Comparative experimental evaluation and thermodynamic analysis of the possibility of using degraded C_{15}-C_{50} crankcase oil waste as thermal storage materials in solar drying systems

NdukwuM. C[a*]; Augustine Edet Ben[a]; B. Lamrani[b]; Hongwei Wu[c]; L Bennamoun[d],F.I. Abam[e]

[a]Department of Agricultural and Bio-resources Engineering, Michael Okpara University of Agriculture, Umudike, P.M.B. 7267 Umuahia, Abia State, Nigeria.
[b] Mohammed V University in Rabat, Faculty of Sciences, MANAPSE Laboratory, Rabat, Morocco.
[c]School of Physics, Engineering and Computer science, University of Hertfordshire Hatfield, UK
[d]Department of Mechanical Engineering, University of New Brunswick, Federincon, Canada
[e]Energy, Exergy and Environment Research Group (EEERG), Department of Mechanical Engineering, Michael Okpara University of Agriculture, Umudike, P.M.B. 7267 Umuahia, Abia State, Nigeria
*Email:ndukwumcu@mouau.edu.ng, Phone: +2348032132924

Abstract
The study presents a comparative thermodynamic analysis of degraded C_{15}-C_{50} grade crankcase oil (DCO) and paraffin thermal storage (PTS) as heat storage materials in solar drying. The goal is to convert DCO from waste to a useful product in solar drying. The assessment was based on drying efficiency, energy and exergy analysis, sustainability assessment and CO_2 mitigation of each solar dryer. The difference in drying efficiency between the dryer with DCO and that with PTS is less than 1.5% while the difference between the specific energy consumption is less than 9%. In contrast, the difference between the dryer with DCO and that without thermal storage is 24.2%. The mean exergy efficiency ranged between 41.6 and 49.9%. The values of the waste exergy ratio (WER), sustainability index (SI) and improvement potential (IP) for the three dryers ranged from $0.00 \leq WER \leq 1.00$, $0.00 \leq SI \leq 34.56$, $0.00 \leq IP \leq 2.68$ kW. Using these dryers instead of diesel, grid-based electricity or coal-powered dryer will limit a maximum of 5792826 tons of CO_2 from the atmosphere.

Keywords: Thermal storage; heat exchanger; paraffin; ginger; solar dryer

Nomenclature the order of the nomenclature needs to be corrected, A, Cp, Deff, …

W	Total weight of ginger to be dried per batch(kg)
C_p	Specific heat (J/kg K)
m	mass (kg)
L_v	Latent heat of vaporization of water (J/kg)
I_T	Total solar radiation incident on the solar collector (W/m^2)
M_c	Moisture content (kg/kg)
M_{dr}	Drying rate (kg of water/kg of dry solid)
t	Total drying time (hr)
A	Collector Area (m^2)
D_{eff}	Effective diffusivity (m^2/s)
L	Thickness (m)
Q_u	Total energy utilized (J)
Q_r	Radiation energy (J)
Q_T	thermal energy released (J)
F_N	Heat removal factor (-)
U_o	Radiation heat loss
T	Temperature (°C)
ΔT	Change in temperature (°C)
f_i	Fraction of ginger dried,
$EFCO_2$	Carbon emission factor,
FCO_2	The equivalent fraction of CO_2 during the burning of the coal
Q_d	The quantity (kg) of ginger dried by the solar dryer
v_d,	The volume of diesel in the generator,
k_d	The heating value of diesel in the generator
Q_e	The specific energy consumption

Subscripts

a	air or ambient
i or 1 or n	initial or inlet
d or dr	drying
c or o	collector
2	final
W	water
m	material
dryer	solar dryer
da	drying air
∞	Reference state,
c	chemical

Greek letters

η	Efficiency (%)
β	The angle of tilt (°)
ṁ	Mass flow rate (kg/s)
τ	Transmittance (-)
η_d	The effectiveness of diesel-powered dryer.

1. Introduction

Solar drying has been used by crop processors for ages. Different design of solar dryers abounds in literature ranging from direct, indirect or mixed-mode design (Ndukwu et al., 2017a and 2017b, 2020a). The design concept of solar dryers offers flexibility to the developer in terms of choice of material and the size of the enterprise. The major challenge in the solar drying design concept is to make it adaptable to different kinds of the environment (Ndukwu et al, 2018). The concern is the dehumidification of inlet air in a highly humid environment to increase its moisture absorption capacity when it comes in contact with evaporated air from the dried product. Therefore, due to weather variations, the adoption of the solar drying system is limited to the periods when the condition is favourable. To overcome this, various researchers have adopted different design strategies to make solar dryers applicable in harsh weather conditions (Ndukwu et al., 2020b and 2020c). The use of thermal storage materials to conserve the heat during the sunshine hours and utilize them during the off-sunshine periods has been extensively studied (Reyes et al., 2018; Baniasadi et al.2017). Initially, stones and gravel has been used. For example, Madhlopa and Ngwalo (2007) utilized stones as thermal storage to design a simple solar dryer. It was tested using twelve batches of fresh pineapple by drying each batch weighing about 20 kg. Results obtained showed that the thermal mass could store part of the burner's absorbed solar energy and heat. Mohanraj and Chandrashekhar (2009) developed an indirectly forced convection drier with gravel as a heat storage material for chilli drying in India. The system is composed of a flat panel solar air heater with a heat storage function, a drying chamber and a radial fan. The dryer was able to dry chilli from the initial moisture content of 72.8% to the final moisture content of about 9.2% (w.b.) and 9.7% (w.b.) in the bottom and top trays. Aissa et al. (2012) have studied a forced convection flat plate solar air heater with granite stone storage material under the climatic conditions of Egypt-Aswan. The test was conducted on five hot summers in July 2008 with different air mass flow rates ranging from 0.016 kg/s to 0.08 kg/s.

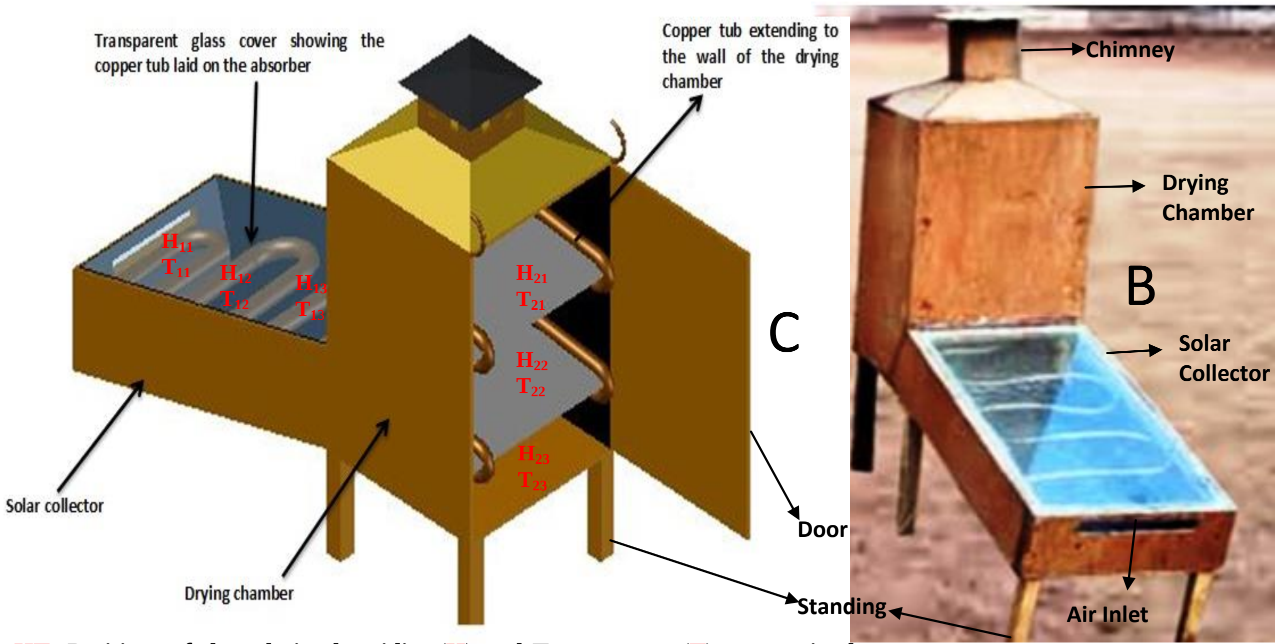
However, thermo-chemical materials such as paraffin, glycerine, desiccants and other eutectics phase change materials like hydrated salts etc., have gained attention as heat storage in solar dryer designs (Sharma et al., 2009 a; Kamble et al 2013, Ndukwu et al 2017a). The heat stored in the phase change material is 5 to14 times more in heat per unit volume than sensible heat materials like rocks or water (Agyenim et al 2010). Ndukwu et al. (2017b) evaluated a mixed-mode solar dryer with sodium sulphate decahydrate and sodium chloride as thermal storage in South Eastern Nigeria for storing red chilli. The dryer consisted mainly of a flat plate solar collector with a double transparent polyethene used as a collector cover. Their results showed that the integrated solar dryer and sodium sulphate, sodium chloride, and the control experiment reduced the water content of red pepper from 72.27% to 7.6, 10.1 and 10.3%, respectively. In contrast, the overall drying efficiency of the three treatments varied from 10.61 to 18.79%, respectively. Krishnananth and Murugavel (2013) created an integrated two-stage solar air heater with heat storage using paraffin wax integrated directly on the solar absorber plate to store the heat. The integrated solar system with heat storage generated relatively high temperatures. The efficiency of the solar air heater integrated with thermal energy storage was also higher than that of the air heater without thermal energy storage. Their study concluded that the presence of heat transfer media in the absorber plate is the best configuration.

Although several thermal storage materials have been used in different designs, researchers have continuously searched for cheap and efficient alternatives with improved designs for one environment to another. Materials like, C_{15} - C_{50} crankcase oil is discarded after completing their duty cycle. Degraded mineral-based crankcase oil is a complex mixture of low and high molecular weight aliphatic and aromatic hydrocarbons, lubrication additives, metals, and various organic and inorganic compounds. The specific heat capacity is in the range of 2.36 to 2.7 J/g ^oC (Santos et al., 2006), therefore, a potentially valuable source of heat storage in low-temperature solar system design. The method of direct disposal adopted by most automobiles mechanics often leads to environmental hazards and defacing the soil with its thick black colour. Therefore, the current work aims to explore its potential in low-temperature solar drying. The result will be compared with paraffin which is known to provide good thermal storage. The only close related research in this area was conducted using “hytherm oil” (Tyagi et al., 2012). However, the effectiveness of the design is very important. In the current study, the degraded oil will be prevented from getting in contact with the food material by infusing it in a tubular coil that runs from the collector to the drying chamber. Evaluation will be based on thermodynamic analyses with the concept of energy and exergy.

2. Material and method

2.1 Description of the developed solar dryers

In the present study, three solar dryers were designed and fabricated. Each solar dryer mainly comprises the collector, drying chamber, drying trays and copper pipe (0.0158 m diameter) carrying thermal storage. The collector has dimensions of 0.79 m in length, 0.18 m in width and 0.16 m in depth. The casing of the collector was made from plywood. The internal walls and base of the collector are made of a 0.002 m thick aluminium plate, which is painted black and serves as the absorber. The collector is placed perpendicular to the direction of wind flow and tilted with a slope of 15.47^o southward. A transparent glass (0.78 m x 0.16 m x 0.004 m) covers the collector at the top, allowing solar radiation into the solar collector. Two liquid thermal storage namely: paraffin (C_{16-18} carbon chain, melting temperature: 16 to 28 ^{o}C, specific heat capacity: 2.14 to 2.9 J/ g.K, thermal conductivity range: 213 to 244 W/m K) and degraded crankcase oil (C_{15} - C_{50} carbon chain range, specific heat capacity: 2.36 to 2.7 J/g. K) (Santos and Souza, 2006; Sharma et al., 2009b; Amir, 2019) were used. The copper coil which also doubles as a heat exchanger is laid horizontally with two coiled cycles on the base absorber plate of the collector and extends into the east and west walls of the drying chamber with two passes on both walls, as shown in Figure 1. The paraffin thermal storage (PTS) and degraded crankcase oil (DCO) were manually filled into the copper tubes using the funnel at the opening provided at the top of the drying chamber. The liquids flow by gravity, and to aid the flow, one leg of the collector was detached and replaced after filling the tube and removed under gravity by opening a stopper provided at one leg of the solar collector. As a result, each of the tubes received 2.18 litres of liquid DCO and paraffin, respectively. The copper tubes were sealed at both ends to prevent splashing out of liquid or coming in contact with the dried product in any way.



HT- Positions of the relative humidity (H) and Temperature (T) sensors in the collector (11 -13) and drying chamber (21 – 23)

Figure 1: (A) schematics of the solar dryer exposing the layout of the copper tubes (B) The picture of the indirect solar dryer showing the copper tubes through the collector cover

An inlet gap (0.03 m x 0.05 m) was provided in the southern part of the collector for the ambient air to flow into the collector by natural convention. The air is heated by solar radiation and thermal storage material as it flows into the drying chamber. The heat transfer to the drying chamber is by convection from the air and conduction from the copper tube carrying thermal storage as illustrated in Figure 2.

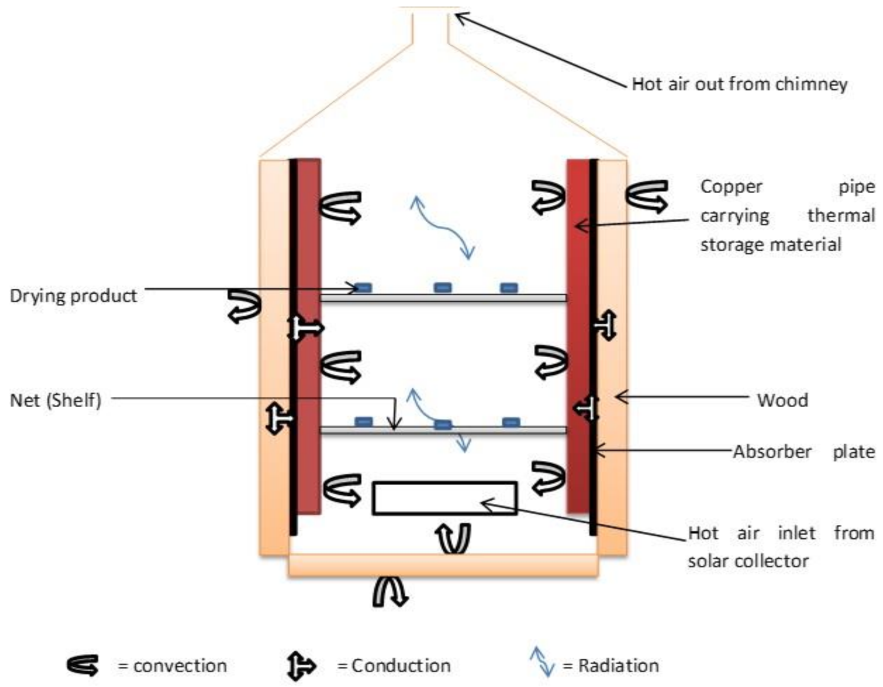


Figure 2: Schematic diagram showing the heat transfer into the drying chamber

The drying chamber (0.66 m x 0.43 m x 0.43 m) is made of plywood. The internal walls of the drying chamber are fitted with an aluminium plate and painted black. Two drying racks of 0.30 m x 0.35 m each are placed horizontally, with one 0.22 m above the other in the drying chamber. The trays are made of wooden frames and nets. Heated air enters the drying chamber from the end of the collector leading to the bottom part of the drying chamber. The hot air circulates vertically and leaves the drying chamber at a 0.08 m x 0.15 m chimney provided at the top. A 0.58 m x 0.34 m wooden door is hinged at the back, opening and closing the drying chamber. The three dryers used are designated as shown in Table 1. Dryer C serves as the control with no thermal storage material and no copper pipe.

Table 1: Solar dryer designs

Dryer	Collector dimension	Drying chamber dimension	Thermal storage
A	0.79 m x 0.18 m x 0.16 m	0.66 m x 0.43 m x 0.43 m	Paraffine
B	0.79 m x 0.18 m x 0.16 m	0.66 m x 0.43 m x 0.43 m	Degraded C_{15}-C_{50} crankcase oil
C	0.79 m x 0.18 m x 0.16 m	0.66 m x 0.43 m x 0.43 m	No thermal storage

2.2 Data collection

The experimental analysis was conducted at a location of 5.53 °N, 7.49 °E, South-Eastern Nigeria from 12th – 14th December 2020. The three solar dryers were set up at the same time to ensure uniformity with weather conditions. Ginger rhizomes were used in the performance evaluation of the dryers. The ginger was sliced into cuboid shapes of a length of 12 mm, breadth of 10 mm, and thickness of 5 mm. Each of the dryers received 200 g of ginger rhizome spread on the drying trays. Drying of the ginger continued until three consecutive weights is recorded. The air temperatures and humidity inside the collector were measured with a temperature and humidity clock (DTH-82; TLX, Guandong China, accuracy ±0.1) while the temperature of the product, drying chamber, and thermal storage material were measured using EXTECH Multi-thermometer attached to a digital thermometer probe (PDT650 made in China). The solar radiation intensity was measured with an APOGEE pyrometer (Model mp.200, serial number hash 1250 with accuracy of ± 0.1 W/m^2/ day). The weights of the ginger were measured with a weight scale (KERRO model, accuracy of ±0.01 g). The wind velocity was measured using a dual wind vane (AM-4826; Landesk, Guangzhou, China, with an accuracy of ± 2 % of velocity). All readings were recorded after every one-hour interval. Microsoft Excel 2019 software and design expert version 6.0.6 were used to analyse and plot the curves.

2.3 Uncertainty error Analysis

The statistic limit error (uncertainty error) of measurement of the relative humidity, temperature and solar radiation intensity was presented with the bias uncertainty error synthesis method as given by Baniasadi et al (2017). The standard deviation (σ) of the sets of the measured data (X) was used to evaluate the precision errors. Eqs. 1 and 2 give the statistical bias uncertainty error (B_u) and the standard deviation while Eq. 3 gives the overall uncertainty.

$$B_u = \frac{\sigma}{\sqrt{r}} \quad 1$$

$$\sigma = \sqrt{\frac{1}{(n-1)}\sum(Z_i - \bar{Z})^2} \quad 2$$

$$\frac{U_o}{S} = \sqrt{\left(\frac{B_u}{X}\right)^2 + \left(\frac{P_u}{X}\right)^2} \quad 3$$

where Pu is the total errors due to instrumentation and measurements given as 0.1 (Baniasadi et al (2017), r is the total number of parameters.

Table 2: Statistical limit error for measurement of temperature, humidity and solar radiations

Solar Dryer	Temperature				Relative Humidity			
	$\bar{Y}$	σ	B_u	$\frac{U_o}{S}$	$\bar{Y}$	σ	B_u	$\frac{U_o}{S}$
A	37.63	0.16	0.034	0.0028	42.82	0.35	0.075	0.0021
B	37.08	0.36	0.077	0.0034	43.2	0.15	0.032	0.0024
C	36.28	0.56	0.120	0.0043	45.17	0.30	0.064	0.0026
Ambient condition	34.33	0.32	0.068	0.0035	46.73	0.18	0.038	0.0023

Solar Radiation measurement				
Days of experiment	$\bar{Y}$	σ	B_u	$\frac{U_o}{S}$
Day 1	363.8	1.8	0.38	0.001
Day 2	361.4	3.2	0.068	0.002
Day 3	354.3	3.4	0.072	0.002

The obtained uncertainty for the measured parameters is presented in Table 2 which is less than 0.5 % for all measured parameters.

2.3 Dryer Performance evaluation parameters

2.3.1 Performance of solar dryer

The basic standard procedure for evaluating solar dryer performance was followed in the analysis. The drying system was evaluated using the solar collector efficiency, drying rate, percentage moisture loss, and drying efficiency. The quantity of moisture as a percentage of the initial mass of a material can be represented on the wet and dry basis and expressed as a percentage by Mohanraj et al. (2009) as follows:

$$M_C = \left[\frac{M_1 - M_2}{M_1}\right] \times 100 \quad (4)$$

The amount of water removed from food during drying is shown by Tonui et al., (2014).

$$M_{dr} = \frac{M_w}{t_d} \quad (5)$$

The efficiency of a solar collector is the ratio of heat gained by the air leaving the collector to the incident solar energy over a particular period. The steady-state thermal efficiency of the solar collector is given by Hottel-Whillier- Bliss equation (Forson et al., 2007a)

$$\eta_c = \frac{\dot{m}_a C_p (T_o - T_a)}{A_C I_T} \quad (6)$$

The products' thermal performance or drying rates are the critical factors used to evaluate the solar drying system efficiency (Forson et al., 2007b). For example, for natural convection solar dryers, the system efficiency can be expressed (Leon et al., 2002).

$$\eta_{dryer} = \frac{M_w L_v}{I_T A_c t_d} \quad (7)$$

2.3.2 Effective moisture diffusivity

The effective moisture diffusivity (D_{eff}) was estimated using the slope (k) of a straight line from the plotting of the moisture data as a natural log of moisture ratio (*Ln* MR) against drying time and taking the slope as follows.

$$k = \frac{\pi^2 D_{eff}}{4L^2} \quad (8)$$

2.4 Energy Analysis

The amount of energy utilized (Q_u) for the drying process consists, of the total radiation energy received and the thermal energy released by the heat exchanger.

$$Q_u = Q_r + Q_T \quad 9$$

Q_r is given by Duffie and Beckman [50] as follows:

$$Q_r = A_c F_N [I\tau - U_O(T_c - T_a)] \quad 10$$

The paraffin and the C_{15}-C_{50} used crankcase oil did not attain their phase change temperature of 16 - 28 °C and < -10 °C respectively, therefore are used purely as sensible heat storage material. The reason is that the ambient temperature during evaluation ranged from 29 to 42 °C, which is always below the collector and drying chamber temperature where the thermal storage is embedded. The heat released by the thermal storage will be determined as follows (Ndukwu et al., 2017a)

$$Q_T = M\left[\left\{\int_{T_o}^{T_m} C_p dT\right\}\right] = MC_p \Delta T \quad 11$$

2.5 Exergy Analysis

The summation of exergy flow of a body is defined by Sagastume et.al (2013) in Eq. 12 as follows

$$\sum e = \mathrm{e_{ch}} + e_{ph} + e_{ki} + e_{po} \quad 12$$

where e_{ch}, $\mathrm{e_{ph}}$, e_{ki} and e_{po} are chemical, physical, kinetic and potential exergies of the defined system, respectively. Expansion of Eq. 12 gives the Eq. 13 below

$$\mathrm{e} = (\mathrm{U} - \mathrm{U}_\infty) - \mathrm{T}_\infty(\mathrm{S} - \mathrm{S}_\infty) + \frac{\mathrm{P}_\infty}{\mathrm{J}}(\mathrm{v} - \mathrm{v}_\infty) + \frac{\mathrm{V}^2}{2\mathrm{gJ}} + (\mathrm{Z} - \mathrm{Z}_\infty)\frac{\mathrm{g}}{\mathrm{g_c J}} + \sum_{\mathrm{c}}(\mathrm{U_c} - \mathrm{U}_\infty)\,\mathrm{N_c} + \mathrm{E_n A_n F_n}(3\mathrm{T}^4 - \mathrm{T}_\infty^4 - 4\mathrm{T}_\infty \mathrm{T}^3) \quad 13$$

However, Ndukwu et.al (2020 c) gave the general exergy formula for exergy stream, assuming that the system is in a steady-state and the fluid is an ideal gas, as follows:

$$EX_R = I\tau\alpha_p A_c\left(1 - \frac{T_a}{T_s}\right) \quad 14$$

$$EX_a = \dot{m}_a\left\{C_{p,a}\left(T - T_0 - T_0 In\frac{T}{T_0}\right) + R_a T_0 \times \left[\left(1 + \frac{M_a}{M_v}H\right) In\frac{1 + \frac{M_a}{M_v}H_0}{1 + \frac{M_a}{M_v}H} + 1 + \frac{M_a}{M_v}HIn\frac{H}{H_0}\right]\right\} \quad 15$$

$$EX_w = m_w\left[\left(h_f(T) - h_f(T_0)\right) + v_f\left(P - P_g(T)\right) - T_0\left(S_f(T) - S_g(T_0)\right) + T_0 R_w In\left(\frac{P_g(T_0)}{P_0 X_v^0}\right)\right] \quad 16$$

Therefore, the exergy input (E_{xi}) is given as follows:

$$E_{xi} = EX_R + EX_{ai} + EX_{wi} \quad 17$$

The output exergy is presented in Eq. 18 as follows

$$E_{xo} = X_{wo} + E_{xao} \quad 18$$

Exergy loss during a drying process is obtained as follows:

$$\mathrm{Ex}_{loss} = \mathrm{Ex}_i - \mathrm{Ex}_o \quad 19$$

According to Akbulut and Durmus (2010), exergy efficiency can be defined as the ratio of exergy used in drying the product to the drying air supplied to the system. Given in Eq. 20 below

$$\eta_{xeff} = \frac{\mathrm{Ex}_o}{\mathrm{Ex}_i} = 1 - \frac{\mathrm{Ex}_{loss}}{\mathrm{Ex}_i} \quad 20$$

_2.6_ Exergy sustainability indicators

Ndukwu et al (2017a) and Caliskan et al (2011) used a set of exegetic sustainability indicators to evaluate the performance of solar drying systems. This index includes sustainability index (SI), waste exergy ratio (WER) and improvement potential (IP). While the waste exergy ratio compares losses in the system, the improvement potential is an indicator that suggests that when losses are minimized in the system the overall performance of the solar dryer can be improved. However, the sustainability index is a function of the exergy efficiency of the solar dryers. These values are presented in Eqs. 21-23 respectively as follows:

$$WER = \frac{Ex_{loss}}{E_{xin}} \quad 21$$

$$SI = \frac{1}{1 - \eta_{x_{eff}}} \quad 22$$

$$\dot{IP} = \left(1 - \eta_{x_{eff}}\right) Ex_{loss} \quad 23$$

2.7 CO_2 mitigation capacity of the solar dryers

The energy utilized by the solar air heaters was used to evaluate the environmental benefit of adopting the solar dryers presented. The comparison was based on mitigated greenhouse gas emissions if the presented solar dryer is used instead of diesel, coal or grid-based electricity-powered dryers. In the case of the diesel-powered dryer, Ndukwu et al. (2017a), gave the energy consumed by such diesel-powered dryer in kWh as Eq. 24 below:

$$W = v_d k_d \eta_d \quad 24$$

Assuming the dryer utilizes an equal amount of diesel to produce the same energy utilized to dry the ginger, Eq. 25 can be equated to Eq. 9 as follows

$$Q_u = v_d k_d \eta_d \quad 25$$

Ndukwu et al. (2017a) gave the mass of CO_2 produced from a litre of diesel as follows

$$m_C = v_d k_f \quad 26$$

where kf, k_d and η_d are given by Ould-Amrouche et al. (2010) as 2.63 kg/l, 10.08 kWh/l and, 30% respectively.

For grid-based electricity, the CO_2 mitigated is given in Eq. 27 as follows

$$M_{CO_2} = EF_{CO_2} x\, Q_e \qquad 28$$

$EFCO_2$ is given as 0.4392 kg of CO_2/kWh for Nigeria

Also, for coal-fired, Simo- Tagne et al (2019) and Kumar et al (2005) gave the mass of CO_2 mitigated using disaggregation of equivalent fossil fuel as follows:

$$M_{CO_2} = \sum_i f_i \left(\frac{f_{es} Q_d Q_u}{\eta_i}\right) EFCO_2 . FCO_2 \left(\frac{44}{12}\right) \qquad 29$$

$FCO_2 = 0.9$; $EFCO_2 = 0.0258$ kg/MJ; $f_i = 1$; $f_{es} = 1$ Ould − Amrouche et al. (2010) .

3.0 Results and discussion

3.1 Effect of thermal storage on collector and drying chamber performance.

Temperatures and relative humidity of the dryers were studied and compared as shown in Figures 3 and 4. During the experiment, the ambient temperature ranged between 29.1 ^oC and 40.2 ^oC with an average of 34.3 ^oC. In contrast, the ambient relative humidity ranged between 31% and 90%, with an average value of 46.7%. Data collection begins at the appearance of a very clear sky at about 9.00 am local time and continues at one-hour intervals until 5.00 pm each day. Minimum ambient temperatures and high relative humidity are observed early in the morning or late in the evening. At the same time, the highest ambient temperature and lowest relative humidity are observed at noontime. This is a function of solar radiation intensity seen in Figure 5, which shows maximum values during noontime and minimum values during the morning and evening. The ranges of solar radiation for the first, second and third day were; 616 W/ m^2 to 108 W/m^2, 635 W/m^2 to 188 W/m^2 and 525w/m^2 to 103 W/m^2 respectively, with an average value of 357.5 W/ m^2. There was a significant difference in the solar radiation intensity between the 3 days under consideration from the ranges obtained.

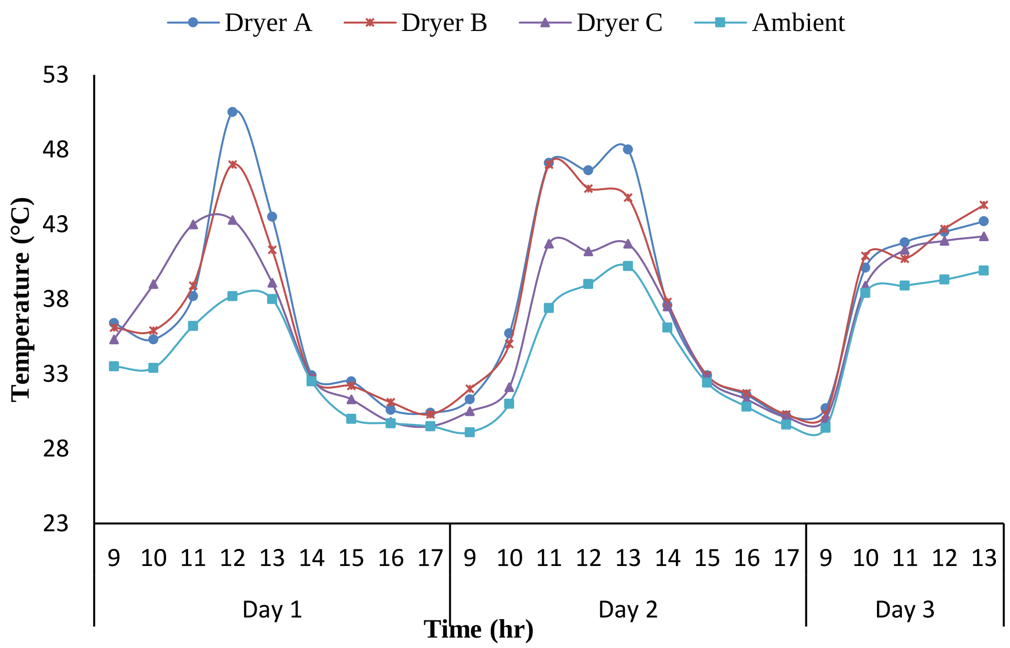


Figure 3: Average collector temperature

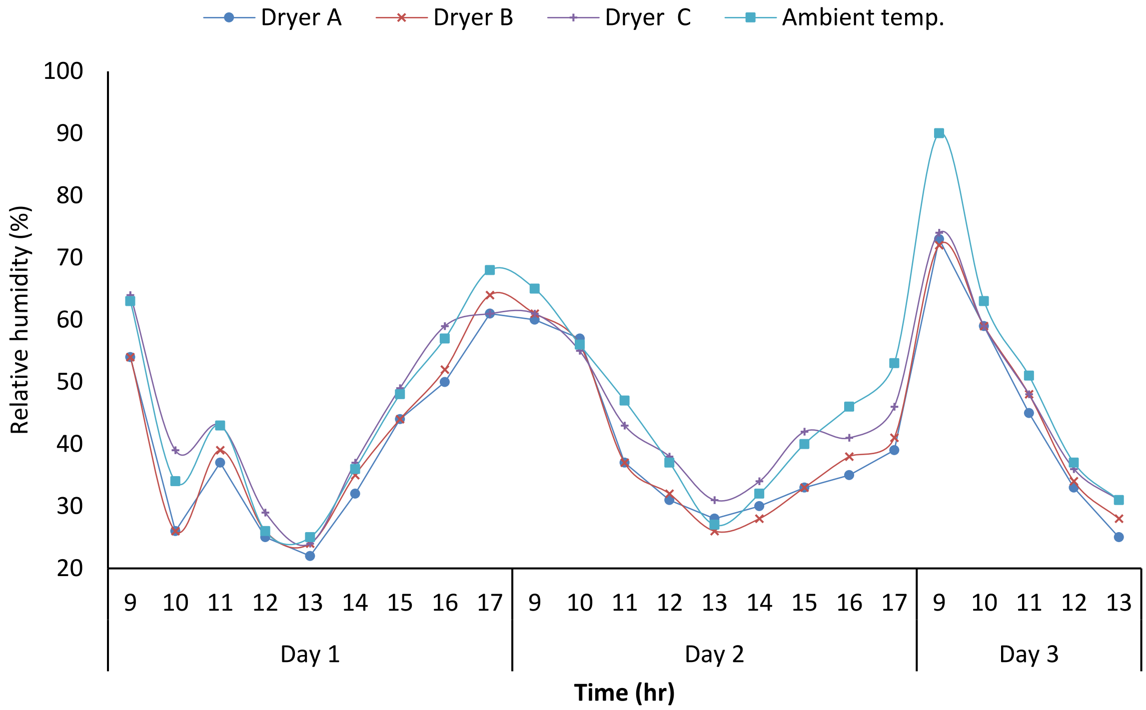


Figure 4: Average collector relative humidity

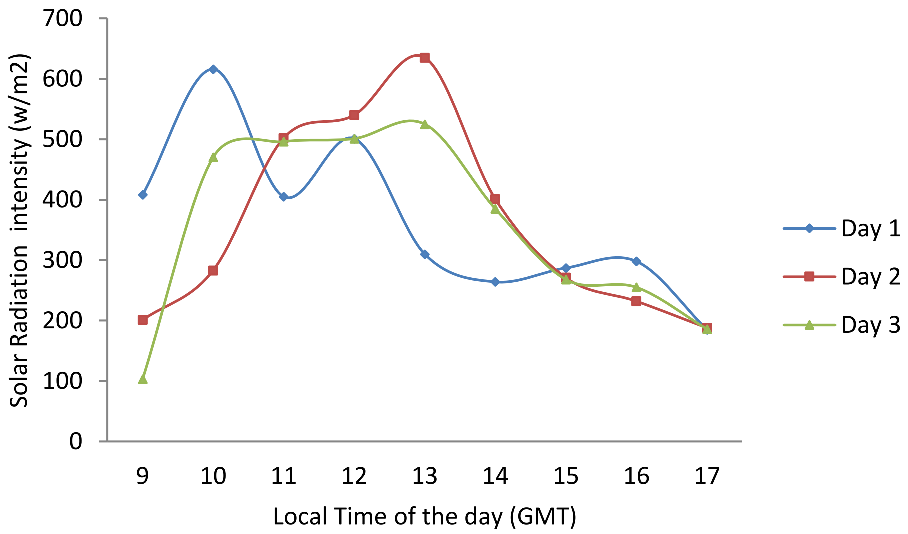


Figure 5: Average Solar radiation intensity for the three days of drying

From Figure 3, the collector temperature measured shows that the collector of dryer A produced the highest temperature for the drying process at noon, with a collector temperature range of 50.5 ^{o}C to 30.2 ^{o}C and an average value of 40.09 ^{o}C while dryer B and C have ranges of; 47 ^{o}C to 30.30 ^{o}C, and 42.2 ^{o}C to 30.10 ^{o}C respectively with average collector temperature values of 39.96^{o} C, and 36.18 ^{o}C respectively. This result is a reflection of the ambient temperature which fluctuates with solar radiation intensity, as shown in Figure 3. This shows a corresponding low relative humidity in the collector of dryer A with a collector relative humidity range of 23 to 63% with an average value of 42.5%. The ranges of collector relative humidity for dryers B, and C are 79 to 25% and 82 to 24%, respectively, with an average of 42.8%, and 45.2%, respectively. High relative humidity was observed in the off-sunshine time when solar radiation was very low or absent, and a clear sky was yet to appear. However, the relative humidity decreases as the temperature increases. The effect of the thermal storage material is obvious as dryers A and B were able to produce higher temperatures due to heat dissipation during the off-sunshine period. The temperature of the thermal storage materials is shown in Figure 6. The variation of the temperature of the collector and humidity is within the experimental error which shows that there is no difference in the performance of the PTS and DCO. The implication is that DCO can be used as thermal storage instead of more costly PTS. The PTS and DCO had higher temperatures than the ambient values throughout the process, thereby contributing to the rise in temperature of the collector and drying chamber for dryers A and B. This can solve the problem of indiscriminate disposal of used DCO as waste material. The graph shows that the PTS and DCO have temperature variations, ranging from 47 to 30 °C and 49 to 30 °C, respectively. The temperature of PTS and DCO are at least 2 °C above the ambient temperature during the off-sunshine period. During the sunshine period, PTS and DCO had a maximum temperature difference of 10.8 °C each above the ambient temperature. However, PTS maintained a higher constant temperature difference throughout the drying period and responded more rapidly to ambient temperature change than DCO. However, using DCO previously discarded in solar dryer design presents a good prospect for cheap heat storage or a heat career in solar drying.

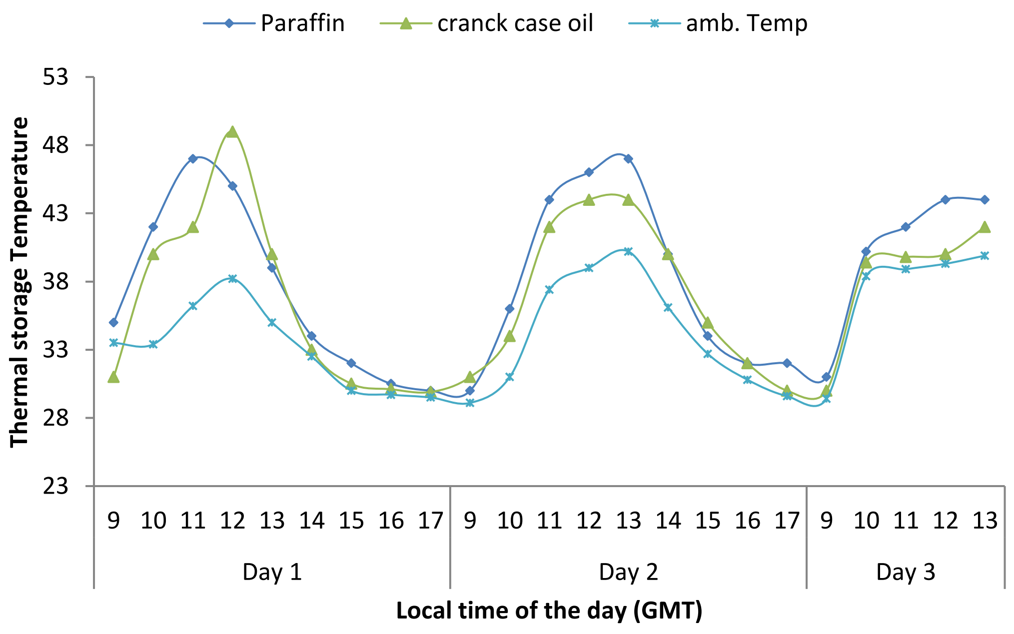


Figure 6: Average Temperatures of thermal storage material

The drying chamber is another important part of the solar dryer where the drying of the product occurs. Comparisons were made among the four dryers to observe the conditions that each dryer provided for drying the ginger. Figures 7 and 8 showed the temperature and relative humidity in the drying chamber. It is observed that the drying chamber temperatures are all higher than the ambient temperature at noon time with ranges of 48.5 to 30.1°C, 46.3

to 29.8 °C and 40.2 to 29.0 °C for dryers A, B, and C, respectively, with corresponding average values of 39.88 °C, 37.04 °C, and 35.73 °C in the same order. The drying chamber temperature reduced in the evening time when solar radiation intensity dropped. The two dryers with thermal storage maintain higher temperature and lower relative humidity in the drying chamber at all times. However, the dryer with PTS shows a slightly lower relative humidity value than the dryer with DCO. The average values were 40.7%, 41.4% and 45% respectively.

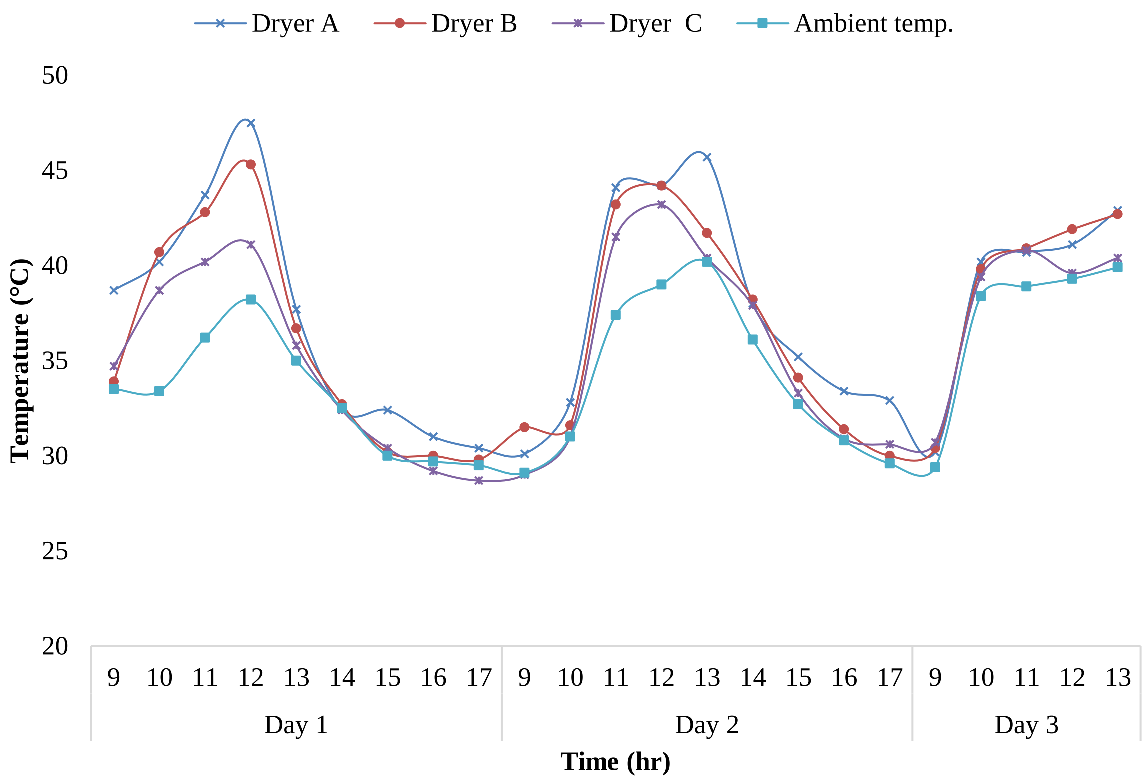


Figure 7 Average drying chamber temperatures

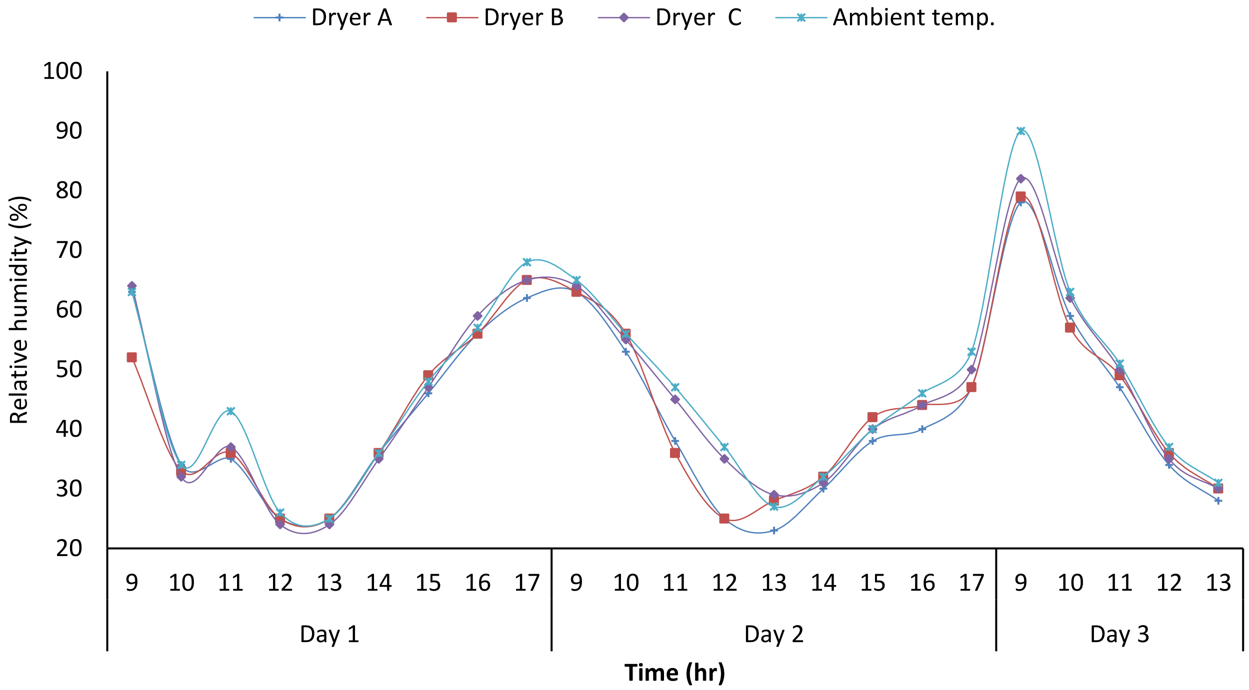


Figure 8 Average drying chamber Humidity

3.2 Collector and Drying efficiency

The efficiency of the three collectors is displayed in Figure 9. From the graph, the efficiencies of collectors are higher during noon time when the ambient temperatures and solar radiation intensity are higher. The collector of dryer A has the highest collector efficiency of 25.56% due to the PTS available in the heat exchanger pipe embedded in the collector. This recorded efficiency is higher than the 24.7% efficiency obtained by Isaac and Sam (2017), and it's similar to the efficiency obtained by Schiavone (2011) for a natural convective dryer. Collectors of dryers B and C have maximum efficiencies of 20.6%, and 10.4% respectively. This shows that dryer B with DCO can compete favourably with dryer A with PTS when every cost component is integrated into the evaluation. This is because DCO was procured at no cost, unlike PTS. The corresponding drying efficiency is shown in Figure 10. The results showed that higher drying efficiency was obtained in dryers with PTS and DCO. The drying efficiency of the dryers A, B and C are 15%, 13.5% and 9.50%, respectively, which corresponds to the efficiency obtained by Schiavone (2011) and is in line with the range of efficiency for a natural convective dryer which is 10% to 15% according to Brenndorfer et al (1987).

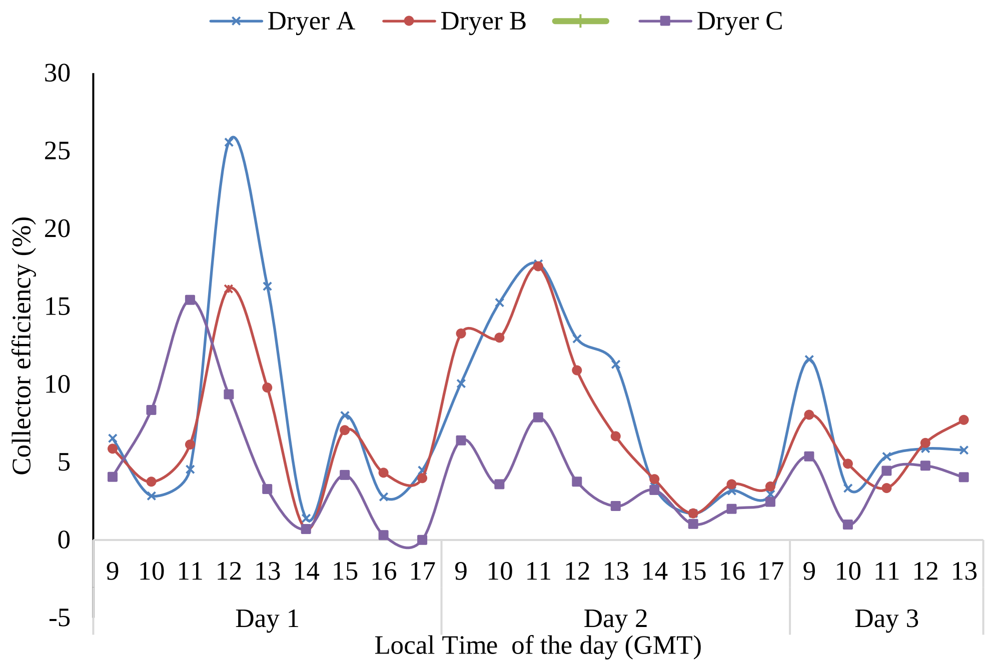


Figure 9: Average Collector Efficiency of the Solar Dryers

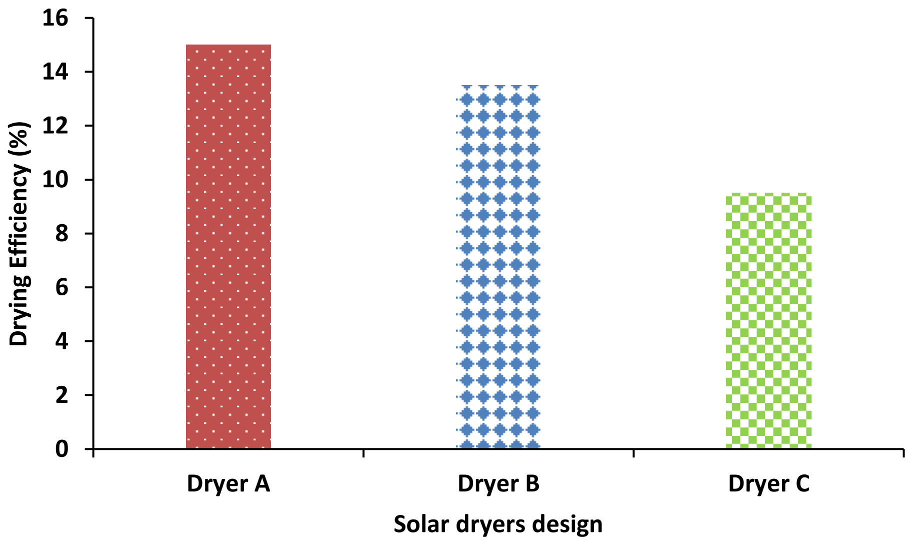


Figure 10: Dryer fficiency for different solar dryers

3.3 Energy Analysis

The energy analyses of the solar dryers are shown in Table 1 below. Solar dryer A with PTS produced 0.016 MJ of energy from its thermal storage material with a total useful energy of 2.97 MJ consumed to dry the sliced ginger from 82.14% wb to equilibrium moisture content of 8.03 ± 0.86% wb within 15 hours as shown in Figure 11.

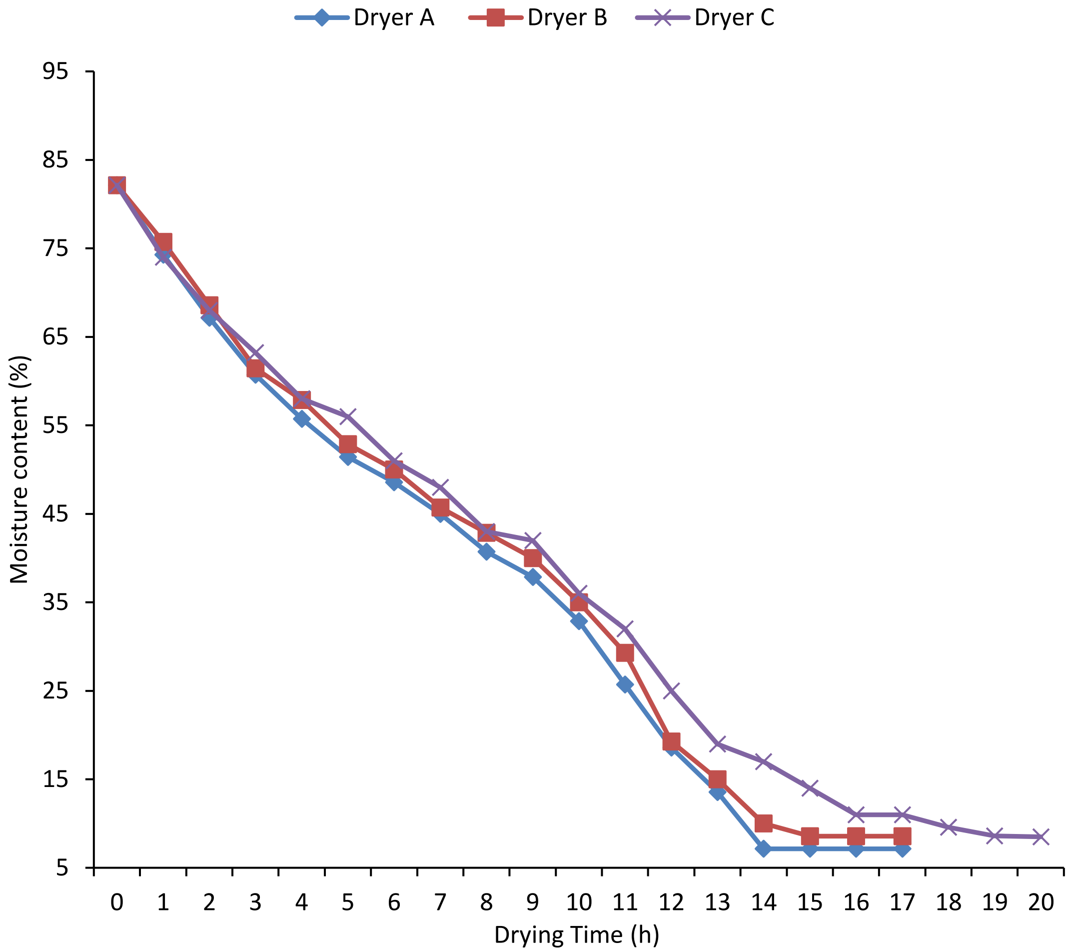


Figure 11: moisture loss profile of the dried ginger

Dryer B with DCO produced thermal storage energy of 0.009 MJ from the DCO and total energy consumption of 3.16 MJ which brought the moisture content of the food product from 82.14% wb to 8.03 ± 0.86% wb within 16 hours. Dryer C without thermal storage yielded total useful energy of 4.0 MJ, to dry the product from 82.14 %wb to 8.03 ± 0.86% wb in 20 hours. Meanwhile, Eze and Agbo (2011) reported that part of the problem of ginger preservation is reducing its moisture content by between 7 and to12%. Hence the final results obtained from the study showed that the developed dryer is good for drying ginger. The effectiveness of energy utilisation is embodied in the specific energy consumption in the drying process, obtained as 4.48, 4.8 and 6.07 316.12, k Wh / kg for dryers A, B and C, respectively. Consequently, the specific moisture extraction rate of the energy required to evaporate 1 kg of water was 0.223, 0.205 and0.164 kg / k W h respectively. The inverse of specific energy consumption is the specific moisture extraction utilized for drying (Fudholi et al., 2010).

Table 1: Performance parameter of the developed solar dryers

Parameters	Dryer A	Dryer B	Dryer C
Average collector temperature (^oC)	40.09	38.96	36.18
Average Drying chamber temperature (^oC)	39.88	37.04	35.7
The average temperature at Chimney (^oC)	35.8	35.5	35.73

Average Ambient RH (%)	46.7	46.7	46.7
Average Collector RH (%)	42.8	43.5	45.2
Average Drying Chamber RH (%)	40.7	41.7	45
Average Drying chamber RH exist air (%)	40.9	41.9	44.1
Initial moisture content (% wb)	82.14	82.14	82.14
Initial mass (kg)	0.20	0.20	0.20
Total drying time (hours)	15	16	20
Dryer Efficiency (%)	15	13.5	10.3
Average wind speed (m/s)	0.10	0.08	0.07
Energy from thermal storage (MJ)	0.016	0.010	-
Total Useful Energy Consumed (MJ)	2.97	3.16	4.0
Specific Energy Consumption (KWh/Kg)	4.48	4.88	6.07
Specific Moisture Extraction rate (Kg/KWh)	0.223	0.205	0.164
Average solar radiation (W/m^2)	357.5	357.5	357.5

3.4 Exergy analysis of the Dryers

Exergy analysis was employed for the thermodynamic analysis of each of the developed dryers to identify areas with high potential for improvement. The sinusoidal shape of the graphs is similar to the result obtained by Ndukwu et al., (2020 c) which shows that the four dryers are affected by environmental factors during the drying process. For example, from figure 12, the maximum inlet values for dryers A, B, and C are 5.4 kW, 3.9 kW and 2.7 kW, respectively, while maximum exit values were 2.8 kW for dryer A, 3.8 kW for dryer B and 1.8 kW for dryer C. Figure 13 shows their respective exergy losses per time throughout the process and figure 14 indicates the exergy efficiencies which is obtained from the exergy loss. The graph shows the exergy efficiency ranging from 7% to 97% for dryer A, 0% to 99% for dryer B, and 0% to 84% for dryer C, with average values of 45% for dryer A, 49.9% for dryer B, and 41.a % for dryer D. This shows the sustainability of dryer B with DCO.

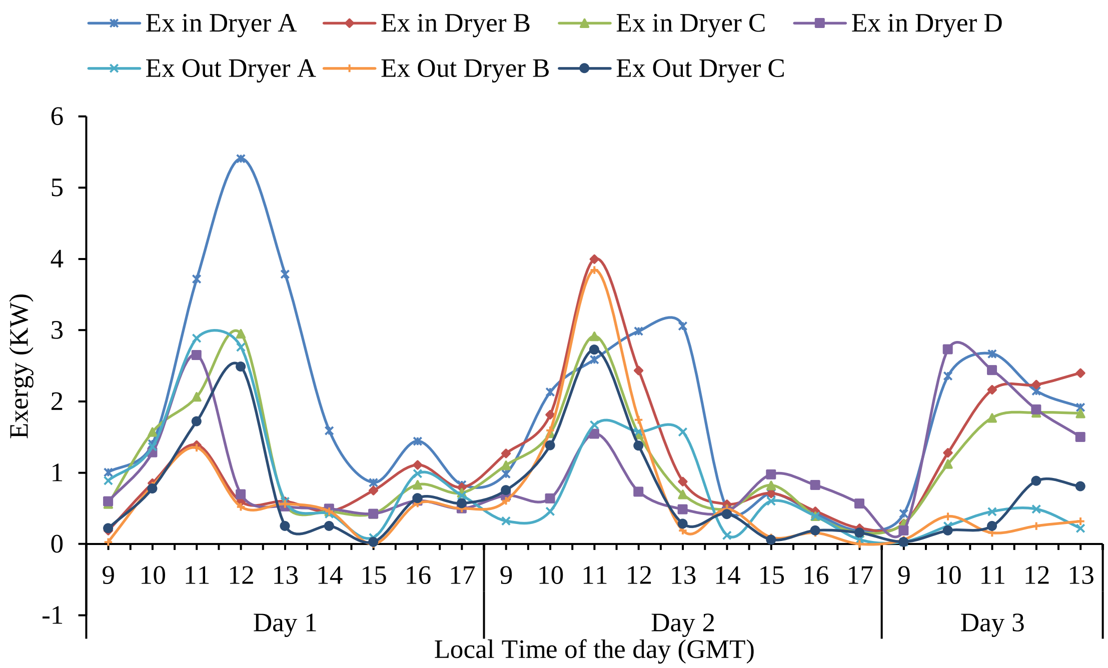


Figure 12 Exergy in and Exergy out of the dryers

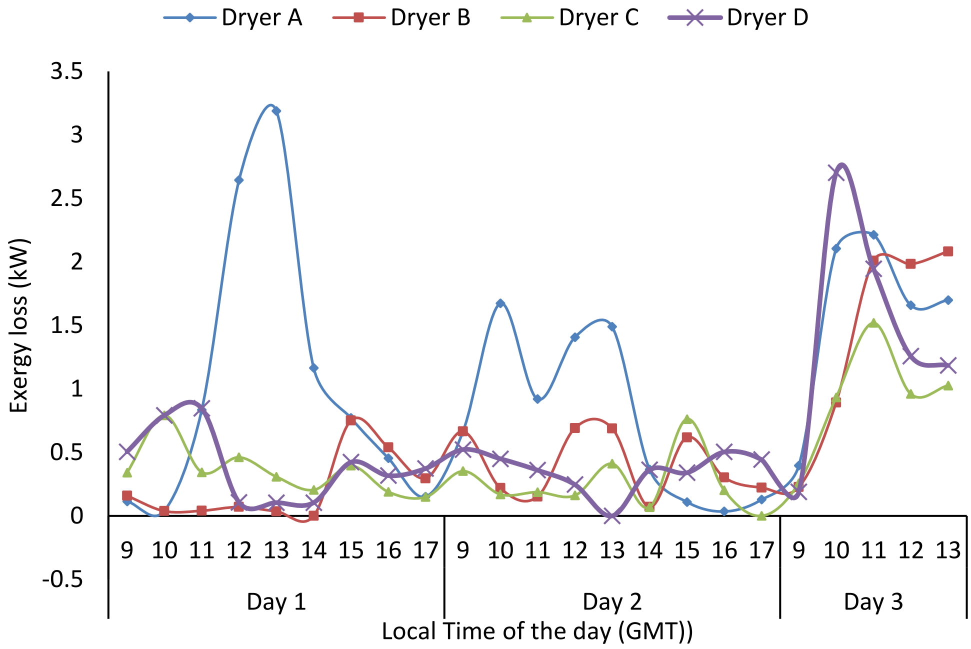


Figure 13: Exergy Loss of the studied dryers

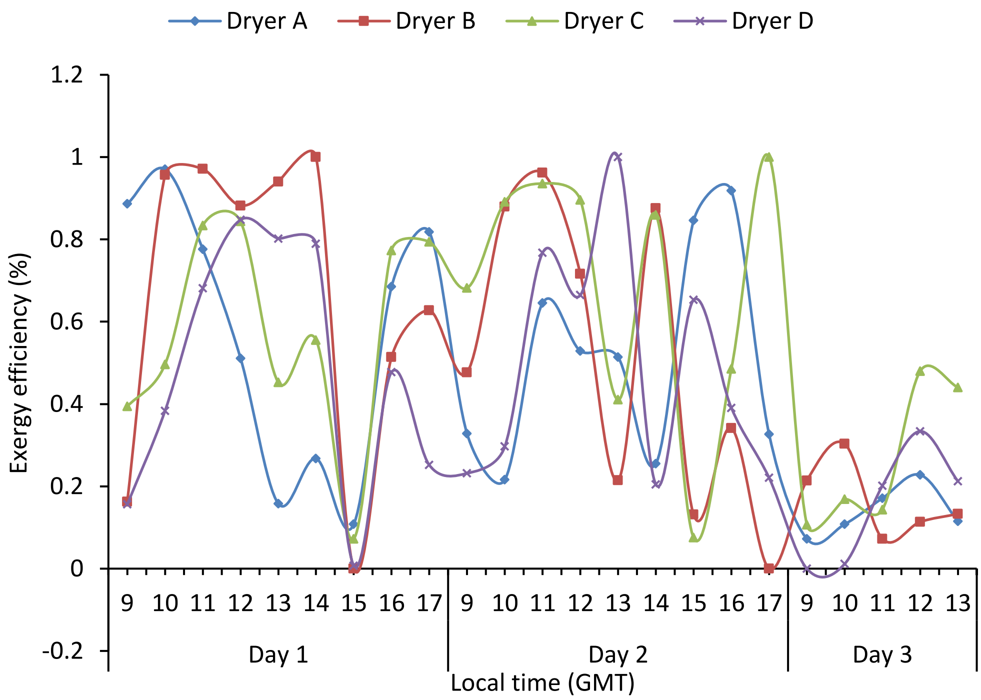


Figure 14: Exergy efficiency of the studied dryers

3.5 Sustainability Analysis

Three exergy-based indices were used to assess the sustainability of employing DCO as thermal storage in solar design. These indices which include, waste exergy ratio (WER), sustainability index (SI) and improvement potential (IP) were assessed in comparison with PTS and control. The graphs are presented in Figures 15 to18. According to Dincer and Rosen (2013) and Ndukwu et al., (2016) the waste exergy ratio is used to compare the amount of exergy loss to the total exergy that enters the solar dryer due to the effect of moisture loss from the product on the thermodynamic equilibrium of the ambient. The values obtained for WER were $0.000 \leq WER \leq 0.928$, $0.000 \leq WER \leq 1.00$ and $0.029 \leq WER \leq 1.00$ for dryers A, B and C, respectively while the corresponding SI values were $0.00 \leq SI \leq 34.32$, $0.00 \leq SI \leq 34.56$ and $1.07 \leq SI \leq 13.83$, respectively. Correspondingly the IP was $0.00 \leq IP \leq 2.68$ kW, $0.000 \leq IP \leq 1.86$ kW and $0.001 \leq IP \leq 2.67$ kW respectively. These values are similar to the values presented by Ndukwu et al., (2017) in literature.

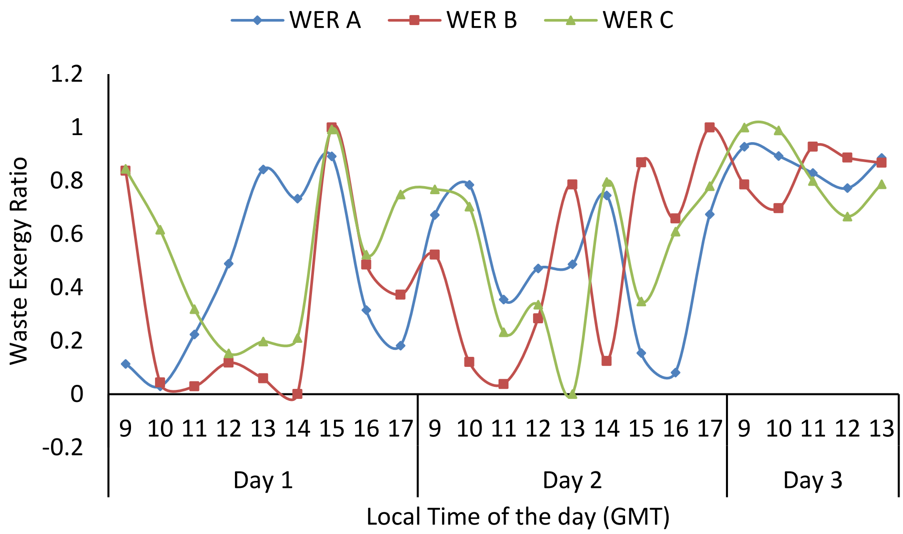


Figure 15: Waste exergy ratio of the studied dryers

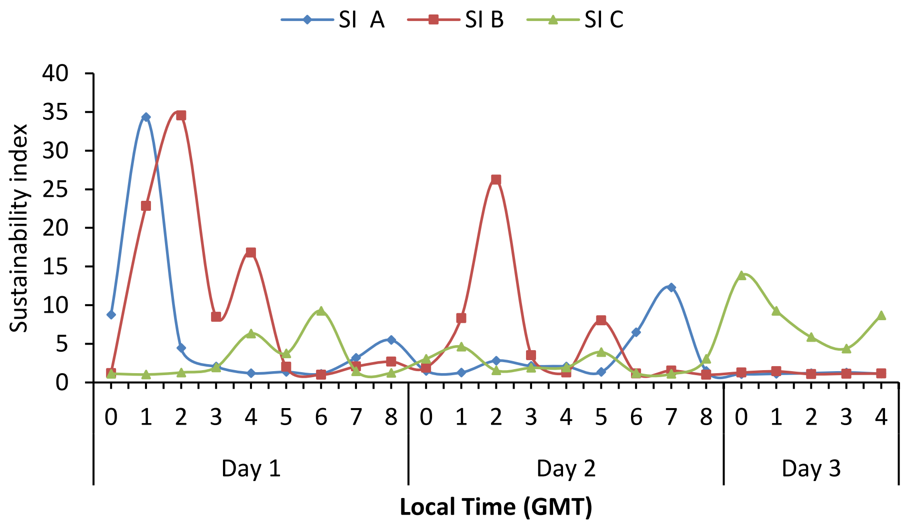


Figure 16: Sustainability index of the studied dryers

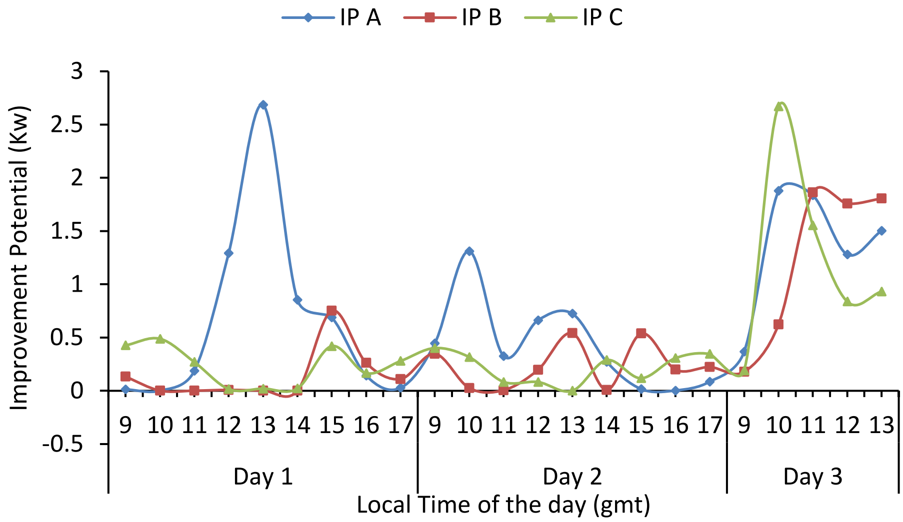


Figure 17: Improvement potential of the studied dryers

3.6 Greenhouse gas mitigation

One of the benefits of solar drying is to explore the abundant solar energy. In this way the use of fossil fuels and their environmental consequences is limited. Therefore, to fully show the advantage of the presented solar dryer, comparisons were made with other sources of energy that can be used to power a similar dryer to accomplish the same function. Therefore, the energy utilized for each solar dryer was compared with diesel, grid-based electricity and coal-fired dryers. The results of the comparisons of mass of CO_2 avoided are presented in Figure 18. Although these values were calculated using the Nigeria scenario, they might differ from one country to another. Using coal-fired dryers limited more CO_2 from entering the atmosphere while grid-based electricity has the list value as shown in figure 18. The values of the results in Figure 18 show the positive environmental impact of using a solar the dryer

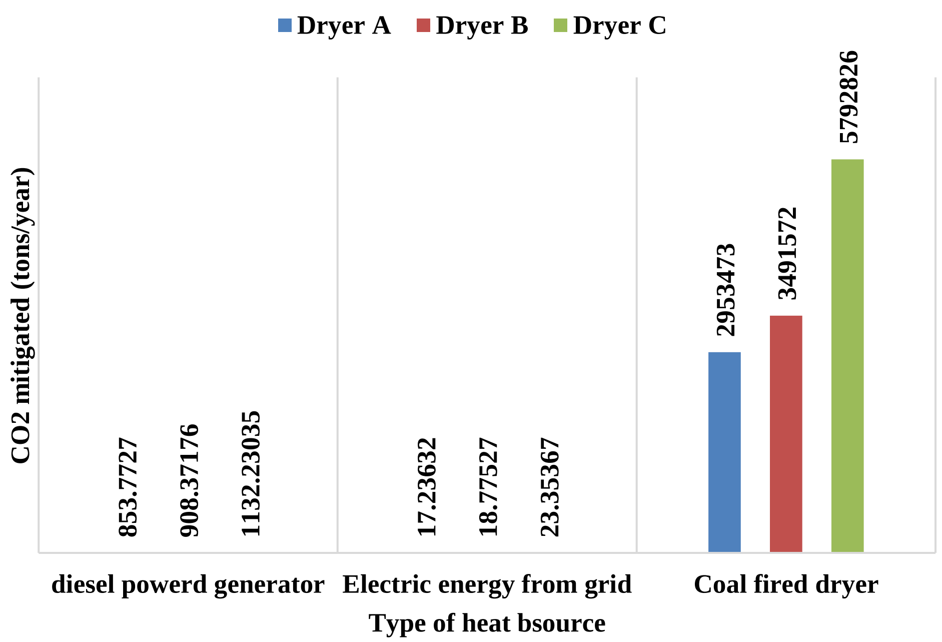


Figure 18: CO_2 mitigation potential of the dryers

4.0 Conclusions

The comparative thermodynamic assessment of employing degraded crankcase oil as thermal storage was done with already known paraffin which has been used and evaluated as good thermal storage material in literature for solar drying. A comparison was also made with a solar dryer without any thermal storage material which served as control. The results obtained were encouraging because there was no difference within the statistical limit error between the drying efficiencies of the solar dryer with paraffin as thermal storage (PTS) and the solar dryer with degraded crankcase oil (DCO) as thermal storage. This shows that DCO can serve as a substitute for more expensive paraffin oil as thermal storage material in solar drying. However, there was a statistical difference in the efficiencies of the solar dryer without thermal storage when compared with the solar dryer with DCO as thermal storage which shows the overall performance improvement of the solar dryer with DCO. In terms of energetic performance, the difference between the energy utilized by the dryer with DCO and PTS is just 8.2% while it was 24.39% with the dryer without thermal storage, showing the effectiveness of DCO as a heat career. Dryer B with DCO showed better exergy effectiveness compared to dryer A and C with dryer A; having average exergy efficiency of 45%, dryer B, 49.9% while dryer C has 41.6 %. In terms of sustainability, dryer B has the highest sustainability index of 34.56 with the lowest Improvement potential which shows the effectiveness of energy utilization. With a reduction in drying time achieved, enhanced useful energy usage efficiency, better exergy sustainability, low or no cost, and environmental protection from waste disposal, the studies inferred that DCO offered a prospect as a suitable heat storage medium in low-temperature solar drying of agricultural products. Therefore, using these dryers as a substitute for a diesel-powered dryer will mitigate 853.77 to 113.23 tons of CO_2 from entering the atmosphere. This is a strong indicator that the evaluated solar dryers can help limit the greenhouse effect by reducing the amount of CO_2 going into the atmosphere which causes global warming. This study is limited to the comparison of using these two thermal storage materials as a heat reservoir for drying as done in most literature. However, the effect of fouling on the pipes and thermal stability, viz-a-viz the chemical decomposition of the thermal storage under application of solar heat was not studied and therefore recommended for future studies. Life cycle analysis of the dryer can be carried out to determine the useful life of the system.

References

Agyenim, F., Hewi, N., Eames, P. and Smith, M. (2010). A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage system, *Renewable and Sustainable Energy Reviews*, 14:615-628.

Aissa, W., El-Sallak, M. and Elhakem, A. (2012). An experimental investigation of forced convection flat plate solar air heater with thermal storage material. *Thermal Science*, 16(4): 1105–1116.

Amir R. V. (2019). paraffin as Phase Change Material, Paraffin - an Overview, Fathi Samir Soliman, IntechOpen, DOI: 10.5772/intechopen.90487. Available from: https://www.intechopen.com/chapters/70480

Akbulut, A. and Durmus, A. (2010). Energy and exergy analyses of thin-layer drying of mulberry in a forced solar dryer. *Energy*, 35:1754–63.

Brenndorfer, B., Kennedy, L. and Mrema, G. (1987). Solar Dryers: Their Role in Post-Harvest Processing, Commonwealth Secretariat.

Baniasadi E., S. Ranjbar, O. Boostanipour, Experimental investigation of the performance of a mixed-mode solar dryer with thermal energy storage, Renew. Energy 2017 (2017), https://doi.org/10.1016/j.renene.2017.05.043

Caliskan, H., A. Hepbasli, I. Dincer, and V. Maisotsenko, Thermodynamic Performance Assessment of a Novel Air Cooling Cycle: Maisotsenko Cycle. International Journal of Refrigeration 34 (2011) 980–990. doi:10.1016/j.ijrefrig.2011.02.001

Eze, John & Agbo, Kevin. (2011). Comparative studies of the sun and solar drying of peeled and unpeeled ginger. American Journal of Scientific and Industrial Research. 2. 136-143. 10.5251/ajsir.2011.2.2.136.143.

Dincer I, M.A. Rosen (2013). Exergy Energy, environment And Sustainable Development. Elsevier Ltd. The Boulevard, Langford Lane, Kidlington, Oxford OX51GB, UK

Duffie J.A and Beckman W.A (2006) Solar Engineering of Thermal Process, Ed Wiley, New York.

Forson, F.K., Nazha, M.A.A., Akuffo, F.O. and Rajakaruna, H. (2007a). Design of mixed-mode natural convection solar crop dryers: Application of principles and rules of thumb. *Renew Energy*, 32(14):2306–19.

Forson FK, Nazha MAA, Rajakaruna H. (2007b). Modelling and experimental studies on a mixed-mode natural convection solar crop -dryer. *Solar Energy*, 81(3):346–57.

Fudholi, A., Sopian, K., Ruslan, M. H., Alghoul, M. and Sulaiman, M. (2010). Review of solar dryers for agricultural and marine products. *Renewable and Sustainable Energy Reviews*, 14(1), 1-30.

Isaac N S and Sam C. (2017). Design and Testing of a Natural Convection Solar Tunnel Dryer for Mango", *Journal of Solar Energy*, vol. 2017, Article doi.10.1155/2017/4525141

Kamble, A.K., Pardeshi, I.L., Singh, P.L. and Ade, G.S. (2013). Drying of chilli using solar cabinet dryer coupled with gravel bed heat storage system. *J Food Res Technol*, 1(2):87–94.

Krishnananth, S. S. and Murugavel, K. K. (2013). Experimental study on double pass solar air heater with thermal energy storage. *Journal of King Saud University*, 25(2): 135-140.

Kumar A., T. C. Kandpal, Solar drying, and CO_2 emissions mitigation: potential for selected cash crops in India. Solar Energy 78 (2005) 321–329

Leon, A. M., Kumar, S. and Bhattachaya, S.C. (2002). A Comprehensive Procedure for Performance Evaluation of Solar Food Dryers, *Renewable and Sustainable EnergyReviews*, 6:367-393

Madhlopa, A. and Ngwalo, G. (2007). Solar dryer with thermal storage and biomass-backup heater. *Solar Energy*, 81(4):449–62.

Mohanraj, M. and Chandrasekar, P. (2009). Performance of Forced Convection Solar Drier Integrated with Gravel as Heat Storage material for Chilli Drying. *Journal of engineering science and Technology*, 4 (3):305-314

Ndukwu, M. C., Abam, F. I., Manuwa, S. I. and Briggs, T. A. (2016). Exergetic performance indicators of a direct evaporative cooling system with different evaporative cooling pads. *International Journal of Ambient Energy*, 38(7):701-709.

Ndukwu, M.C., Bennamoun, L., Abam, F.I., Eke, A.B., Ukoha, D., (2017a). Energy and exergy analysis of a solar dryer integrated with sodium sulphate decahydrate and sodium chloride as a thermal storage medium. Renew. *Energy* 113, 1182–1192.

Ndukwu, M. C. and Bennamoun, L. (2017b). Potential of integrating Na2SO4 · 10H2O pellets in the solar drying system. *Drying Technology*, 36(9), 1017–1030.

Ndukwu, M. C., Bennamoun, L. and Abam, F. I. (2018). Experience of Solar Drying in Africa: Presentation of Designs, Operations, and Models. *Food Engineering Reviews*,

10:211–244
Ndukwu, M.C., Simo-Tagne, M., Abam, F.I., O.S. Onwuka, S. Prince, and L. Bennamoun, (2020b). Exergetic sustainability and economic analysis of hybrid solar-biomass dryer integrated with copper tubing as a heat exchanger, *Heliyon*, 6(2): e03401,
Ndukwu, M. C., Simo-Tagne, M. and Bennamoun, L. (2020c). Solar drying research of medicinal and aromatic plants: An African experience with assessment of the economic and environmental impact. *African Journal of Science, Technology, Innovation and Development,* 1–14. *doi:10.1080/20421338.2020.1776061*
Ndukwu, M. C., Diemuodeke, E. O., Abam, F. I., Abada, U. C., Eke-ekemezie, N. and Simo Tagne, M. (2020a). Development and modelling of heat and mass transfer analysis of a low-cost solar dryer integrated with biomass heater: Application for West African Region. *Scientific African*, e00615. *doi:10.1016/j.sciaf.2020.e00615*
Ould-Amrouche, O., D. Rekioua, and A. Hamidat,.2010.Modelling Photovoltaic Water Pumping Systems and Evaluation of their CO_2 Emissions Mitigation Potential. Applied Energy 87 (2010) 3451–3459. doi:10.1016/j.apenergy.2010.05.021
Reyes A, J. Vásquez, N. Pailahueque, and A. Mahn.2018. Effect of drying using solar energy and phase change material on kiwifruit properties, *Dry. Technol.,*2018. 1–13
Santos J C O; A.G Souza (2006). Sliquid specific heat capacity of motor lubricant after thermal degradation. Journal of Applied Engineering and Applied Sciences, 1, 495-499.
Sagastume, G. A., J. B. C. Martínez, and C. Vandecasteele. 2013. “Energy and Exergy Assessments of a Lime Shaft Kiln.” *Applied Thermal Engineering* 51: 273–280.
Schiavone, F. (2011). Development and Evaluation of a Natural Convection Solar Dryer for Mango in Rural Haitian Communities [MasterThesis], University of Florida.
Sharma, A., Chen, C. R. and Lan. N. V. (2009a). Solar-energy drying systems: A review. Renewable and Sustainable Energy Reviews 13 (6-7):1185–210.
Sharma A V.V. Tyagi, C.R. Chen, D. Buddhi (2009b). Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews 13, 318–345
Simo-Tagne, M., Ndukwu, M.C., Zoulalian, A., Bennamoun, L., Kifani-Sahban, F., Rogaume, Y., 2019. Numerical analysis and validation of a natural convection mix-mode solar dryer for drying red chilli under variable conditions, *Renewable Energy*, doi. 10.1016/j.renene.2019.11.055.
Tyagi, V. V., Pandey, A. K., Giridhar, G., Bandyopadhyay, B., Park, S. R. and Tyagi, S. K. (2012) “Comparative study based on exergy analysis of solar air heater collector using thermal energy storage," *International Journal of Energy Research,* 36(6): 724–736.
Tonui K.S, Mutai E.B.K, Mutuli, D.A, MbugeO.O and Too K.V (2014). Design and Evaluation of Solar Grain Dryer with a Back-up Heater. *Research Journal of applied science, Engineering and Technology*. 7 (15): 3036-3043