**Energy and exergy analysis of solar dryer with triple air passage direction collector powered by a wind generator**

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**Declarations**

- The authors have no relevant financial or non-financial interests to disclose.
- The authors have no conflicts of interest to declare that they are relevant to the content of this article.
- All authors certify that they have no affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript.
- The authors have no financial or proprietary interests in any material discussed in this article.

**Funding**

This research received no funding or support from any organization

**Conflicts of interest/Competing interests**

There is no conflict of interest whatsoever among the authors or institutions

**Availability of data and material**

Not applicable

**Code availability**

Not applicable

**Abstract**

The objective of this study is to thermodynamically investigate the performance of solar dryers by delaying the airflow in the collector. For this reason, a triple air path on a single pass collector with the fan powered by a wind generator was developed and evaluated in a very humid climate. The evaluation parameters were drying efficiency, energy and exergy analysis, sustainability assessment, $CO_2$ mitigation ability and effective moisture diffusivity of dried product. The results showed that the collector efficiency of triple air passage path collector designs improved the direct passage collector by 119 %. The overall collector and drying efficiencies were 8.43 % and 2.6 % higher than the direct flow path collector. The specific energy consumption was 1.1033 kWh/kg while the specific moisture extraction rate was obtained as 0.273 kg/kW, respectively. The average exergy efficiency ranged between 38.09 % and 63.81 % while the waste exergy ratio, improvement potential and sustainability index for the three dryers ranged from 0.00 to 1.13, 7.54 x $10^{-7}$ to 2.003 kW and 0.00 to 11.47, respectively. Using the solar dryers instead of the coal-powered dryer will mitigate more $CO_2$ into the atmosphere in the range of 9741.334 to 21481. 476 tons of $CO_2$ per year while using grid-based electricity will limit the least amount of $CO_2$ in the range of 12.981 to 14.153351.50 tons of $CO_2$ per year.

**Keywords:** Collector design, energy and exergy–based sustainability, Solar drying, cocoyam, wind generator

| **Nomenclature** | |
|---|---|
| $A_C$ | Area of the collector ($m^2$) |
| $C_p$ | Specific heat (kJ/kg.K) |
| $e_s$ | Specific exergy (kJ/kg) |
| **E** | Thermal energy (J) |
| $F_R$ | Overall heat removal factor |
| **h** | Enthalpy (kJ/kg) |
| **H** | Absolute humidity of the air ($kg_{water}$ kg $d_{ry\ air}$) |
| **I** | Intensity of radiation ($W/m^2$) |
| **k** | Heating value of diesel |
| **L** | Thickness (m) |
| ***L*** | Latent heat of vapourization of (kJ/kg) or thickness of Cocoyam (m) |
| **M** | Mass of product dried per day (kg/day) or molecular mass (g/mol) or moisture content (db or wb) |
| **m** | Mass (kg) |
| **P** | Internal moisture pressure of the product or pressure (Pa) |
| **Q** | Heat (J) |
| **r** | Equivalent radius (m) |
| **R** | Universal gas constant (kJ/kg.K) |
| **S** | Entropy (kJ/kg. K |
| **T** | Temperature (°C) |
| **U** | Overall heat loss ($W/m^2$ °C) |
| **W** | Mass of moisture expelled from the product (kg) |
| $X^0_v$ | Molar ratio of water vapour in the air |
| $y_i$ | Mole fraction of chemical species in the gaseous mixture at these same conditions |
| $y_0$ | Mole fraction of chemical species in the ambient air at reference temperature |

| ***Greek Symbols*** | |
|---|---|
| $\tau$ | Transmittance |
| $\alpha$ | Absorbance of the plate |
| $\dot{m}$ | Mass flow rate |
| $\eta$ | Efficiency of the generator |
| $v$ | Volume of diesel generator |

| ***Subscripts*** | |
|---|---|
| a | Air |
| bd | Bone dried |
| b | Back or biomass |
| e | Edge or equilibrium |
| f | Final or fuel |
| g | Gas |
| i | Initial |
| 0 | Initial or reference state |
| p | Pebbles or planum |
| r | Radiation |
| s | Sun |
| t | Top or time |
| v | Vapour |
| w | Water |

## 1. Introduction

Drying is a technique of preserving farm and forestry produce that involves removing moisture to prevent the growth of organic microbes like mould, bacteria, fungi or insect attack, which causes spoilage [1, 2]. One of the ancient procedures applied in food preservation is to remove moisture as quickly as possible by applying a heat source. When the moisture in a product is high and warm, micro-organisms will grow quicker before the product is adequately dried [3]. Drying lowers the moisture content and increases the shelf life of the product. This will enable the farmer to sell their product at the right price and makes more money, which will strengthen their economic situation and improve the nutritional condition of the crop. However, drying is classified as a high energy-consuming process and is responsible for significant $CO_2$ emissions [4]. Thus, using abundant solar energy in this operation presents an advantageous solution. Drying agricultural products, such as Cocoyam [5] in the open sunlight, is one of the oldest techniques used to keep perishable agro-products from spoilage. It is the traditional method of crop preservation in many developing countries because of its low cost [6]. However, despite its low capital investment, open sun drying produces dried products of poor quality that might be contaminated probably due to long drying periods because of weather uncertainty [7]. To reduce the drying time, sun drying can be replaced with hot air drying [8] or solar drying [9]. However, hot-air dryers are energy-intensive and expensive and ultimately increase the product cost [10] consuming between 7 % and 15 % of the industrial energy in the industrialized countries. Solar drying maximizes the advantages provided by free solar radiation and optimizes the efficiency of drying using the energy radiating from the sun. [11]. The technology involves using a solar dryer, with a collector [12]. Furthermore, solar drying is regarded as one of the healthiest and most appropriate methods to preserve the quality of dry products [13]. Thus, the nutritional contents like vitamins of the dried products are preserved by drying using solar dryers [ 14].

Different designs of solar-air dryers exist in literature and these dryers can be operated in passive mode by relying on natural air ventilation or in dynamic (active) mode by driving the convective air through the collector using a fan or blower which improves the drying rate [15]. Dynamic mode solar dryers have proven to outperform natural convection solar dryers. However, due to electricity penetration density in many developing countries adopting this in solar dryers is also a challenge. Again, adopting a dynamic mode adds to the initial cost and most time requires extra components like an electricity source or solar panel with an inverter to power the fan. This additional cost coupled with low electricity penetration density discourages poor farmers from developing countries from adopting this technology. Therefore, to overcome the challenge of lack of electricity to power the solar dryer fans, a wind generator which depends on the wind without electricity can be used to power the fan [7]. The dynamic nature of wind and the enormous free energy it drives along can be tapped into powering the solar dryer fan. Therefore, any solar drying system that can drive the inlet air without electricity will encourage the adoption of solar drying in the drying process. The product dried can receive the heat directly or through the collector or both [16,]. This area of research in solar drying is also being exploited [7].

The idea of developing a solar crop dryer is not new in concept but an effort to improve its performance with a better design concept is ongoing [17]. Southern Nigeria has high wind and low solar radiation intensity most time of the year, adopting solar drying is difficult. The challenge is the humidity of the inlet air coupled with low solar intensity. This has denied farmers the benefit of adopting this low-cost drying system. Although most solar dryers design has a single-pass collector [18, 19], delaying the airflow in the collector to make it stay longer and develop fully the turbulence in the collector will likely aid the heat transfer between the solar collector absorber and the inlet air [20-]. This will enable the inlet air to shade some of the moisture at an elevated temperature above the ambient [21]. This area of research on fluid flow path through the collector is gaining attention and being investigated with different design configurations [22, 23]. The longer the fluid passage path and turbulence fully developed, the better the performance [24]. Thus, the proposed research aims to develop and investigate the effect of multiple air-flow passages (single, double and triple) in the collector combined with the wind-powered suction fan on the drying performance of the solar dryer. To holistically assess a renewable energy system, energy and exergy analysis is carried out [25]. While it's common to carry out energy analysis but the concept of exergy analysis is now at the forefront of system evaluation in solar drying. This shows the quality of energy passing through components and indicates where attention is needed [26]. Again, environmentalists will be keen to know the effect of engineering design in preserving the environment with the critical issues of climate change for the evaluation to be holistic and sustainable. Therefore, to assess the performance of the presented solar dryer's energy and exergy analysis, sustainability analysis and environmental impact analysis will be carried out to compare the three proposed systems. Thus, the objectives of this study were (1) to investigate the performance of newly designed wind-powered solar dryers with multiple airflow path collectors under a humid climate; (2) to study the effect of using the three different types of solar air heaters on the drying kinetic of Cocoyam corm, and (3) to perform energy, exergy, and environmental assessment on the proposed indirect solar dryers under actual operation conditions.

## 2. Material and methods

### 2.1 Description of the developed solar dryers

The dryers were all constructed with the same locally sourced, cheap material, structural features like woods and the collectors are airtight to achieve the aim of drying. The dryer consists of an air collector (direct and triple path airflow direction on a single pass collector) sections, a drying chamber and a chimney section fitted with the wind generator shaft. The drying chamber is just a simple cabinet of 1.60 m from the floor and 0.6 m× 0.6 m. The schematic diagrams of the two fabricated indirect-active solar dryer types with triple airflow paths through the collectors are presented as shown in Figure 1.

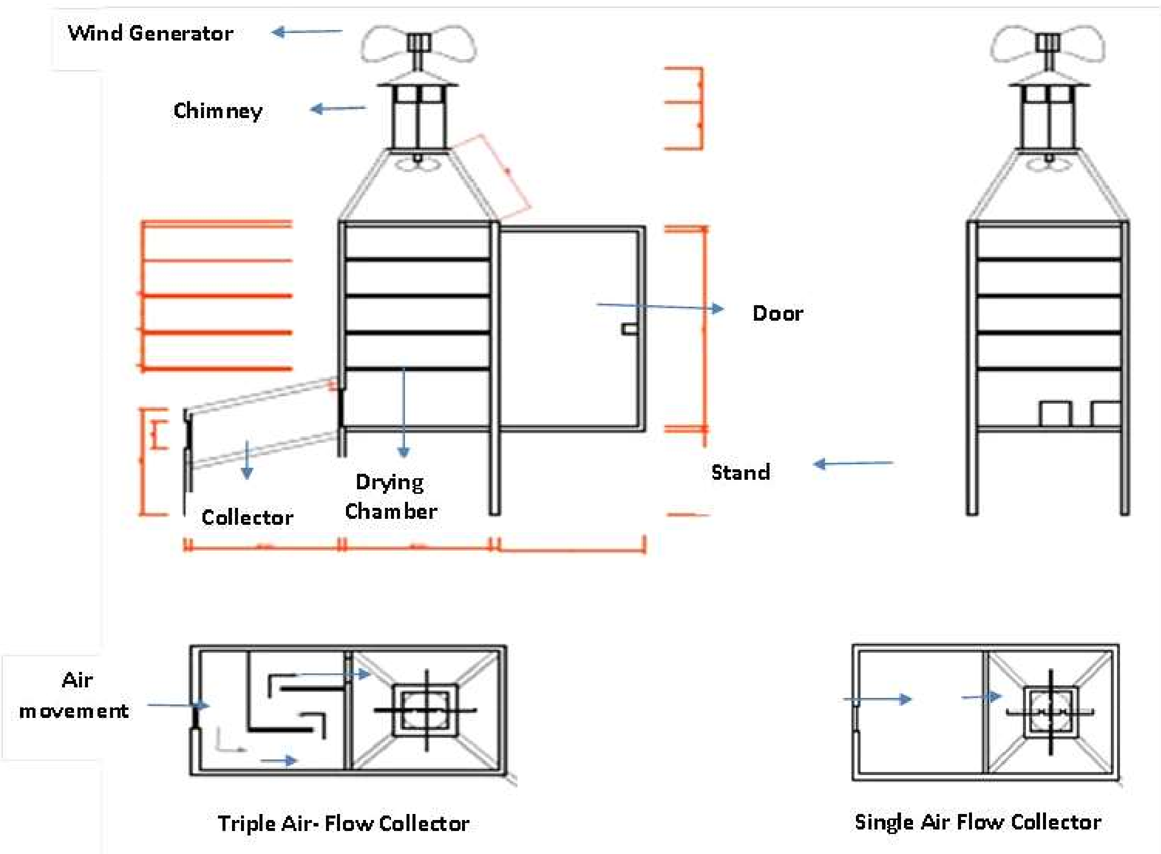


**Fig.1.** Schematic view of the direct and triple path single pass solar dryer design showing the wind generator, chimney, door, collectors, drying chamber and direction of air movement

The drying chamber is supported by four leg-stands at a height of 0. 36 m above the ground. The top of the drying chamber is the chimney constructed with a galvanized cylindrical metal pipe of 0.12 m in diameter and 0.3 m in length. The chimney is fitted with a wind generator through a freely rotating shaft and bearing assembly. The wind generator has three light aluminium arms, which with the help of the wind, sets the suction fan attached at the end of the shaft inside the drying chamber in motion. The solar air collector (0.6 m x 0.6 m x 0. 59 m) tilted at an angle of $15^0$ was partially partitioned horizontally in the middle. It also had a double longitudinal partial partition with a clearance of 0.15 m between the sections to create triple path airflow. Also, a second solar dryer was designed with no partition, thus allowing the air to move straight into the drying chamber to serve as a control solar dryer.

In the current work, all the collectors have the same dimensions and structure too. Partitioning was done with 0.2 × 0.45 m plywood. The solar collector absorber is a black painted aluminium sheet. A transparent glass sheet of 4 mm thickness covers the top of the solar collector and serves as a transitivity medium for solar energy radiation. Four holding trays made of 2 × 2 cm thick wood were fitted into the drying chamber at a gap of 0. 15 m above each other. The lower part of the solar collector consists of a square air inlet to allow airflow through the collector. the pictorial arrays of the solar dryers are uploaded as supplementary material.

### 2.2 Data collection

All the experimental studies were carried out at the Michael Okpara University of Agriculture, Umudike (MOUAU) located in Umudike Nigeria (longitude $7^0$ $05^0$E and latitude $5^0$ $25^0$N) from 2nd – 4th September because the prevalence of high humidity and frequent rainfall abruptly reduced solar radiation intensity. The parameters monitored for the performance evaluation were the intensity of solar radiation, ambient temperature, the temperature of collectors, temperature of the drying chambers, relative humidity, wind speed, and the moisture content of the drying crop determined on a wet basis. The solar radiation intensity was measured using a Lutron SPM-1116SD SD card data recorder solar power pyranometer (made in Taiwan, SO-22834, 1.5V Battery X6 UM-3.AA. R6) with an accuracy of 0.1W/$m^2$. The ambient relative humidity and temperature were measured with Lutron MHB-382SD SD card data logger, Humidity and Temperature data recorder (made in Taiwan). The wind speed was measured with a CR2032, 3V lithium cell Anemometer. The weight of the product was measured using an SF-400 Electronic kitchen weighing scale. (Measuring capacity: 1000g × 1g, 353oz × 0.1oz, made in China). Weight reduction was recorded every one-hour interval starting from 9:00 am to 5:00 pm daily. The temperature of the drying chamber and collector of the dryer was measured using a type -T thermocouple measuring instrument. All measurements were at three points and the average values were determined and used for analysis.

### 2.3 Experimental procedure

Cocoyam (*Xanthosoma Sagittitolium* species) tubers purchased from a local farm located in Abia State Nigeria for this study were thoroughly washed to remove sand and other contaminants. The cocoyam tubers were then peeled and sliced manually to an approximate thickness of 5 mm and a uniform square shape to ensure weight uniformity. Subsequently, 500 g of these square-shaped Cocoyam slices were placed on the drying trays that were placed inside the drying chamber of the solar dryers. The ambient temperature, relative humidity, solar radiation intensity, wind speed, the weight of the dried product, drying chamber temperature and the collector temperature were measured - hourly (in triplicate) from 9:00 am to 5:00 pm for 3 days.

The experimental uncertainties of measurement of relative humidifies, temperatures, air velocities, solar radiations, and weight loss were measured during the drying of the cocoyam. The obtained data were used to calculate the uncertainties from drying rate, moisture contents, and moisture ratio using the equation as follows [27]

$$U_R = \left[\left(\frac{\partial R}{x_1}\right) y_1{}^2 + \left(\frac{\partial R}{x_2}\right) y_2{}^2 + \cdots + \left(\frac{\partial R}{x_2}\right) y_n{}^2\right]^{1/2} \quad \text{1a}$$

Where $y_1$, $y_2$ and $y_n$ are the uncertainty in variables $x_1$, $x_2$ and $x_n$. The calculated uncertainties where ± 0.019, ± 0.019, ± 0.09. For moisture contents, drying rate, and moisture ratios

## 2.4 Dryer Performance evaluation parameters

### 2.4.1 Performance of solar dryer

The volume of water removed from the Cocoyam during drying at a given time on a dry basis is given by Das Purkayastha et al. [28]

$$M_t = \left[\left(\frac{m_t}{m_i}\right)\{(M_i + 1) - 1\}\right] \quad \text{1b}$$

The Solar dryer collector efficiency is given as follows [29, ]:

$$\eta_C = \frac{Ma \times C_p \times (\Delta T)}{Ic \times \tau \times A_C} \times 100 \quad \text{2}$$

The drying efficiency of the solar dryer is given as follows [30, 31]:

$$\eta_d = \frac{M_w Lv}{I_C A_c t} \times 100 \quad \text{3}$$

### 2.4.2 Effective moisture diffusivity

The effective moisture diffusivity was estimated using the slope of a straight line by plotting data concerning the natural log of the moisture ratio (MR) against drying time, with a slope (*k*).

$$k = \frac{\pi^2 D_{eff}}{4L^2} \quad \text{4}$$

## 2.5 Energy Analysis

The total energy utilized ($Q_u$) for drying the Cocoyam in the solar dryer is the radiation energy given by Duffie and Beckman [32] as follows:

$$Q_u = A_c F_R[I\tau - U_O(T_c - T_a)] \quad \text{5}$$

The specific energy consumed, and specific moisture extraction rate is given by Equation 6 and 7 as follows [7]

$$E_s = \frac{Q_r}{W_w} \tag{6}$$

$$\mathrm{SMER} = \frac{W_w}{Q_r} \tag{7}$$

## 2.6 Exergy Analysis

The exergy flow consists of the chemical, physical, kinetic and potential energies as defined by Sagastume et al. [33] as follows:

$$\sum e = \mathrm{e_{ch}} + e_{ph} + e_{ki} + e_{po} \tag{8}$$

Where $e_{ch}$, $e_{ph}$, $e_{ki}$ and $e_{po}$ are chemical, physical, kinetic and potential exergies of the described system, respectively.

However, Ndukwu et al. [35] and Hatami et al. [36] stated that in the drying of biomaterials exergy exchange with the product should be considered in determining the exergy efficiency. Therefore, the exergy stream in the drying process should include exergy of the solar radiation ($X_R$), airstream ($X_a$), and exergy of the moisture ($X_w$) in the material being dried presented as equations 9 -11[36]

$$X_R = I\tau\alpha_p A_c\left(1 - \frac{T_a}{T_s}\right) \tag{9}$$

$$X_a = \dot{m}_a\left\{C_{p,a}\left(T - T_0 - T_0 In\frac{T}{T_0}\right) + R_a T_0 \times \left[\left(1 + \frac{M_a}{M_v}H\right) In\frac{1+\frac{M_a}{M_v}H_0}{1+\frac{M_a}{M_v}H} + 1 + \frac{M_a}{M_v}HIn\frac{H}{H_0}\right]\right\} \tag{10}$$

$$X_w = \dot{m}_w\left[\left(h_f(T) - h_f(T_0)\right) + v_f\left(P - P_g(T)\right) - T_0\left(S_f(T) - S_g(T_0)\right) + T_0 R_w In\left(\frac{P_g(T_0)}{P_0 X_v^0}\right)\right] \tag{11}$$

Therefore, the exergy input ($E_{xi}$) for the solar dryer is presented in equation 12 as follows:

$$E_{xi} = X_R + X_{ai} + X_{wi} \tag{12}$$

Equation 14 gives the output exergy as follows

$$E_{xo} = X_{wo} + E_{xao} \tag{13}$$

Exergy loss during drying of Cocoyam is given as:

$$\mathrm{Ex}_{loss} = \mathrm{Ex}_i - \mathrm{Ex}_o \tag{14}$$

The exergy efficiency is defined as the ratio of exergy used in drying the Cocoyam to the exergy of the drying air supplied to the system.

$$\eta_{eff} = \frac{Ex_o}{Ex_i} = 1 - \frac{Ex_{loss}}{Ex_i} \quad (15)$$

***Exergy sustainability indicators***

The evaluation of the energy system's performance using sustainability indicators for energy growth was introduced by Dincer [37]. This index includes waste exergy ratio (WER), improvement potential (IP) and sustainability index (SI) [38]. Ndukwu et al. [13] have shown that this value varies with temperature in solar drying operations. They gave the indexes as follows:

$$WER = \frac{Ex_{loss}}{E_{xin}} \quad (16)$$

$$SI = \frac{1}{1 - Ex_{eff}} \quad (17)$$

$E_{xeff}$ is the exergy efficiency

The improvement potential (IP) of the system was calculated as follows [39]:

$$\dot{IP} = (1 - Ex_{eff})Ex_{loss} \quad (18)$$

***$CO_2$ mitigation using multi airflow path solar dryers***

The energy consumed by the multi-airflow pathway solar dryers was compared with a dryer that uses a diesel generator, nuclear-powered sources, or electricity as an energy source to determine the $CO_2$ mitigation potential of the dryer compared to those sources. According to Ndukwu et al. [13], the energy utilized by such a dryer in kWh is given below:

$$E_g = v_d k_d \eta_d \quad (19)$$

Where $v_d$,$k_d$ and $\eta_d$ are the volume of diesel in the generator, the heating value of diesel in the generator and the effectiveness of the diesel-powered dryer.

Assuming the exact amount of diesel fuel is to be consumed to extract the equal amount of energy utilized to dry the Cocoyam slice, therefore equating this with thermal energy given in Equation 5:

$$Q_u = v_d k_d \eta_d \quad (20)$$

Therefore, the volume of diesel consumed that will give the same thermal energy for the same drying purposes is given by:

$$\boldsymbol{v_d = \frac{Q_u}{k_d \eta_d}} \quad (21)$$

Ndukwu et al. [13] determined the mass of $CO_2$ produced for a litre of diesel fuel as proposed in Equation 22:

$$m_C = v_d k_f \quad (22)$$

The values of $k_f$, $k_d$ and $\eta_d$ were given by Ould-Amrouche et al. [40] as 2.63 kg/l, 10.08 kWh/l and, 30% respectively.

Comparing the energy with a grid electricity source Youmatter[41] gave the mass of $CO_2$ mitigated as equation 23 below:

$$M_{CO_2} = \mathrm{EF}_{\mathrm{CO_2}} x \, Q_e \qquad 23$$

Where $EFCO_2$ is the emission factor (0.4392 kg of $CO_2$/kWh for Nigeria), $Q_e$ is the specific energy consumption

Comparing the energy utilized with a coal (fossil fuel) powered dryer to dry the equivalent mass of Cocoyam, Simo- Tagne et al [42] gave the mass of $CO_2$ mitigated based on disaggregation of equivalent fossil fuel in equation 24 as follows:

$$M_{CO_2} = \sum_{\mathrm{i}} \mathrm{f_i} \left(\frac{\mathrm{f_{es}} \mathrm{Q_d} Q_u}{\eta_{\mathrm{i}}}\right) \mathrm{EFC}O_2 . \mathrm{FC}O_2 \left(\frac{44}{12}\right) \qquad 24$$

Where $f_i$ is the fraction of Cocoyam dried, $\eta_i$ is the efficiency of the solar collector, $EFCO_2$ is the carbon emission factor, $FCO_2$ is the equivalent fraction of $CO_2$ during the burning of the coal, $Q_d$ is the quantity (kg) of Cocoyam dried by the solar dryer, $Q_u$ is the useful energy (MJ) dissipated for drying of Cocoyam ($\mathrm{FC}O_2 = 0.9$; $\mathrm{EFC}O_2 = 0.0258$ kg/MJ; $\mathrm{f_i} = 1$; $\mathrm{f_{es}} = 1$[ 42].

## 3. Results and discussions

### 3.1 Performance Evaluation

The three developed solar dryers were tested under the ambient conditions of Umudike situated in the south-eastern region of Nigeria, located at 5.53° N, 7.49°E. In August, a trial was conducted with Cocoyam samples (*Xanthosoma sagittifolium species*), which were dried using the three solar dryers. This was the harvesting period of Cocoyam in this region. The period was characterized by heavy rainfall, occasional high wind, low solar radiation intensity, very high humidity, and low ambient temperature, as shown in Figures 3 to 5. The highest values of the temperature were obtained between 12 pm and 3 pm for the three days. However, the highest humidity was registered on the first day at the beginning of the drying process. Nevertheless, the highest values of the humidity, for the second and third days were registered at the end of the day. The solar radiation, the ambient temperature and the relative humidity had a sinusoidal variation. The obtained maximum values were 521.7 W/m$^2$, 5.1 m/s, 40.1 °C and 88.1 % for solar intensity, wind speed, ambient temperature, and ambient relative humidity, respectively, while the corresponding minimum values were 80.6 W/m$^2$, 0.1 m/s, 22.4 °C and 51.7 %, respectively also. The average values of these measured parameters are presented in Table 1. Figures 4 and 5 showed that the ambient conditions obtained drying results for all tested solar dryers. Due to high relative humidity within this period, it is difficult to raise the temperature or lower the relative humidity of the ambient values in the collector. However, using the proposed design of the solar dryers, it was possible to raise the ambient temperatures to 3.4 °C and 9.4 °C for single and triple airflow pathway collectors, respectively.

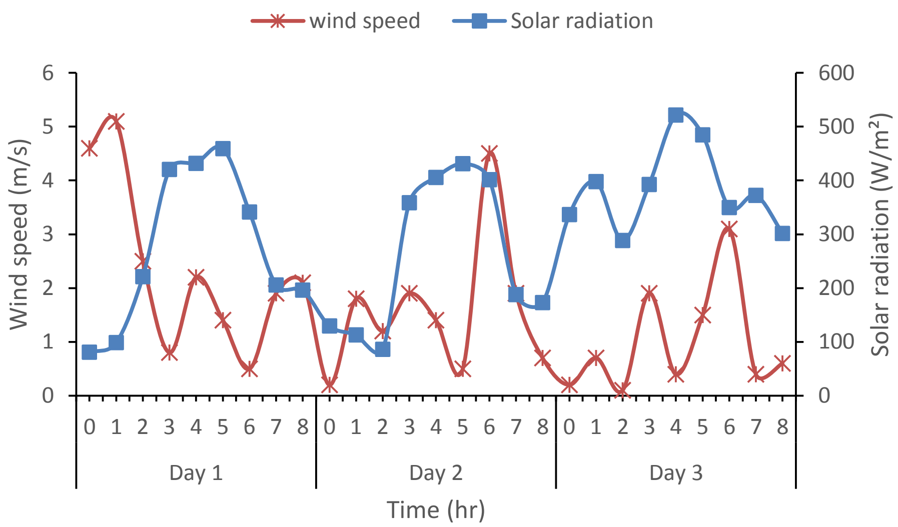


**Figure.3.** Solar radiation intensity and wind speed.

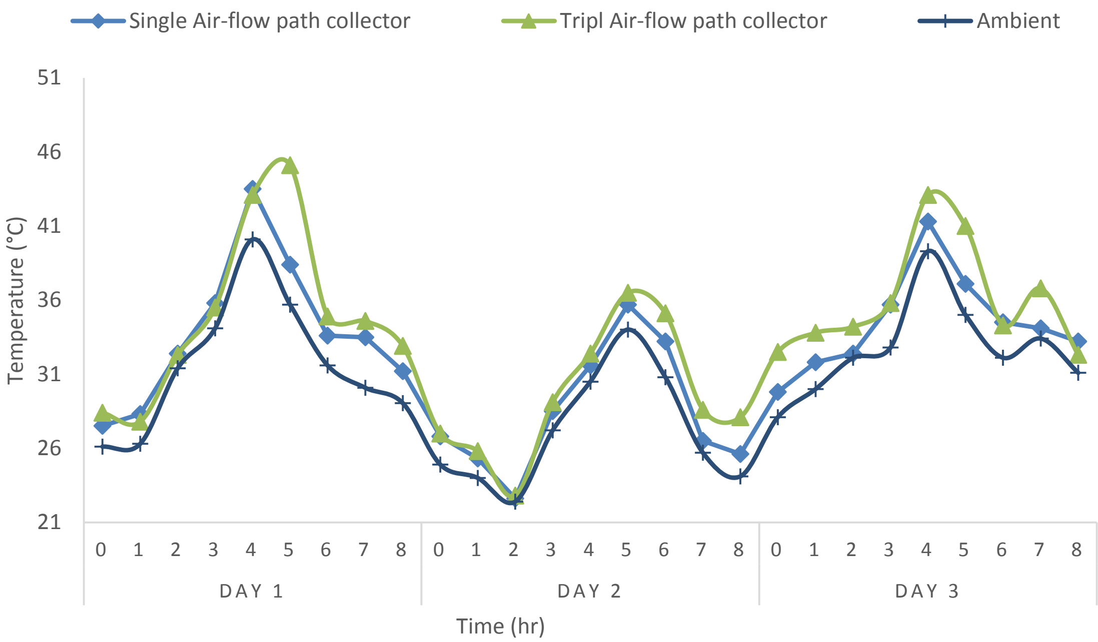


**Figure.4.** Average ambient temperature and temperature of the solar collector.

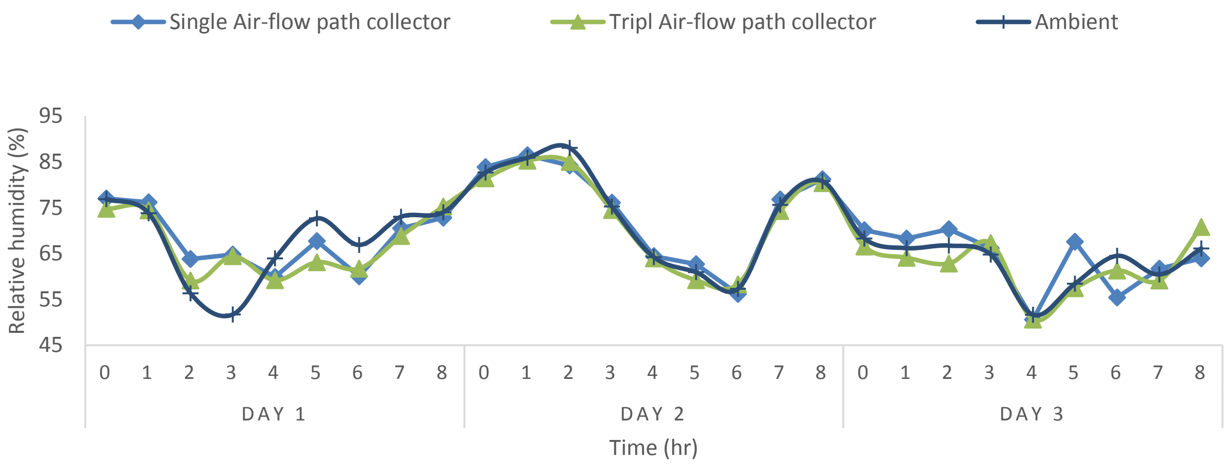


**Figure.5.** Average ambient relative humidity and relative humidity of the solar collectors.

This showed the effectiveness of the multi passageway in the collector to increase the exit air temperature. The implication is that air travelling through the collector is delayed in the collector to absorb more heat. In addition to the residence time of air in the collector, the heat exchange area between air and the collector is also increased when multi passageways are used [21]. The result is similar to those obtained by Mahmood et al [17]. The temperature values are inversely reflected in the relative humidity of the collector with an average difference of 0.15 and 2.18 %, for direct and triple passageway collectors, respectively. Considering the frequent rain in this period with its attendant high humidity in this environment, this is huge and could drive the drying process. Variations in the drying temperature and relative humidity of the drying chamber are presented in Figures 6 and 7. After absorbing moisture from the product, the temperature of the convective air decreased while the relative humidity increased. The average values were 31.2 and 32.63 ºC for single and triple passageway collectors, respectively. Correspondingly, the average relative humidity was 69.10 and 67.92%. The obtained values showed the capacity of multi-air flow collectors over direct pathway collectors. The marginally higher temperature of the triple airflow path collector is the effect of the multi-air flow that increases the collector temperature before entering the drying chamber at a comparatively higher temperature than others.

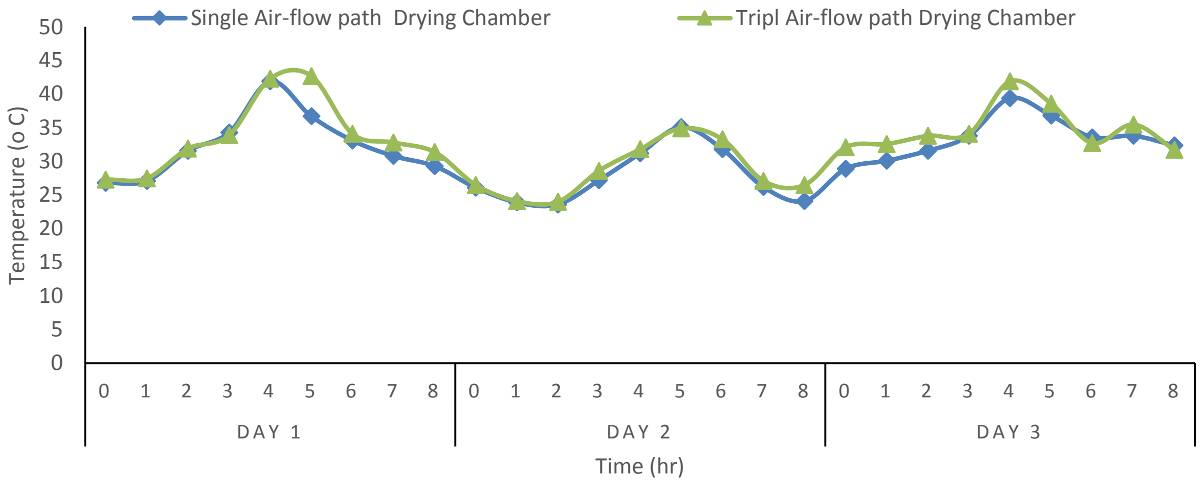


Figure.6. The average temperature of the Drying chamber for the two dryers.

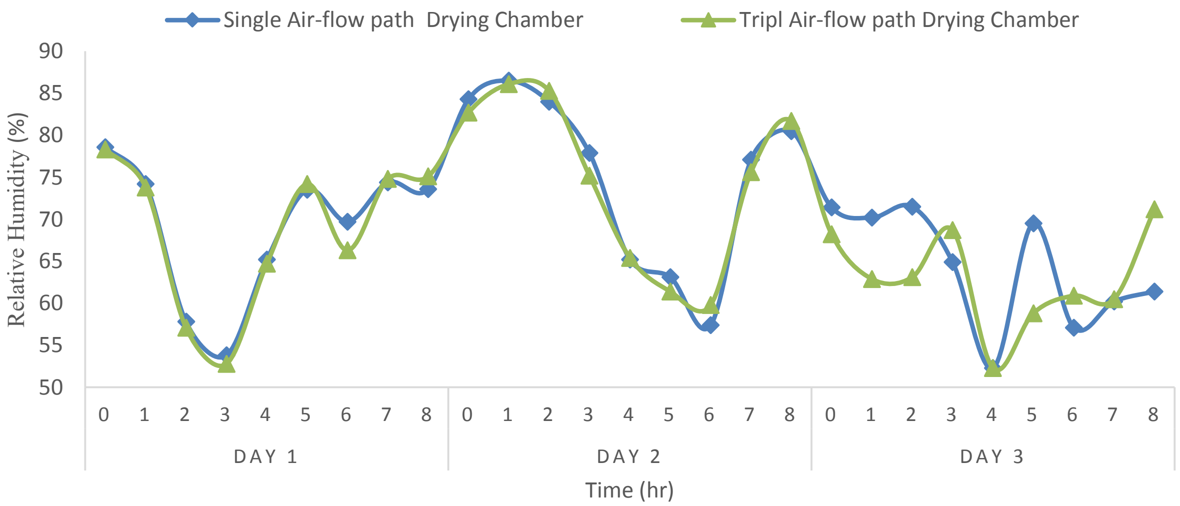


Figure.7. Average relative humidity of the solar drying chamber.

The variation of the collector efficiencies with time is shown in figure 8 below. The figure showed that the triple airflow path collector consistently had higher collector efficiency than the direct air collector. The collector efficiencies showed a significant difference ($p < 0.05$) among the two solar collector designs compared. The average collector efficiency was 7.04 and 15.47 %, respectively, for the direct and triple airflow path collector as presented in Table 1. The lower collector efficiency might be due to higher relative humidity during the drying period. The observed collector efficiency is lower than that obtained by Kesavan and Arujan [18] but their result showed the effect of relative humidity on the collector efficiency. Higher efficiency obtained **by** Kesavan and Arujan [18] can be attributed to the very much lower ambient relative humidity within their study environment. Though, the obtained collector efficiency in this research is within the range for most solar dryers.

However, considering the humidity of incoming air due to occasional rains, this value is encouraging and shows that the multi-airflow path collector design can improve the performance of solar dryers.

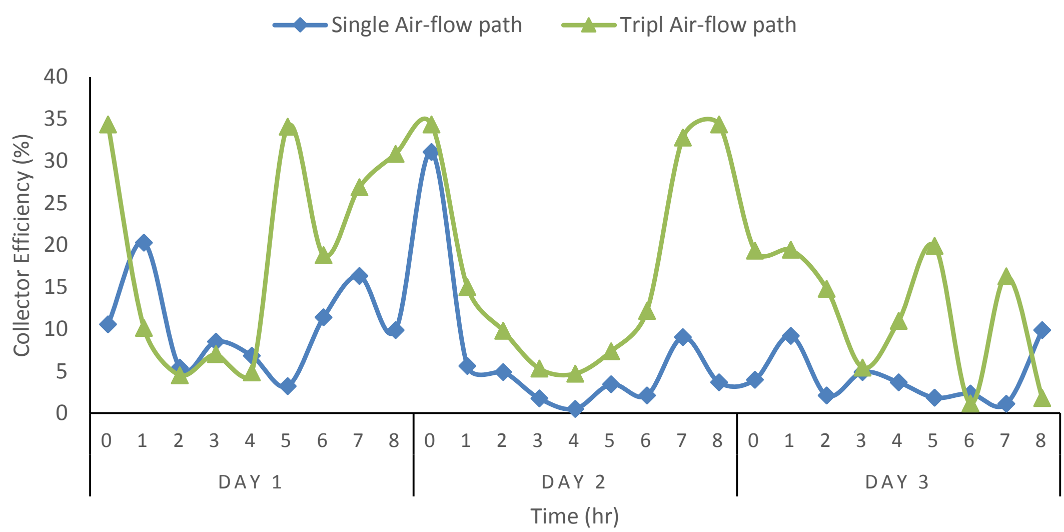


Figure.8. Variation in collector efficiency with time.

The evolution of the drying rate and the moisture content of the Cocoyam slices for three days period (24 hrs drying time) are presented in Figures 9 and 10 for the designed dryers. At the onset, the drying rate of the product was high but decreased with drying time. The evolution of the drying rate was not a smooth curve like isothermal drying due to inconsistencies in weather conditions which affected the temperature and relative humidity that drives the moisture removal process. This is common with solar dryers as shown in the literature [3, 7]. From the figures, comparatively, the triple airflow path dried quicker than direct airflow, though this was not so at the first fours of drying, which might be attributed to the faster reaction time of the direct airflow collector[1]. This is due to consistently higher collector temperature and lower humidity, providing a better thermodynamic condition for moisture transfer. The average drying rate was 19.79 x $10^{-3}$, and 21.96 x $10^{-3}$ kg of water/kg of dried solid per hour, for the direct and triple airflow path collector, respectively. This is reflected in their effective moisture diffusivity presented in Table 1, which varies from 2.97 x $10^{-10}$ $m^2/s$ to 3. 43 x1 $0^{-10}$ $m^2/s$ with the triple airflow path collector exhibiting the highest value. This is advantageous as a high drying rate has been reported to produce a good quality dried product in solar dryers [43]. This shows that the delaying of the air in the collector provides higher thermal mass for faster drying, though it has been reported that thermal mass alone might not be sustainable in drying during inclement weather [44]. The overall drying efficiency for the two systems was 16.06 and 18.61 % for the single and triple airflow path collector, respectively. Although this value is lower than that obtained by Ndukwu et al [7] and Yassiene et al [21] but the values follow the range of drying efficiencies for most solar dryers in the literature [45].

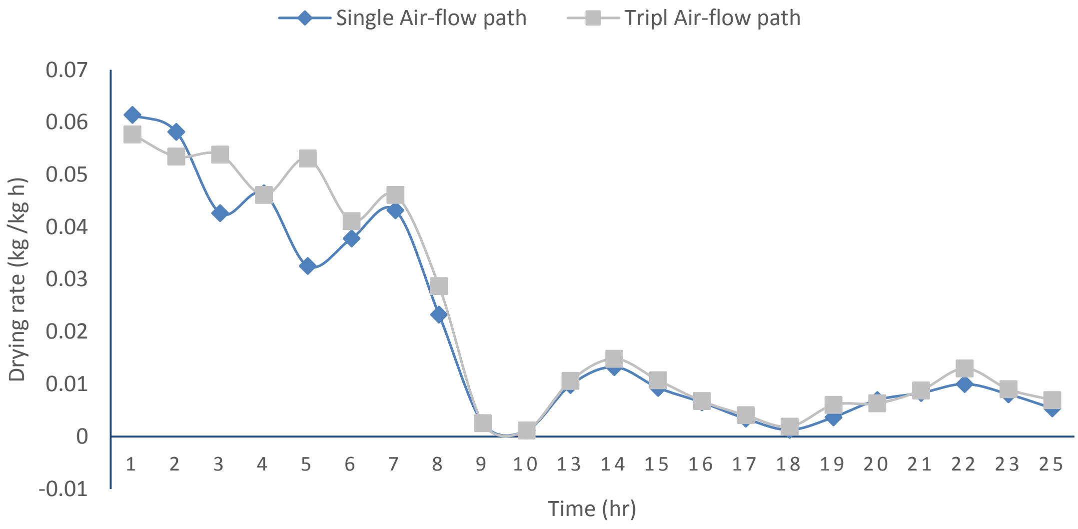


Figure.9. The drying rate of the Cocoyam slice for the three-dryer design.

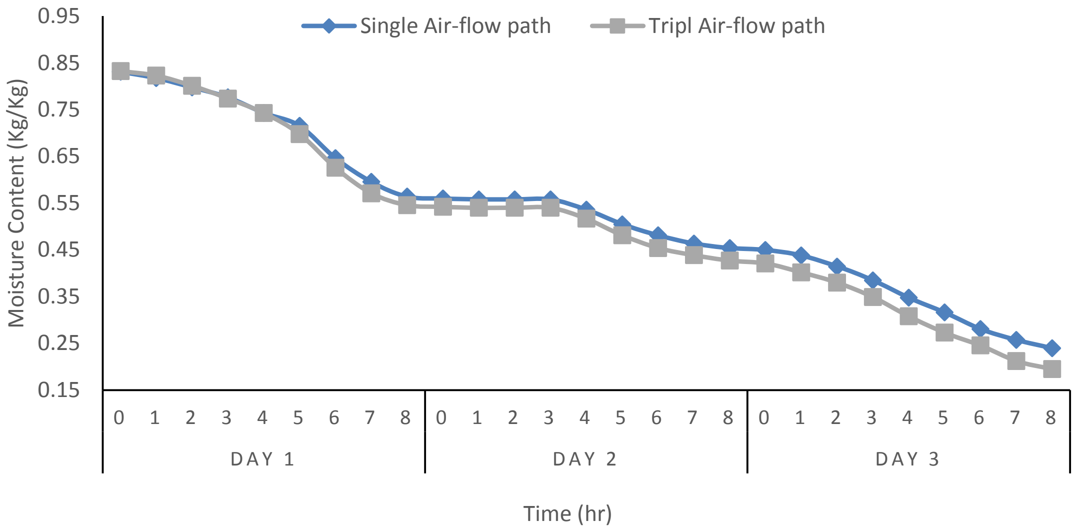


Figure.10. The moisture content of dried Cocoyam.

**3.2 Energy analysis**

Table 1 shows the values of the energy expended by the two dryers. Since drying was stopped simultaneously (after 24 hrs) the energy utilized is almost the same and was determined as 3.976 ±0.009 MJ. However, the energy efficiency of each system is embodied in the specific energy consumption and the specific moisture extraction rate [12]. The direct passage path collector design utilized the above amount of solar energy to remove only 0.301 kg of moisture from the Cocoyam in 24 h hours of drying, while the same amount of energy was used to remove 0.327 kg of moisture at the same time for triple airflow path collector, respectively. It was observed that unfavourable weather conditions affected the performance of the solar dryers. Still, the result obtained revealed the effectiveness of delaying the air in the collector by increasing its passage path through the collector before exiting into the drying chamber. The quality of the energy consumption per kilogram of the dried product is embodied in the specific energy consumption determined as 1.1073 and 1.1033 kWh/kg for single and triple airflow path collectors, respectively. Therefore, the specific moisture extraction rate, which is an indicator of the turnaround effects on energy utilization [3] for drying and has been defined as the amount of energy utilized to remove a kg of water, was obtained as 0.273and 0.296 kg/kW h, for single and triple airflow path collector, respectively.

**Table 1** Summary of the drying performance of the three developed solar dryers

| Parameters | Single airflow path | Triple airflow path |
|---|---|---|
| Initial moisture content on a wet basis (%) | 83.10 | 83.24 |
| Final moisture content on wet basis (kg/kg) | 0.24 | 0.19 |

| | | |
|---|---|---|
| Moisture diffusivity (m/s) | 2.97 x$10^{-10}$ | 3.43 x$10^{-10}$ |
| Average collector efficiency (%) | 7.04 | 15.47 |
| Overall solar drying efficiency (%) | 16.01 | 18.61 |
| Drying time (hrs) | 24 | 24 |
| Weight of water removed (kg) | 0.301 | 0.327 |
| Energy consumed (MJ) | 3.986 | 3.972 |
| Specific energy consumption (kWh/kg) | 1.1073 | 1.1033 |
| Specific moisture extraction rate(kg/kWh) | 0.296 | 0.273 |
| Mass of $CO_2$ saved (tons) | 351.50 | 350.23 |

### 3.3 Exergy analysis

The exergy performance analysis of the three solar dryers is shown in Figure 11, while the exergy loss and exergy efficiency are plotted in Figures 12 and 13, respectively. The exergy flow was affected by the change in the weather conditions. This is common with solar dryers because the collector temperature depends on the available solar radiation that is affected by the vagaries of weather [6]. The range of the exergy stream for the inlet (exin) and the outlet (exout) for the two developed dryers exists within 0.00019 ≤ Exin ≤ 6.646 kW and 0.000 ≤ exout ≤ 3. 485 kW and 0.0553 ≤ Exin ≤ 8.660 and 0.0041 ≤ exout ≤ 4.495 kW with an average value of 1.606 and 0.6123 kW, 2.411 and 1.419 for the inlet and outlet exergy stream of the direct and triple airflow path collector respectively. The range determined is similar to the observed range of exergy for solar dryers in literature [1]. The average exergy loss for the two dryers was 0.9942and 0.9929 kW for direct and triple airflow path collectors. From Figure 13, more exergy loss is a function of the weather too. The high the solar radiation and ambient temperature coming into the collector, the higher the exergy loss. Correspondingly, the average exergy efficiency exists at 38.09 and 58.81 % for single and triple airflow path collectors. The implication is that more energy destruction occurred on the single airflow path collector than on the multi-airflow path collector, requiring more attention. The values are within the range reported in solar dryers using forced and natural convention [46].

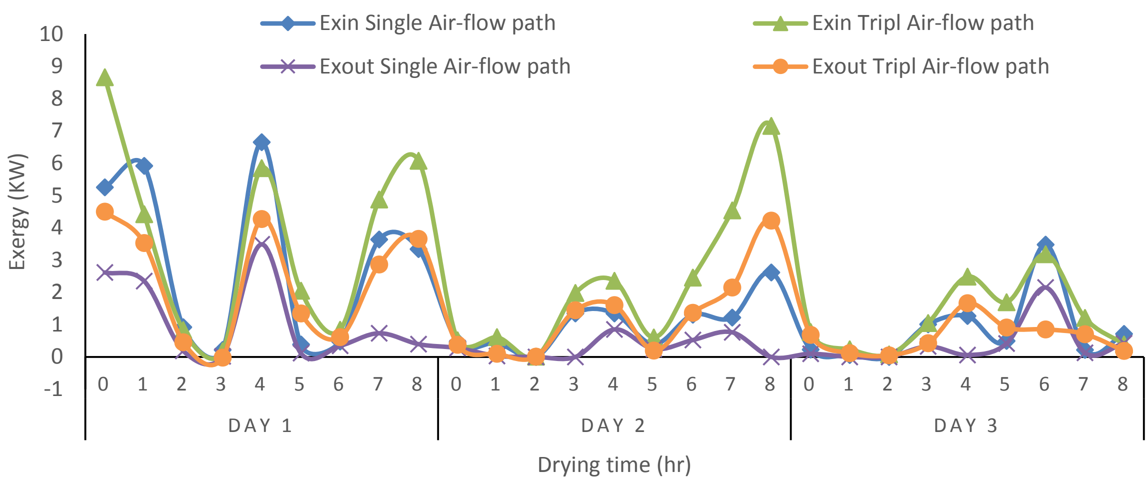


Figure.11**.** Exergy flow stream for the three solar dryers

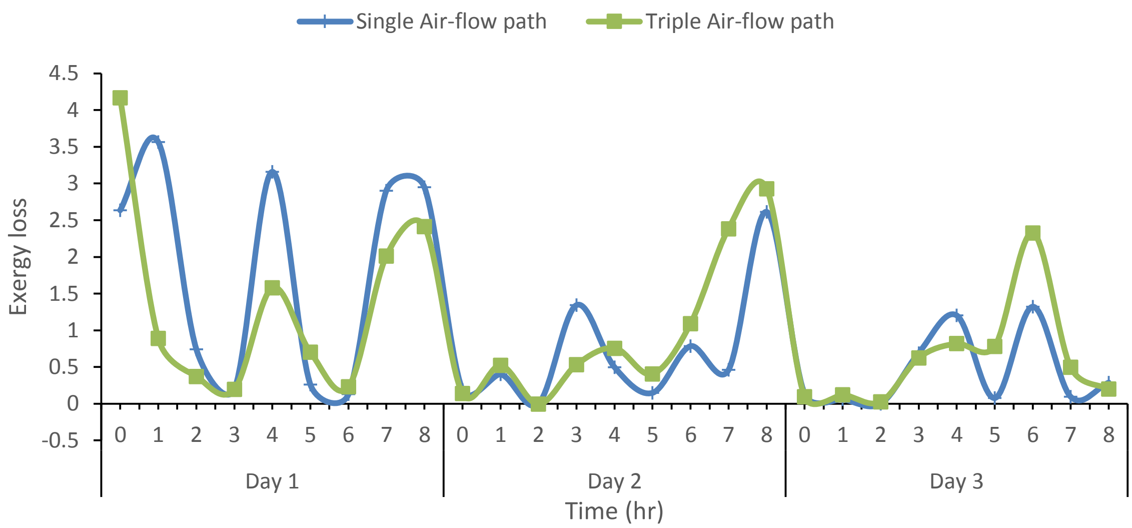


Figure.12. Exergy loss for the three solar dryers

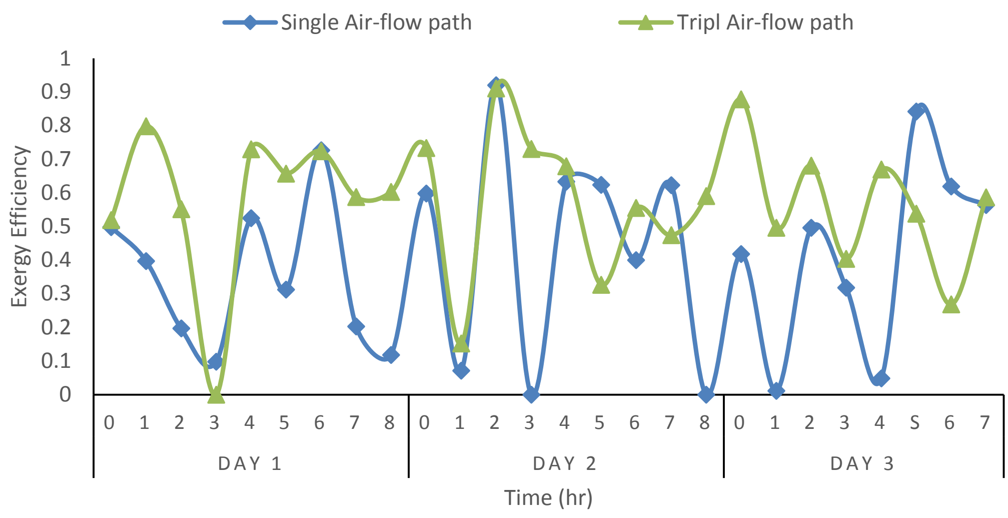


Figure.13. Exergy efficiency for the solar dryers

**3.4 Exergetic Sustainability assessment**

The exergetic sustainability assessment sustainability index adopted for the performance of the solar systems include the waste exergy ratio (Fig.14), improvement potential (Fig.15) and sustainability index (Fig.16) for the solar dryers. The waste exergy ratio compares the extent of exergy loss to the amount of exergy that enters the system. According to Dincer and Rosen [47], this assessment is necessary because of the impact of exergy loss through the evaporated moisture on the thermodynamic equilibrium of the environment. They stated that in the case of solar radiation, this could lead to re-radiation of the solar radiation. The function of the solar collector is to increase the ambient air temperature coming into the collector, making it shade some of its moisture (lower humidity and vapour pressure) which will create a gradient for moisture transfer between the dried Cocoyam and the surrounding air. Through this mechanism, some of the exergies will be lost to the environment with the evaporated moisture. The values of the waste exergy ratio (WER) ranged from $0.020 \leq \text{WER} \leq 1.00$ and $0.000 \leq \text{WER} \leq 1.12$ for single and triple airflow path collectors, respectively. Correspondingly the improvement potential was $7.54\ \text{x}10^{-7} \leq \text{IP} \leq 2.62$ kW and $0.005 \leq \text{IP} \leq 2.003$ kW while the sustainability index, which is a function of exergy efficiency, ranged from $1.00 \leq \text{SI} \leq 6.33$, and $0.00 \leq \text{SI} \leq 8.24$, respectively. The values are within the range obtained by Ndukwu et al [7]. The improvement potential suggests that minimizing losses in the system will improve the performance of the solar dryers [3]. At the same time, the sustainability index depends on the exergy effectiveness of the solar dryers. It shows that the higher the exergy efficiency of the dryers, the more sustainable they will be [26].

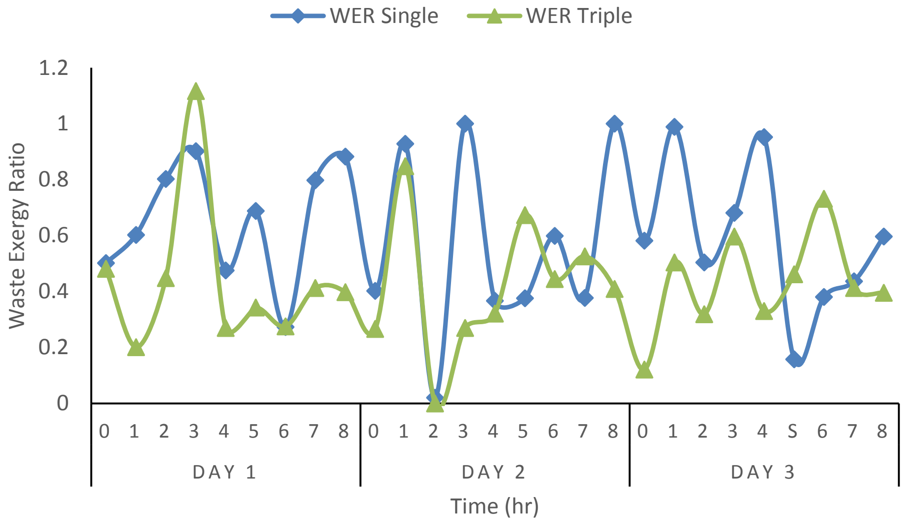


Figure.14. Waste exergy ratio for the solar dryers

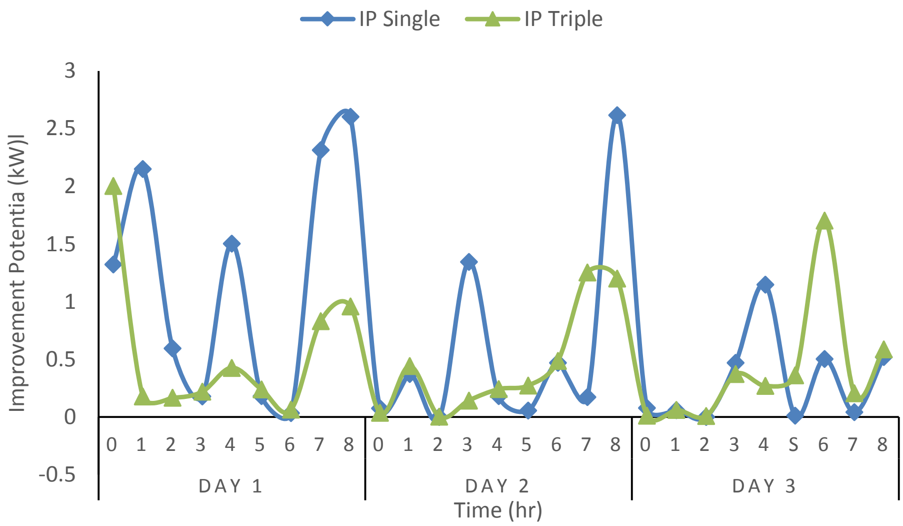


Figure.15. Improvement potential for the solar dryers

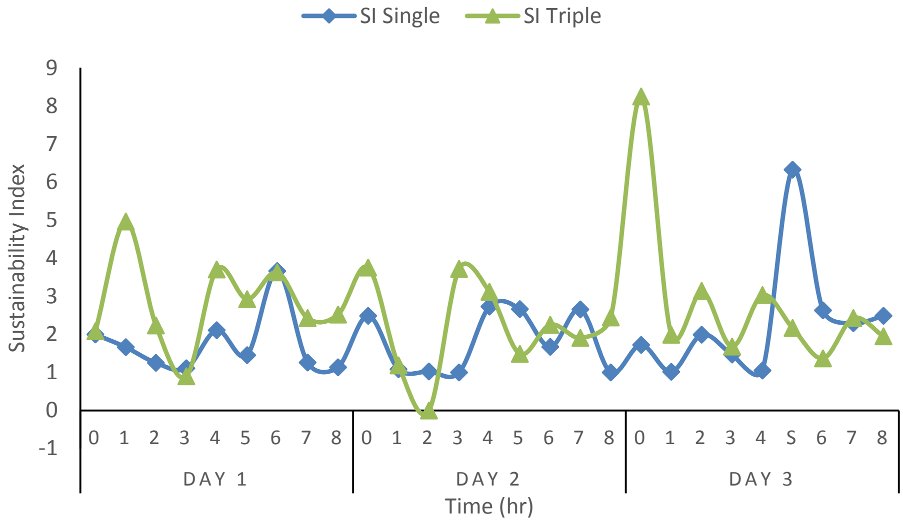


Figure.16. Sustainability index for the solar dryers

### 3.5 Environmental impact analysis

Unlike other drying systems that use fossil fuel or energy derived from fossil fuel, the solar dryer can mitigate greenhouse gas emissions into the atmosphere. Apart from the lack of access to electricity and the high cost of hydrocarbon-based energy sources, limiting $CO_2$ emission is very important to stem the tide of climate change [40]. All these are the reasons for adopting wind energy to power the fan of the analysed solar dryer. Therefore, the comparison of the three driers was made in terms of energy utilized and the amount of $CO_2$ emitted to produce the same amount of energy if a diesel generator, grid-based electricity, or coal is to be used to dry the Cocoyam. The values obtained were presented in figure 17 using the Nigeria scenario in the case of grid-based electricity. The results showed that using coal will mitigate more $CO_2$ into the atmosphere from 9741.334 to 21481. 476 tons of $CO_2$ per year while using a diesel-powered dryer will mitigate 350.09 to 351.50 tons of $CO_2$ per year for three dryer designs. Also, using grid-based electricity will limit the least amount of $CO_2$ in the range of 12.981 to 14.153351.50 tons of $CO_2$ per year. Higher $CO_2$ mitigation for using coal has also been reported by Simo-Tagne et [2]. These values might vary from one country to another due to variations in emission factors for different countries. However, the obtained values for Nigeria give hindsight on the benefit of using this dryer to reduce environmental impact by reducing greenhouse gas emission

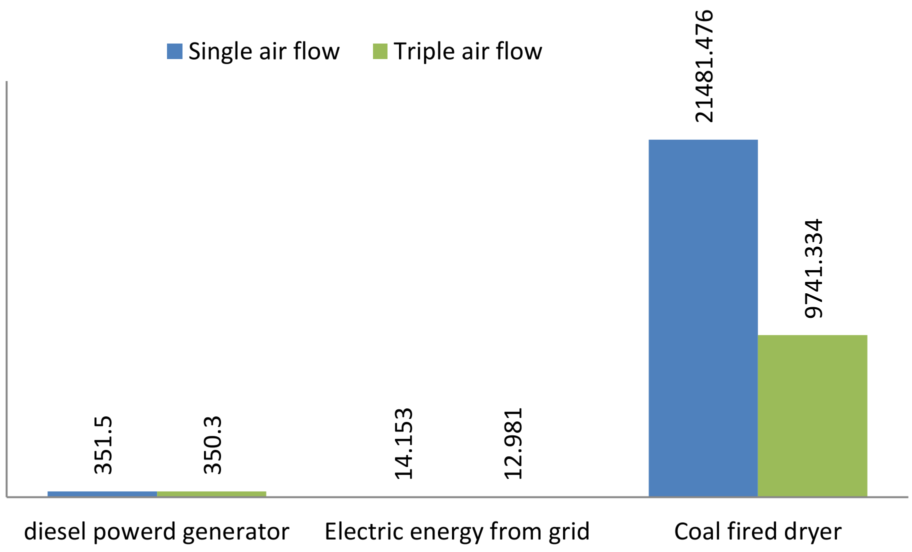


Figure.17. Compared mitigated $CO_2$ emissions for the studied dryers using different heat sources

## 4. Conclusions

The comparative assessment of the performances of the direct and triple air passage paths solar dryers for drying Cocoyam showed that delaying the air through the collectors by increasing the passage path improved the collector and drying efficiency despite the unpleasant weather conditions. This led to an improvement in the collector efficiency by 119.74 % for the triple airflow path collector from the direct airflow collector. This corresponds to overall drying efficiency of 16.06 and 18.61 %, respectively, for the two systems. The average drying rate achieved in the solar dryers strongly demonstrated that the triple airflow path collector exhibited the highest drying rate and moisture diffusivity. Similarly, the triple airflow path collector consumed the least amount of energy and yet facilitated the removal of moisture contents from the Cocoyam compared to the other systems. Also, the average exergy efficiency was 38.09 % and 58.81 % for single, double and triple airflow path collectors, respectively. The values of the waste exergy ratio ranged from 0.020 to 1.00 and 0.000 to 1.12 for direct and triple airflow path collectors, respectively. This represents an improvement potential of $7.54\ X10^{-7}$ to 2.62 kW and 0.005 to 2.003 kW; a sustainability index ranging from 1.00 to 6.33and 0.00 to 8.24 for direct and triple airflow path collectors, respectively. Therefore, using this dryer as a substitute for a diesel-powered generator will limit about 350.09 to 351.50 tons of $CO_2$ from entering the atmosphere which is a strong indicator that solar dryers can help to mitigate the greenhouse effect by reducing the amount of $CO_2$ released into the atmosphere which causes global warming. This study is limited to single-pass collectors only

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