\left(\mathrm{hot} + \frac{\mathrm{V\ out}^2}{2}\right) - \sum \dot{m}_{in}\left(\mathrm{h_{in}} + \frac{V_{\ in^2}}{2}\right) \tag{4}$$

where $\dot{Q}$ represents the inflow of heat energy (kJ/hr), $\dot{W}$ is the rate of energy utilization (kJ/hr), h_{in} and h_{out} represent dryer enthalpy kJ/kg at the inlet and outlet temperature respectively, v_{in} and v_{out} are inlet and outlet velocities of air at respectively (m/s). Neglecting the mechanical work component in the dryer, equation (4) becomes

$$\dot{Q} = \sum m_{out}\dot{\mathrm{h}}_{\mathrm{out}} - \sum \dot{m}_{in}\left(\mathrm{h_{in}} + \frac{V_{\mathrm{in}^2}}{2}\right) \tag{5}$$

Since there is no motion in the tray drying process, the momentum elements $\frac{V_{out}{}^2}{2}$ and $\frac{V_{in}{}^2}{2}$, is eliminated. Thus, equation (5) becomes

$$\dot{Q} = \sum m_{out\mathrm{h_{out}}} - \dot{\sum} \mathrm{m_{in_{h_{in}}}} \tag{6}$$

The drying air mass flow rate is expressed as:

$$\dot{m}_{dra} = \rho_{Dra} V_{dra} \tag{7}$$

where ρ_{Dra} represents dry air density (kg/m^3), V_{dra} represents drying air volumetric flow rate (m^3/s).

The drying air enthalpies (h_{out} and $h_{in)}$ at the inlet and outlet temperatures were obtained by applying equation (8)

$$\mathrm{h} = C_{Dra}T_{dra} + Wh_{satv} \tag{8}$$

where C_{Dra} is the dry air specific heat (kJ/kg), T_{dra} is the drying air temperature (^{o}C), W is the drying air humidity ratio (kgH_2O/kgDra) and Dra is dry air, h_{satv} is the saturated vapour enthalpy of the kJ/kg.

The dry specific heat of air was calculated using Eqn. (9) as follows

$$C_{Dra} = 1.0029 + 5.4 \times 10^{-5} T_{dra} \tag{9}$$

Utilization energy (EU) was obtained using the thermodynamics first law as:

$$\mathrm{EU} = \dot{m}_{dra}(\mathrm{h_{ain}} - \mathrm{h_{aout}}) \tag{10}$$

where h_{ain} and h_{aout} represent the air enthalpy (kJ/kg) at the dryer inlet and outlet temperature respectively.

The ratio of energy utilization (EUR) was expressed given as follows using equation (11):

$$\mathrm{EUR} = \frac{\dot{m}_{dra}(h_{ain} - h_{aout})}{\dot{m}_{dra}(h_{ain} - h_{am\infty})} \tag{11}$$

where $h_{am\infty}$ is the enthalpy ambient dry air (kJ/kg) and $\dot{m}_{dra}$ is the drying air mass flow rate of (kg/s).

Energy efficiency (η_{En}) was measured as the energy ratio consumed to the energy supplied using the following term:

$$\eta_{En} = \frac{En_{in} - En_{out}}{En_{in}} = \frac{\dot{m}_{dra}(h_{ain} - h_{aot})}{\dot{m}_{dra}h_{ain}} \tag{12}$$

Collector efficiency.

According to the first law, the collector efficiency ($\eta_{coll.}$) can be expressed as follows:

$$\eta_{coll.} = \frac{\dot{m}_{dra}C_{Dra}(T_{aout} - T_{ain})}{A_{coll.}S_r} \tag{13}$$

where $\dot{m}_{dra}$ is the mass flow rate (kg/s), C_{Dra} is the specific heat capacity of air at constant pressure (J/kg K), T_{ain} and T_{aout} is the temperature (^{o}C) at inlet and outlet respectively, S_r is the radiation on the collector from the sun, $A_{coll.}$ represents the collector area (m^2).

2.3.2. Exergy analysis

In the second law analysis, the exergy inflow total, outflow, and losses of the forced convective solar dryer were estimated because part of the exergy entering a thermal system is destroyed as a result of irreversibilities within the system [6]. The basic exergy analysis procedure of the drying chamber determines at steady-state points the exergy values and causes of exergy variation for the process [3, 9].

Exergy equation application in general form for steady flow system is given as [28,29]:

$$E_{sy} = E^{PHE} + E^{CHE} + E^{KHE} + E^{PTE} \tag{14}$$

where E_{sy} is the system exergy totoal; E^{PHE} is the physical exergy as a result of the change of system chemical constituents from those of the environment; E^{CHE} is the Chemical exergy as a result of the deviation of the system chemical composition from that of the environment; E^{KHE} is the kinetic exergy resulting from determined device speed relative to the environment, and E^{PTE} is the potential exergy due to measured system height with the atmosphere [37].

Expanding equation (14) we have [3]:

$$E_{sy} = (U_{in} - U_{\infty}) - T_{\infty}(S_{in} - S_{\infty}) + P_{\infty}(V_{in} - V_{\infty}) + \frac{V^2}{2} + (Z_{in} - Z_{\infty})g + E^{RC} + E^{NRC} \tag{15}$$

where $U_{in} - U_{\infty}$ is given as a component of internal energy (kJ/kg), T_{∞} is the temperature at ambient (°C), $S_{in} - S_{\infty}$ represents the component of entropy (kJ/kg), P_{∞} $(V_{in} - V_{\infty})$ gives the component of work (kJ/kg), $\frac{V^2}{2}$ is the component of momentum (kJ/kg) and $(Z_{in} - Z_{\infty})g$ is the gravitational component (kJ/kg), subscript ∞ represents the conditions of reference of thermodynamic surrounding, and E^{RC} and E^{NRC} denotes the respective reactive and non-reactive exergy.

Few terminologies in equation (14) are used in the exergetic analyses of several other systems, but not all are included. Since exergy is the accessible energy from any source, it can be produced using the flow of electric current, magnetic fields, and material diffusion flow. One simple generalisation is to replace enthalpy with the internal energy and work components applicable to steady-flow systems. In situations, where the force of gravity and momentum terms are not considered, Eqn. (15) is commonly utilised. Also, changes in pressure within the system are not considered because $V_1 = V_{\infty}$. Hence eqn. (15) is simplify generally as [3,9,10,27,36]:

$$E_{sy} = \dot{m}\, C(T - T_{\infty}) - T_{\infty} \ln\frac{T}{T_{\infty}} \tag{16}$$

The inflow and outflow of exergy, as well as the exergy loss, can be determined respectively using the application of Eqn. (16):

Exergy Inflow:

$$\mathrm{E_{in}} = \dot{m}_{dra} C_{Dra}(T_{in} - T_{\infty}) - T_{\infty} \ln\frac{T_{in}}{T_{\infty}} \tag{17}$$

Exergy outflow:

$$\mathrm{E_{out}}\ \dot{m}_{dra}\ C_{Dra}\ (T_{out} - T_{\infty}) - T_{\infty} \ln\frac{T_{out}}{T_{\infty}} \tag{18}$$

Losses of exergy during the drying operation:

$$\sum E_{loss} = \mathrm{E_{in}} - \mathrm{E_{out}} \tag{19}$$

2.3.3. Exergy efficiency

The ratio of the outflow exergy to inflow exergy is known as exergetic efficiency. (η_E) [9],which is written in general form as [28]:

$$\eta_E = \frac{E_{in} - E_{loss}}{E_{in}} \tag{20}$$

$$= 1 - \frac{E_{loss}}{E_{in}} \tag{21}$$

2.3.4. Computation

Experimental data and drying air properties like density, enthalpy, humidity ratio, specific heat, etc. were used in the computation of the thermodynamic analysis of the solar drying system using an Excel 2016 package.

3. Results and discussion

Fig. 2 shows the variation of temperatures and solar radiation with time during four full drying experiments with black coated STSM. It is obvious that the temperatures rose with a rise in solar radiation towards midday until 13:00 h, and also showed a similar pattern with each other. The 10 kg capacity solar drying system (forced convection type) as reported by Komolafe et al. [14] took 50 h to reduce the moisture content of the fermented cocoa beans from 0.60 to 0.059 g/g w.b. respectively.

It is glaring also that at 18:00 h, the drying chamber temperature was 4.2 and 4.5C higher than that of ambient. However, apart from the drying chamber temperature curve, all other temperature curves converged at 18:00 h. Although, the drying chamber curve later joined others and begin to have approximately the same value during the night (18:00 a.m.–8:00 a.m. the next morning), although the solar radiation was 0 W/m^2 starting at 20:00 a.m. until 8:00 a.m. the next day. It was observed that temperatures ranged from 34 to 89.3 °C during sunshine hours at various dryer locations and were greater than the maximum ambient temperatures (31.8 °C). Also, the drying chamber temperature was higher than that of ambient throughout the experiment. The maximum drying chamber temperature for the two days was 53.5 and 54.0 °C respectively. The minimum and peak of solar radiation during drying time were 12.9 and 759.6 W/m^2 at 19:00 and 13:00 h, while the solar radiation between 19:00 and 8:00 h of the drying period ranged between 0 and 28.1 W/m^2 respectively. However, the minimum drying chamber temperature and solar radiation for the daytime 1 and two

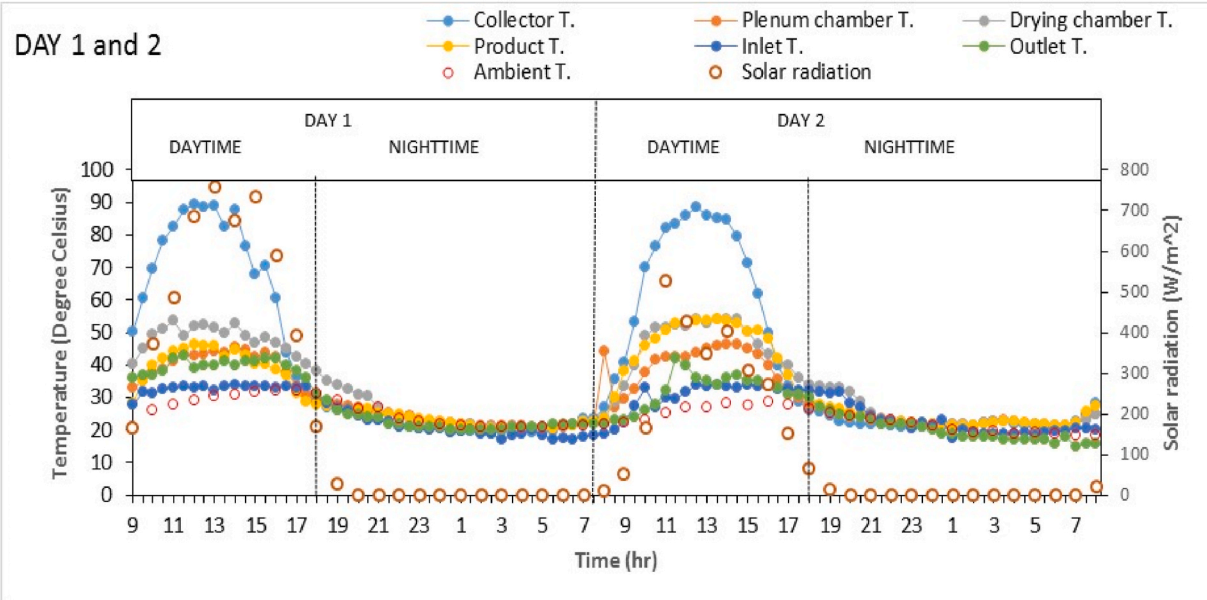


Fig. 2. Temperature and solar radiation versus time with STSM.

were 35.5 and 35 °C, and 169.1 and 64.7 W/m^2. In general, as the drying process progresses, the temperature increased until solar radiation reached its peak and decreased when the solar radiation started decreasing.

Fig. 3 explains the variation of various temperatures and relative humidities with time under full load condition with black coated STSM. From the figure, it can be seen that during day time (9:00–13:00 h), temperatures were increased with time increase while there was a decrease in humidity with time. In the night time, it was the other way round, there was an increase in humidities with time as temperatures decrease with time. Also, it was observed that the profiles for ambient and exit relative humidities sometimes at night were almost the same. The minimum and maximum relative humidities of the drying process were 34.0 and 98.0% at 13:00 and 18:00 h respectively. As expected, an increase in temperature caused a decrease in relative humidity and vice versa.

Fig. 4 exhibits the variation of energy utilization (EU) with time for a 2-day time of solar dryer's load process. It is observed that

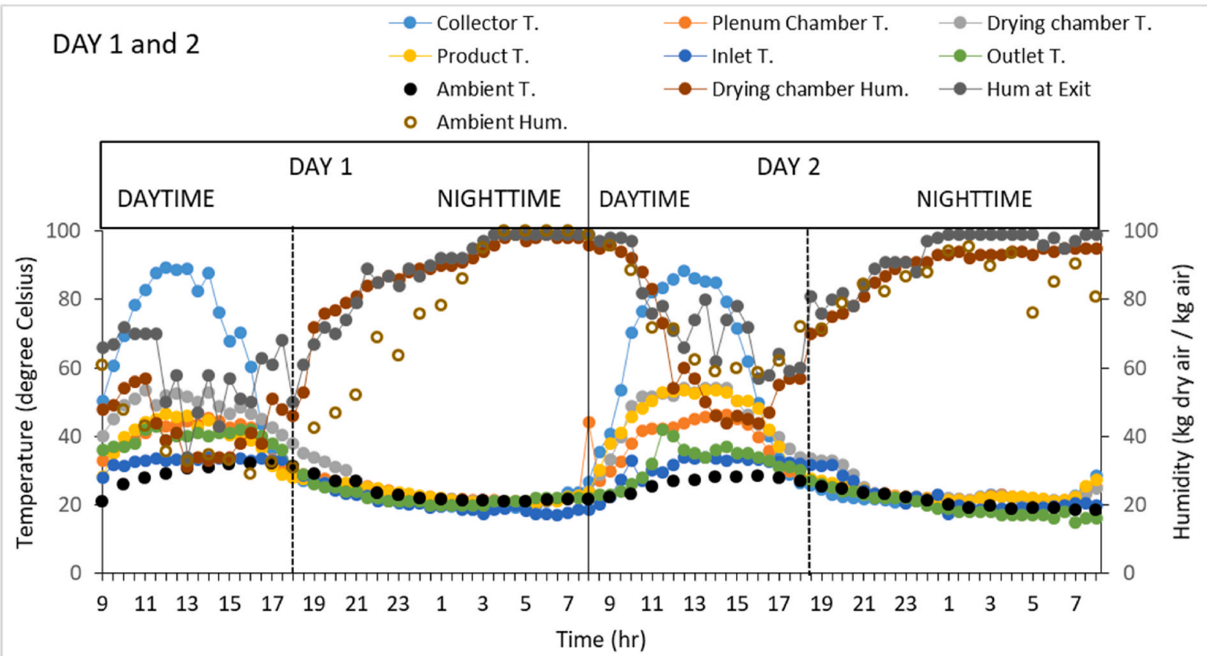


Fig. 3. Temperature and humidity versus time under full-load with STSM.

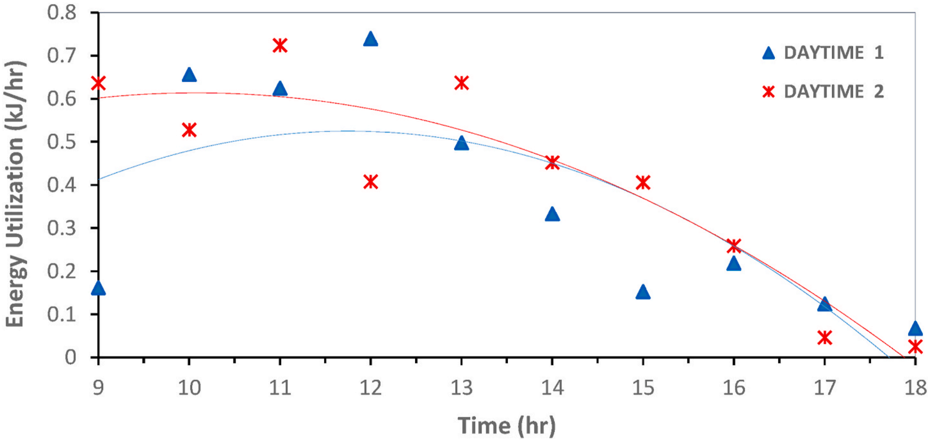


Fig. 4. Variation of energy utilization with time.

energy utilization in the drying chamber during the day time 1 drying process ranged from 0.162 to 0.739 kJ/h between 9.00 and 12.00, while during the day time 2, it ranged from 0.637 to 0.724 kJ/h between 9:00 and 11:00 h depending on the intensity of the solar radiation. However, energy utilization for the first and second day time decreased with the increase in time from 12:00 to 18:00 respectively. A similar trend was reported by Refs. [28,29] for the solar drying of pistachio. The mass flow rate during the drying period ranged between 0.014 and 0.056 kg/s. The energy utilization values were similar to each other for the two daytimes drying processes. This is in line with the report of [3].

Fig. 5 shows solar radiation and collector efficiency relationship with time during two day time solar drying experiments. It can be seen that the collector efficiency varied between 4.2 and 61.2% while the minimum and maximum solar radiation were 49.6 and 759.6 W/m^2 at an average mass flow rate of 0.030 kg/s. The maximum solar radiation during daytime 1 and 2 were 759.6 and 526.8 W/m^2 at 13:00 and 11:00 h respectively. However, in both cases, it is evident that there was an increase in collector efficiency at low solar radiation. This assertion is incongruent with reports on the solar drying of seaweed, red chili, and cocoa respectively [7,38,39] (see Fig. 6).

Fig. 6 depicts the variance of energy efficiency with the function of time. From the Figure, it can be seen that during the first

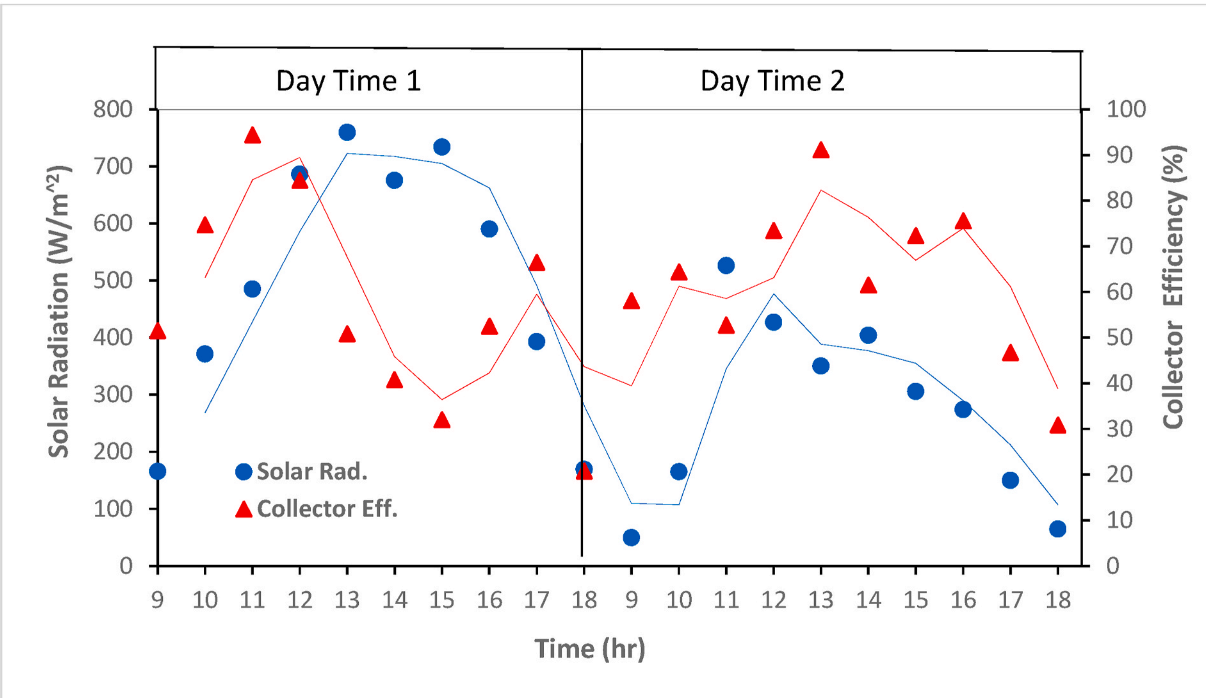


Fig. 5. Variation of solar radiation and collector efficiency with time.

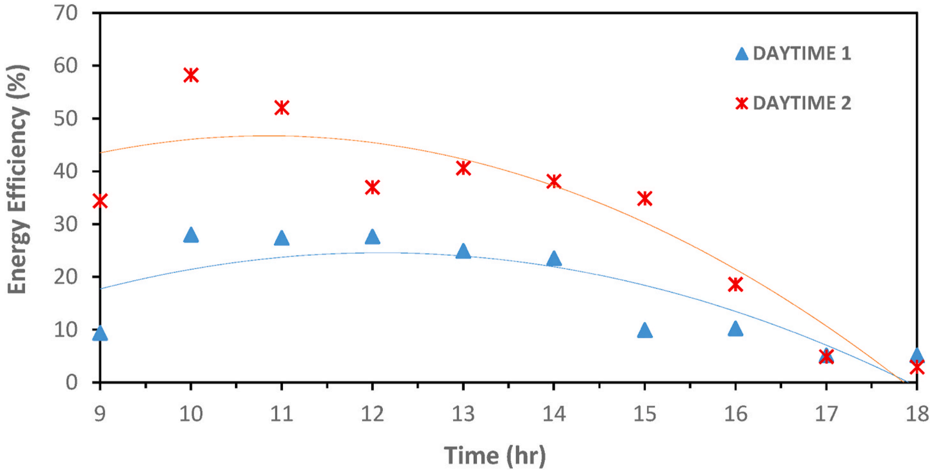


Fig. 6. Energy efficiency as a function time.

daytime, the energy efficiency values varied between 2.92 and 28.0%, while during the second day, it varied between 2.92 and 58.2% respectively. These energy efficiencies are higher than the range of 1.25–3.89% reported for the solar drying of Moroccan horehound leaves [40]. The maximum energy efficiencies for the two day times (28.0 and 58.2%) were obtained at 10:00 h. In general, the energy efficiency for the second day time was higher than that of the first.

To know when and where the maximum and minimum values of the exergy losses occurred during the drying process, it is important to show the time dependence of the exergy [28]. Fig. 7 shows the dependence of exergy on drying time during two-day time drying operations. During the first-day time experiment, the maximum exergy inflow in the drying chamber was 7.53 kJ/kg at 11:00 after which a decaying characteristic was noticed. During the second-day time operation, the time variation of the exergy showed similar behaviour to that of the first day time. During the first 2 h (From 9:00–11:00 h), a rising pattern was found, accompanied by a decaying behaviour. In this work, the maximum inflow of exergy value was 8.33 kJ/kg. In other words, the curves followed the same pace for the two-day time experiments. The two curves showed an increasing pattern from the first 2 h (11:00hr) after which a decaying pattern was noticed. A similar observation was reported for solar drying of OMW [3]. The increase and decrease behaviour of exergy inflow could be a result of variations in solar radiation. However, the minimum and maximum exergy losses depicted in the Figure were 0.048 and 4.83 kJ/kg; and 0.157 and 8.175 kJ/kg respectively for the first and second-day time experiments.

The curve representing the change in the exergy efficiency with drying time for two-day time operation is shown in Fig. 8. The maximum exergy efficiencies of the drying chamber for daytime 1 and 2 were 65.8 and 53.3% respectively. These values fall within the range of 48.11–72.98% reported for solar drying of sardine waste under natural and forced convection [41]. In the first 1 h, a decreasing pattern was observed, then changed to an increasing behaviour at 12 noon and 11 h for the daytime 1 and 2 and later a decreasing and increasing pattern following a parabolic function toward 18:00 h. A similar trend was observed and reported by Ref. [28] for the solar drying of pistachio.

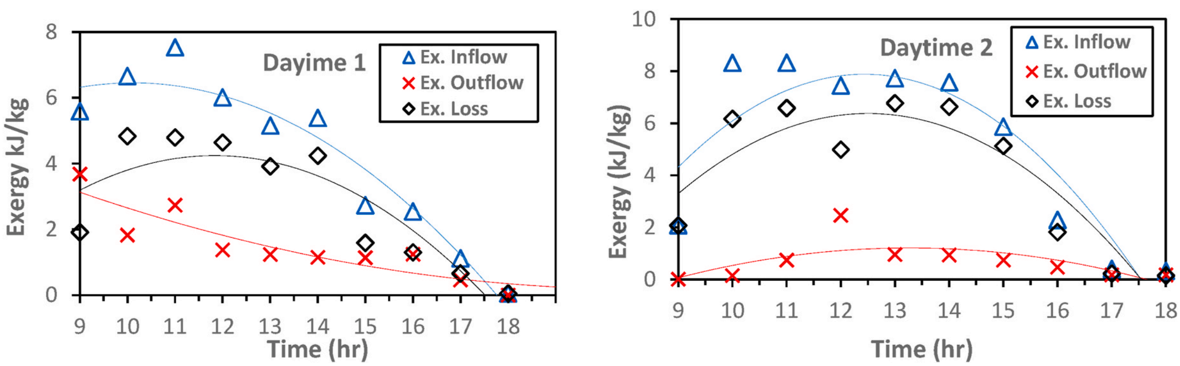


Fig. 7. Variation of exergy with time.

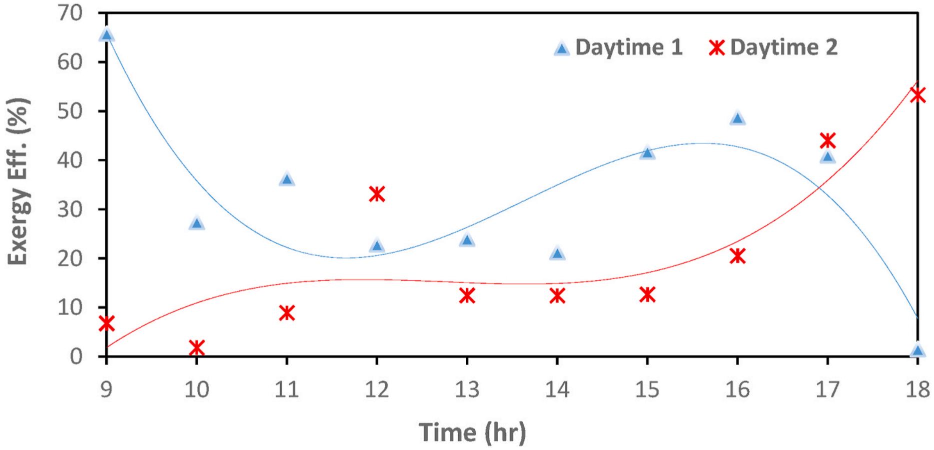


Fig. 8. Variation of exergy efficiency with time.

4. Conclusions

Thermodynamic analysis of forced convective solar drying of cocoa integrated with black coated sensible thermal storage material (firebrick) has been investigated to account for the amount of energy involved in the drying process of cocoa. The locally-made STSM (firebrick) from the termite mound served as backup to increase the dryer's operation period. From the results obtained in this study, the following conclusions were drawn.

1. Drying temperature values for cocoa beans were in the range of 30–54 °C for the corresponding solar radiation values range of 0 and 759.6 W/m^2 at 20:00 and 13:00 h respectively. Generally, the temperature increased with an increase in solar radiation. Also, an increase in temperature caused a decrease in relative humidity and vice versa
2. Energy utilization of the drying chamber during the first daytime drying process ranged from 0.162 to 0.739 kJ/h between 9:00 and 12:00 h, while during the second daytime, it ranged from 0.637 to 0.724 kJ/h between 9:00 and 11:00 h depending on the intensity of the solar radiation. Energy utilization for the first and second daytime decreased with the increase in time from 12:00 to 18:00 h respectively with a mass flow rate range of 0.014–0.056 kg/s.
3. The collector efficiency ranged from 4.2 to 61.2% while the minimum and maximum solar radiations were 49.6 and 759.6 W/m^2 at an average mass flow rate of 0.032 kg/s. The maximum solar radiation during daytime 1 and 2 were 759.6 and 526.8 W/m^2 at 13:00 and 11:00 h respectively.
4. The maximum drying chamber exergy inflow and loss for the two-day time drying process were 7.53 and 8.33 kJ/kg, and 4.83 and 8.175 kJ/kg respectively. The curves showed an increasing pattern for the first 2 h (11:00 h) after which a decaying pattern was noticed.
5. The maximum energy efficiencies for the two day times (28.0 and 58.2%) were obtained at 10:00 h. Generally, the energy efficiency for the second daytime was higher than that of the first daytime.
6. During the first daytime experiment, the exergy efficiency varied between 1.52 and 65.81%, while it varied between 1.82 and 53.30% during the second daytime experiment. However, it was noticed that the exergy efficiency of the daytime 1 experiment was higher than that of daytime 2.
7. The energy loss ranged from 0.124 to 0.739 kJ/kg, and 0.259–0.724 kJ/kg as their corresponding energy utilization increased from 0.661 to 4.642, and 0.259–7.589 kJ/kg. In both cases, there was a linear increase in exergy loss with energy utilization in the drying chamber.

Analysis of this convective solar drying system has shown that solar energy is a reliable and effective renewable source for drying cocoa beans of high quality.

Author's statement

Thanks for your valuable comments. We have checked through and all the comments/suggestions have been attended to appropriately.

Declaration of competing interest

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

References

[1] C.A. Komolafe, M.A. Waheed, T.S. Olabamiji, Experimental determination of modulus of elasticity of oven-dried cocoa-beans varieties, Int. J. Mech. Eng. Technol. 9 (11) (2018) 732–740.
[2] S. Syahrul, F. Hamdullahpur, I. Dincer, Exergy analysis of fluidized bed drying of moist particles, Exergy An Int. J. 2 (2) (2002) 87–98, https://doi.org/10.1016/S1164-0235(01)00044-9.
[3] A. Celma, F. Cuadros, Energy and exergy analyses of OMW solar drying process, Renew. Energy 34 (3) (2009) 660–666, https://doi.org/10.1016/j.renene.2008.05.019.
[4] M. Aghbashlo, H. Mobli, S. Rafiee, A. Madadlou, A review on exergy analysis of drying processes and systems, Renew. Sustain. Energy Rev. 22 (2013) 1–22, https://doi.org/10.1016/j.rser.2013.01.015.
[5] I. Dincer, Moisture transfer analysis during drying of slab woods, Heat Mass Tran. 34 (4) (1998) 317–320, https://doi.org/10.1007/s002310050265.
[6] N.A. Aviara, I.N. Onuoha, O.E. Faslola, J.C. Igbeka, Energy and exergy analyses of native cassava starch drying in a tray dryer, Energy 73 (2014) 809–817, https://doi.org/10.1016/j.energy.2014.06.087.
[7] A. Fudholi, K. Sopian, M.Y. Othman, M.H. Ruslan, Energy and exergy analyses of solar drying system of red seaweed, Energy Build. 68 (2014) 121–129, https://doi.org/10.1016/j.enbuild.2013.07.072.
[8] E.K. Akpinar, A. Midilli, Y. Bicer, The first and second law analyses of thermodynamic of pumpkin drying process, J. Food Eng. 72 (4) (2006) 320–331, https://doi.org/10.1016/j.jfoodeng.2004.12.011.
[9] A. Akbulut, A. Durmuş, Energy and exergy analyses of thin layer drying of mulberry in a forced solar dryer, Energy 35 (4) (2010) 1754–1763, https://doi.org/10.1016/j.energy.2009.12.028.
[10] R. Prommas, P. Rattanadecho, D. Cholaseuk, Energy and exergy analyses in drying process of porous media using hot air, Int. Commun. Heat Mass Tran. 37 (4) (2010) 372–378, https://doi.org/10.1016/j.icheatmasstransfer.2009.12.006.
[11] I. Dincer, Y.A. Cengel, Energy, entropy and exergy concepts and their roles in thermal engineering, Entropy 3 (3) (2001) 116–149, https://doi.org/10.3390/e3030116.
[12] S. Kaushik, V.S. Reddy, S. Tyagi, Energy and exergy analyses of thermal power plants: a review, Renew. Sustain. Energy Rev. 15 (4) (2011) 1857–1872, https://doi.org/10.1016/j.rser.2010.12.007.
[13] V.S. Reddy, S. Kaushik, S. Tyagi, Exergetic analysis of solar concentrator aided natural gas fired combined cycle power plant, Renew. Energy 39 (1) (2012) 114–125, https://doi.org/10.1016/j.renene.2011.07.031.
[14] C.A. Komolafe, M.A. Waheed, S.I. Kuye, B.A. Adewumi, I.O. Iyiola, T.M.A. Olayanju, Sun drying of cocoa with firebrick thermal storage materials, Int. J. Energy Res. 44 (2020) 7015–7025, https://doi.org/10.1002/er.5364.
[15] C.A. Komolafe, J.O. Ojediran, F.O. Ajao, O.A. Dada, Y.T. Afolabi, I.O. Oluwaleye, A.S. Alake, Modelling of moisture diffusivity during solar drying of locust beans with thermal storage material under forced and natural convection mode, Case Studies in Thermal Engineering 15 (2019) 100542, https://doi.org/10.1016/j.csite.2019.100542.
[16] S.R. Park, A.K. Pandey, V.V. Tyagi, S.K. Tyagi, Energy and exergy analysis of typical renewable energy systems, Renew. Sustain. Energy Rev. 30 (2014) 105–123, https://doi.org/10.1016/j.rser.2013.09.011.
[17] J.A. Folayan, F. Osuolale, P. Anawe, Data on exergy and exergy analyses of drying process of onion in a batch dryer, Data in brief 21 (2018) 1784–1793, https://doi.org/10.1016/j.dib.2018.10.132.
[18] A. Lingayat, V. Chandramohan, V. Raju, Energy and exergy analysis on drying of banana using indirect type natural convection solar dryer, Heat Tran. Eng. 41 (6–7) (2020) 551–561, https://doi.org/10.1080/01457632.2018.1546804.
[19] B. Pattanayak, S.S. Mohapatra, H.C. Das, Energy and exergy analyses of paddy drying process in a vertical fluidised bed dryer, Int. J. Exergy 28 (2) (2019) 113–125, https://doi.org/10.1504/IJEX.2019.097975.
[20] M. María Castro, C. Román, M. Echegaray, G. Mazza, R. Rodriguez, Exergy analyses of onion drying by convection: influence of dryer parameters on performance, Entropy 20 (5) (2018) 310, https://doi.org/10.3390/e20050310.
[21] I. Hamdi, S. Kooli, Exergy and Energy Analysis of the Solar Drying Processes of Tomatoes in Tunisia in, 9th International Renewable Energy Congress (IREC), 2018, https://doi.org/10.1109/IREC.2018.8362493, 2018. IEEE.
[22] M. Azadbakht, A. Ziaratban, M.V. Torshizi, H. Aghili, Energy and exergy analyses during eggplant drying in a fluidized bed dryer, Agricultural Engineering International: CIGR Journal 19 (3) (2017) 177–182.
[23] Y. Abbaspour-Gilandeh, A. Jahanbakhshi, M. Kaveh, Prediction kinetic, energy and exergy of quince under hot air dryer using ANNs and ANFIS, Food Sci. Nutr. (2019), https://doi.org/10.1002/fsn3.1347.
[24] M.C. Ndukwu, M. Simo-Tagne, F.I. Abam, O.S. Onwuka, S. Prince, L. Bennamoun, Exergetic sustainability and economic analysis of hybrid solar-biomass dryer integrated with copper tubing as heat exchanger, Heliyon 6 (2) (2020), https://doi.org/10.1016/j.heliyon.2020.e03401 e03401.
[25] H. Darvishi, M. Zarein, Z. Farhudi, Energetic and exergetic performance analysis and modeling of drying kinetics of kiwi slices, J. Food Sci. Technol. 53 (5) (2016) 2317–2333, https://doi.org/10.1007/s13197-016-2199-7.
[26] D. Rabha, P. Muthukumar, C. Somayaji, Energy and exergy analyses of the solar drying processes of ghost chilli pepper and ginger, Renew. Energy 105 (2017) 764–773, https://doi.org/10.1016/j.renene.2017.01.007.
[27] A. Boulemtafes-Boukadoum, A. Benzaoui, Energy and exergy analysis of solar drying process of Mint, Energy Procedia 6 (2011) 583–591, https://doi.org/10.1016/j.egypro.2011.05.067.
[28] A. Midilli, H. Kucuk, Energy and exergy analyses of solar drying process of pistachio, Energy 28 (6) (2003) 539–556, https://doi.org/10.1016/S0360-5442(02)00158-5.
[29] E.K. Akpinar, C. Sarsilmaz, Energy and exergy analyses of drying of apricots in a rotary solar dryer, Int. J. Exergy 1 (4) (2004) 457–474, https://doi.org/10.1504/IJEX.2004.005790.
[30] F.S. Dina, H. Ambarita, F.H. Napitupulu, H. Kawai, Study on the effectiveness of continuous solar dryer integrated with desiccant thermal storage for drying cocoa beans, Case Studies in Thermal Engineering 5 (2015) 32–40, https://doi.org/10.1016/j.csite.2014.11.003.
[31] A.O. Fagunwa, A.O. Koya, M.O. Faborode, Development of an intermittent solar dryer for cocoa beans, Agricultural Engineering International: CIGR Journal (2009).
[32] C.A. Komolafe, M.A. Waheed, Design and fabrication f a forced convection solar dryer integrated with heat storage materials, Annale de Chimie-Science des Materiaux 42 (1) (2018) 215–223, https://doi.org/10.3166/ACSM.42.23-39.
[33] M.A. Waheed, C.A. Komolafe, Temperatures dependent drying kinetics of cocoa beans varieties in air-ventilated oven, Frontiers in Heat and Mass Transfer (FHMT) 12 (2018), https://doi.org/10.5098/hmt.12.8.
[34] C. Hii, M.B. Tukimon, Evaluation of Fermentation Techniques Practiced by the Cocoa Smallholders, The Planter, Malaysia, 2002.
[35] S. Karaman, S. Ersahin, H. Gunal, Firing Temperature and Firing Time Influence on Mechanical and Physical Properties of Clay Bricks, 2006.
[36] N. Panwar, S. Kaushik, S. Kothari, A review on energy and exergy analysis of solar drying systems, Renew. Sustain. Energy Rev. 16 (5) (2012) 2812–2819, https://doi.org/10.1016/j.egypro.2011.05.067.
[37] G. Tsatsaronis, Definitions and nomenclature in exergy analysis and exergoeconomics, Energy 32 (4) (2007) 249–253, https://doi.org/10.1016/j.energy.2006.07.002.
[38] A. Fudholi, K. Sopian, M.H. Yazdi, M. HafidzRuslan, M. Gabbasa, H.A. Kazem, Performance analysis of solar drying system for red chili, Sol. Energy 99 (2014) 47–54, https://doi.org/10.1016/j.solener.2013.10.019. Persistent link using digital object identifier.

[39] C.A. Komolafe, Development of Numerical and Experimental Cocoa-Beans Solar Dryer, Department of Mechanical Engineering, Federal University of Agriculture, Abeokuta, Nigeria, 2019. Ph.D. thesis.
[40] Y. Bahammou, Z. Tagnamas, A. Lamharrar, A. Idlimam, Thin-layer solar drying characteristics of Moroccan horehound leaves *(Marrubium vulgare L.)* under natural and forced convection solar drying, Sol. Energy 188 (2019) 958–969, https://doi.org/10.1016/j.solener.2019.07.003.
[41] Y. Bahammou, H. Lamsyehe, M. Kouhila, A. Lamharrar, A. Idlimam, N. Abdenouri, Valorization of co-product of sardine waste by physical treatment under natural and forced convection solar drying, Renew. Energy 142 (2019) 110–122, https://doi.org/10.1016/j.renene.2019.04.012.