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Design and Fabrication of Solar Dryer for High Potential Agro-Produce in Midwest Region of Nigeria

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Abstract- Solar drying utilizes sun energy to heat air for the drying of materials. It enhances preservation and shelf life of agricultural-produce. The limitations of the conventional open sun drying which include direct exposure to sun rays, animal attack, improper hygiene and unpredictable rainfall, necessitated the development of a forced draft solar dryer to mitigate such setbacks using locally sourced materials. The produced dryer comprises of solar collector, fan and drying chamber with tray racks. Air from the DC powered fan is heated up in the collector and channelled to the drying chamber where it aids drying. Design and analysis were done with consideration of the geographical region and period under review. Meteorological data for relative humidity, solar irradiation, wind speed and ambient temperature were obtained using standard equipment. The topography, direction, and maximum solar irradiance impinging on the solar collector were determined by measuring the angle of tilt which was a major factor in the drying process. Test procedures carried out with drying of yam, cassava and plantain chips within the given period showed that average temperature of the dryer was 45°C and average ambient temperature was 39.4°C. Drying was completed in 2 to 3 days with the dryer, while open sun drying was completed in 5 or more days. Fabrication and testing of the machine was carried out in a given planting and harvesting period (October to December) in the Midwest southern region of Nigeria hence, data recorded for the period under review will be helpful to farmers in forecasting weather trends and enable them carry out agricultural processing effectively. The rapid rate of drying in the dryer showed it is efficient in the drying of agricultural produce.

Keywords Solar drying, solar irradiance, temperature, humidity, south Nigeria.

1. Introduction

Drying is one of the oldest methods of food preservation. For many years, people have been preserving agricultural produce by drying until caning was developed at the end of the 18th century (Ekechukwu and Norton, 1997). The importance of dried foods cannot be overestimated as the kitchens and food stores in any country will confirm the quantity and diversity of dried food in use. Drying is essentially a process of moisture removal due to simultaneous heat and mass transfer. It is a classical method of food preservation which provides longer shelf life, lighter weight for transportation and small space for storage. Drying could be of various methods such as open sun drying, direct and indirect solar drying etc. Open sun drying is the most commonly used method to preserve agricultural produce such as grains, fruits and vegetables in most developing countries, which have abundant sunshine. Such drying under hostile climatic conditions leads to severe losses in the quantity and quality of the dried produce. These losses are due to contamination by dirt, dust, bird droppings and infestation by insects, rodents and animals as well as the quality of the produce being degraded due to uncontrolled heat in open sun drying even up to the extent that the food produce becomes inedible (Hii et al., 2012). Therefore, the introduction of solar dryers in developing countries can reduce crop losses and improve the quality of the dried produce significantly when compared to the traditional method. Solar dryers could be either natural or forced convection type. The mechanical solar dryer is such that it controls the drying process and protects the agricultural produce from contamination by insects, dust, bird droppings, invasions by animals, and in comparison to open sun drying, it generates higher temperature, lower relative humidity, lower produce moisture content and reduce spoilage during drying process. Forced convection dryer essentially consist of a blower, that forces the air through the collector into the drying chamber, and Indirect-mode forced dryers essentially consists of an air heater or absorber cover with glass, drying chamber, and a blower or fan to duct the heated air to the drying chamber (Hii et al., 2012). Sun light, like other energy sources such as wind, rain, tide and geothermal are renewable energy which is energy generated from natural resources that are continually naturally replenished. The sun which is the source of solar radiation is a continuous fusion reactor. Solar energy is essentially black body radiation corresponding to a temperature of about 6000k and is therefore of high thermodynamic quality (Faninger, 2010). Solar thermal technology uses the sun's energy, rather than fossil fuels, to generate low-cost, environmentally friendly thermal energy. This energy is used to heat water or other fluids, and can also power solar cooling systems. The greatest advantage of solar energy as compared with other forms of energy is that, it is clean and can be supplied without environmental pollution. Over the past century, fossil fuels provided most of our energy, because these were much cheaper and more convenient than energy from alternative energy sources, and until recently, environmental pollution has been of little concern (Soteris, 2009). In Nigeria, solar thermal has been developed for various applications; some of these are solar cookers, solar pulverizer, chick brooding devices and drying of crop produce. Regarding the drying of Agricultural produce, there are four major drying techniques namely: open air drying, fire wood/fuel drying, electrical drying and solar drying (Akinboro et al., 2012). The National Energy Policy Document 2010, states that Nigeria lies within a high sunshine belt and within the country; solar radiation is fairly well distributed. The annual average of total solar radiation varies from about 12.6 MJ/m2 per day (3.5 kWh/m2 per day) in the coastal latitudes to about 25.2 MJ/m2 per day (7.0 kWh/m2 per day) in the far North. Assuming an arithmetic average of 18.9 MJ/m2 per day (5.3 kWh/m2 per day), Nigeria therefore has an estimated 17, 459, 215.2 million MJ per day (17.439 TJ per day) of solar energy falling on its 923,768 km2 land area.

2. Methodology

The solar dryer consists of a fan for a forced draft of air to the drying chamber through the collector. Different concepts of solar dryers were considered and evaluated for possible flaws. Selection of the material to be used was carefully done to meet operational standards and specifications of the dryer. Mathematical calculations and experiments were done to obtain design and operational variables. Specific weather conditions that influence the drying process were measured and recorded. The data acquired were put into graphical form for ease of interpretation.

2.1. Measurement of Weather Conditions

Weather conditions which affect the rate of drying were measured for their average values in Benin City. They include; Solar Irradiance, Relative Humidity, Orientation, Wind Speed, Ambient Temperature

The various standard measuring devices used for the various experimental measurement are listed in Table 1.

Table 1. Description of proposed distribution feeder.

DATA	MEASURING INSTRUMENT	ACCURACY
Solar Irradiance	Solar seaward 200R	100-1500 W/m^2
Wind Speed	Extech 3-in-1	≤937ft/min: ±3%F.S.
Humidity	Extech 3-in-1	±4%RH (from 10% to 70%RH)
Orientation	Solar seaward 200R	0^0 to 360^0
Ambient Temperature	Solar seaward 200R	±(1% to 1^0C)

3. Design of the Solar Drying System

Various concepts were developed and considered with respect to some key criteria which include the cost of production, efficiency, hygiene, operational cost, material availability, safety requirement, and weight. Haven considered various concepts through a decision matrix the forced draft solar dryer shown in Figure 1 was adopted.

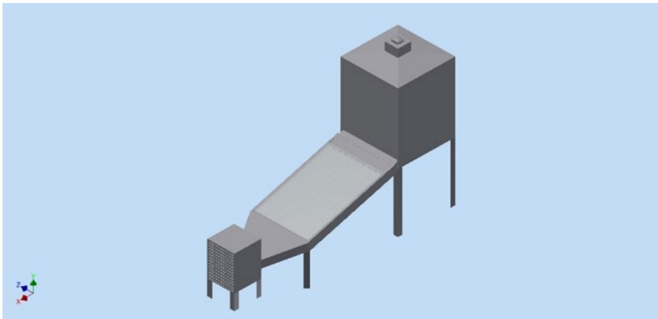

Fig. 1. Forced draft solar dryer.

3.1. Design Nomenclature

M_{air} = Mass of air (kg)

$\dot{m}_{air}$ = Mass flow rate of air (kg/s)

ρ = Density of air

α = Absorptance of glass cover

Va = Volume of air (m3)

Nu = Nusselts Number

FR = Heat removal factor

h = Heat Coefficient W m2/k

Ac = Area of solar collector (m2)

M = Moisture content

Mf = Final moisture content

ηc = Collector Efficiency

Re = Reynolds Number

K = Thermal conductivity

Ic = Solar insulation (MJ/m2/day)

ύ = Volume flow rate of air (m3/sec)

Wf = final weight of plantain(g)

Wl = initial weight of plantain (g)

WT = Total weight of plantain in dryer (kg)

Lc = Characteristic length of collector (m)

3.2. Angle Of Tilt (B) of Solar Collector/Air Heater

The angle of tilt (β) of the solar collector is given as

$$\beta = 100 + \text{lat.}\Phi \quad (1)$$

Where lat. Φ is the attitude of the collector location, the latitude of Benin where the dryer was designed is latitude 60N.

Hence, the suitable value of β use for the collector:

$$\beta = 10 + 6 = 160° \quad (2)$$

3.3. Dryer Efficiency

$$The\ dryer\ Efficiency\ (\eta d)(\%) = \frac{work\ output}{work\ input} x\ 100 \quad (3)$$

Where (work output) is the final mass of the crop after drying and (work input) is the initial mass of the crop before drying.

3.4. Moisture Content (M.C.)

The moisture content is given as:

$$Mc = Mi - Mf \quad (4)$$

Mi = mass of sample before drying

Mf = mass of sample after drying.

3.5. Moisture Loss

The Moisture Loss is given as

$$(Mi - Mf)(g) \quad (5)$$

Mi is the mass of the sample before drying

Mf is the mass of the sample after drying.

3.6. Moisture Extraction Rate (M. E. R.)

$$M.E.R = \frac{Mi - Mf}{drying\ time\ (t)} \quad (6)$$

3.7. Collector Efficiency

$$\eta c = \frac{\rho CpV\Delta T}{IcAc} \quad (7)$$

3.8. Energy Losses from The Collector

$$Q_{loss} = \frac{T_p - T_a}{R_l} = U_l A_c (T_p - T_a) \quad (7)$$

3.9. Design Parameters

Area of one tray = 71cm×47.5cm = 3372.5cm2

Total weight of plantain chips in the dryer = 1792 g

Heat capacity of Mild steel = 0.62J/kg

Expected Moisture content after drying = 35%

Humidity ratio at dry bulb temperature = 0.0146kgH20/kg of dry air

Humidity ratio after water absorption = 0.027kgH20/kg of dry air

Change in humidity ratio = 0.027 – 0.0146 = 0.0124kgH20/kg of dry air

FR = Heat Removal factor of flat plate collector = 0.5 Garg (1987)

3.10. Determination of Moisture Content

To obtain the moisture content of dried plantain it was necessary to obtain the weight difference between wet and dried Plantain. In achieving this, an open sun drying was done in order to obtain the dried weight. In this experiment, 3 days' open sun drying with Plantain chips of almost regular thickness of 3mm were dried for 8hrs. the weight of the plantain chips before and after drying were determined as shown in Table 2.

Table 2. Determination of mean weight.

Sample no.	Wet weight (g)	Weight after 1st Day (g)	Weight after 2nd Day (g)	Weight after 3rd day (g)
$\sum$(W)	440	256	183	163

Moisture content,

$$M = \frac{Mi - Mf}{Mi} \times 100\%$$

$$= \frac{440 - 163}{440} \times 100\% = 62.95\%$$

Therefore, the mass of water to be removed

$Mw = W_i(M)$ = 440 x 0.6295 = 276.98g

Total energy required for evaporation of water (Abdullahi et al. 2013).

$$Q_T = MwL$$

= 276.98×2800 = 775544 J = 775.544 KJ

3.11. Mass of Air Required For Drying

$$\text{Mair} = \frac{\text{mass of water}}{\text{change in humidity ratio}}$$

$$= \frac{0.27698kg}{\frac{0.0124kgH_20}{kg}\ dry\ air}$$

$$= 22.337 \text{ kg of air} \quad (8)$$

3.12. Volume of Air

The volume of air required was determined using the gas law.

$$PV_a = M_{air}RT \quad (9)$$

$$V_a = \frac{M_{air}RT}{P}$$

$$\frac{22.337 \times 0.291 \times 312}{101.3} = 20.02\ m^3$$

3.13. Collector Efficiency

The calculation of collector efficiency was done using Hottel-Whiller Bliss equation.

$$\eta = F_R\tau\alpha - F_R h\frac{T_e - T_a}{I_c} \quad (10)$$

η, the transmittance of a glass cover for solar radiation depends on the angle of incidence. From interpolation, the value of transmittance ɽ at 160 solar collector inclination was given as,

$$\tau = 0.87$$

The absorptance α of the black plate for solar radiation also depends on the angle of incidence. Also by interpolation, the value of absorptance at 160 solar collector inclination is given as,

$$\alpha = 0.9$$

3.14. The Average Solar Radiation

From solar radiation in table 4.2, the average solar irradiation Ic is given as 496.85 W/m2 = 30.05MJ per day.

3.15. Reynolds Number

$$\text{Re} = \frac{\rho VLc}{\mu} \quad (11)$$

From steam table (Rogers and Mahew) at 600C, the density of air;

325^0k	1.086
318^0k	ρ
300^0k	1.177

By interpolation, ρ =1.11148 kg/m3

From steam table, dynamic viscosity air μ is;

325^0k	$1.962(10^{-5})$
318^0k	μ
300^0k	$1.846(10^{-5})$

By Interpolating;

$\mu = 1.92952 \times 10^{-5}$ kg/m^3

$$\text{Re} = \frac{1.11148.\times 2.0 \times 1.0}{1.92952.\times 10^{-5}}$$

= 115207.9274

3.16. Nusselt Number

The Nusselt Number Nu = 0.90Re0.23

= 176.947

3.17. Heat Coefficient

$$h = \frac{Nu\ K}{Lc} \quad (12)$$

From steam table; the value of Thermal conductivity was obtained by interpolation.

325^0k	$2.816(10^{-5})$
318^0k	K
300^0k	$2.624(10^{-5})$

giving k = 2.76224 (10-5) KW/m2

$$h = \frac{Nu\ K}{Lc}$$

$$h = \frac{176.947 \times 2.76224 \times 10^{-5}}{1.0}$$

= 4.8877 W/m^{2}k

The collector efficiency was calculated as;

$$\eta = F_R\tau\alpha - F_R h\frac{T_e - T_a}{I_c}$$

$$\eta = 0.5 \times 0.87 \times 0.9 - 0.5 \times 4.8877 \times \frac{45 - 40}{496.85}$$

$$= 0.3669$$

$$= 36.69\%$$

3.18. Velocity of Air Flow

The velocity of air flow was measured using the extech 3-in-1 measuring instrument and gotten to be 2.0m/s.

3.19. Mass Flow Rate

The main flow rate, as determined by

$$\frac{\text{Mass of air}}{\text{daily drying time}} \tag{13}$$

Taking 8-hour sunshine period

$$\dot{m} = \frac{\frac{22.337}{8 \times 60 \times 60} kg}{s}$$

$$= 7.7559 \, x \, 10^{-4} \frac{kg}{s}$$

3.20. Volumetric Flow Rate

The volumetric flow rate is given as

$$\dot{V_a} = \frac{\dot{m}_{air}}{\rho} \tag{14}$$

$$\dot{V_a} = \frac{7.7559 \times 10^{-4}}{1.11148}$$

$$= 6.978 \, x \, 10^{-4}$$

3.21. Area of Inlet Vent

The Area of vent was determined by the formulae presented by (Abdullahi et al. 2013).

$$\text{Area of inlet } = \frac{\text{volumetric flow rate}}{\text{Air velocity}} \tag{15}$$

$$= \frac{7.7559 \times 10^{-4}}{2}$$

$$= 3.87795 \times 10^{-4}$$

4. Results

From the experiment and the mathematical analysis carried out, the table of results for the average weather conditions for solar irradiance, relative humidity, orientation, wind speed and ambient Temperature for weather and solar dryer conditions during the period under review are shown in Tables 3 and 4 respectively. From table 4.2 the total averages for solar irradiation, drying chamber temperature and ambient temperature are 497.963W/m2K, 450C and 39.40C respectively. Graphs showing ambient and solar dryer conditions comparison curves for relative humidity against time, wind speed against time, solar irradiation against time, drying chamber temperature against time and ambient temperature against time are shown in figures 2, 3, 4, 5 and 6 respectively

Table 3. Average daily weather readings for relative humidity and wind speed.

	OCTOBER		NOVEMBER		DECEMBER	
TIME	RELATIVE HUMIDITY(%)	WIND SPEED (m/s)	RELATIVE HUMIDITY(%)	WIND SPEED (m/s)	RELATIVE HUMIDITY(%)	WIND SPEED (m/s)
8AM	55.15	0.2	57.05	0.1	62.10	0.1
9AM	42.55	1.7	40.25	1.6	43.3	1.8
10AM	28.05	1.8	30.15	1.6	31.95	2.26
11AM	17.10	1.3	21.45	2.2	27.65	1.0
12AM	9.85	1.9	17.45	2.0	18.55	1.6
13PM	12.30	0.9	16.75	0.9	16.35	1.8
14PM	14.0	1.4	17.25	2.4	18.05	1.5
15PM	21.6	0.7	28.00	1.4	25.7	1.9
16PM	18.3	1.0	20.6062.1	1.6	21.2	1.5
Average	24.3222	1.2111	27.6611	1.5333	29.4277	1.5333

Table 4. Averaged daily readings for solar irradiation, solar dryer and ambient temperatures.

Time	OCTOBER			NOVEMBER			DECEMBER		
	Solar irradiation (W/m^2K)	Drying chamber temp (^0C)	Ambient temp (^0C)	Solar irradiation (W/m^2K)	Drying chamber temp (^0C)	Ambient temp (^0C)	Solar irradiation (W/m^2K)	Drying chamber temp (^0C)	Ambient temp (^0C
8AM	225	26	28	103	24	25	219	27	28
9AM	290	32	34	306	32	35	317	38	32
10AM	300	35	38	471	40	41	303	38	37
11AM	697	46	37	715	48	43	717	48	44
12PM	738	51	43	777	54	47	7999	50	46
13PM	740	52	42	794	55	42	829	56	50
14PM	667	52	43	668	55	49	630	55	51
15PM	473	49	40	469	50	40	430	52	47
16PM	251	43	37	211	42	36	306	49	42
Average	486.7778	42.8889	38	501.5556	44.4444	38.7779	505.5556	45.8889	41.5556

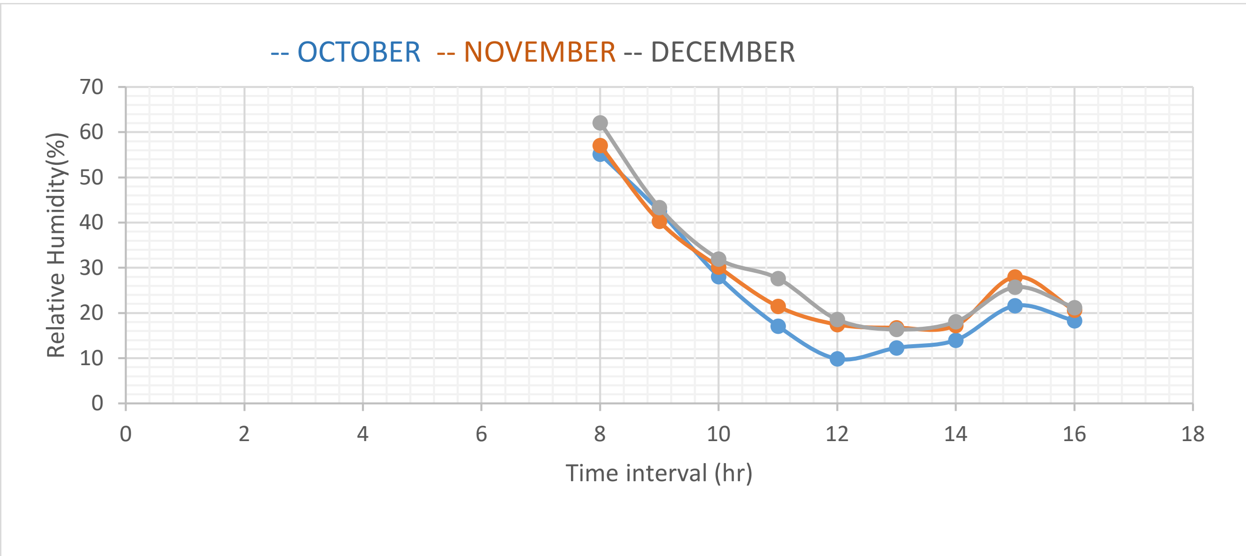

Fig. 2. Graph of average daily relative humidity against time for 3 months.

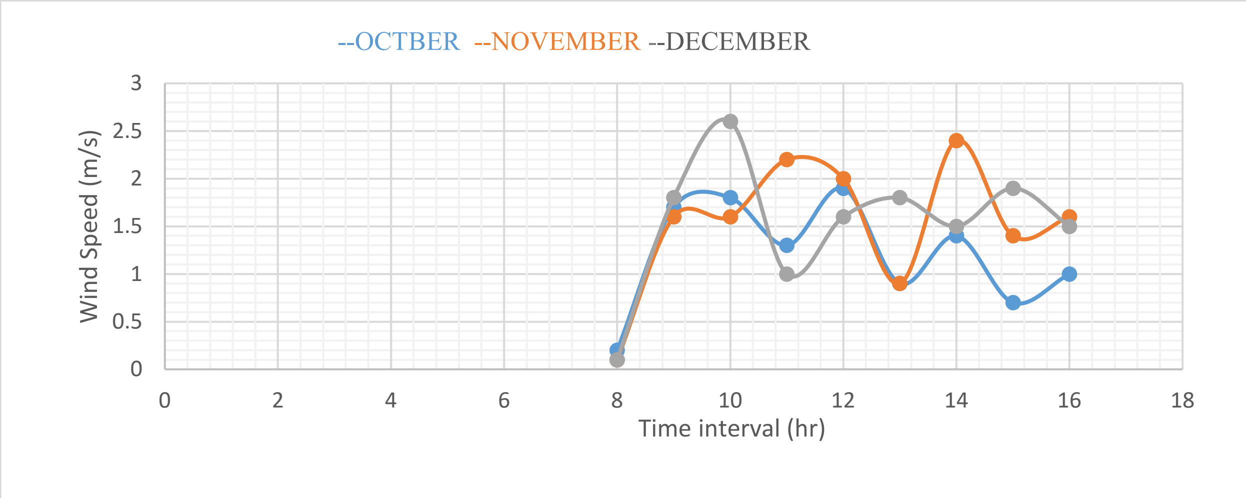

Fig. 3. Graph of wind speed against time.

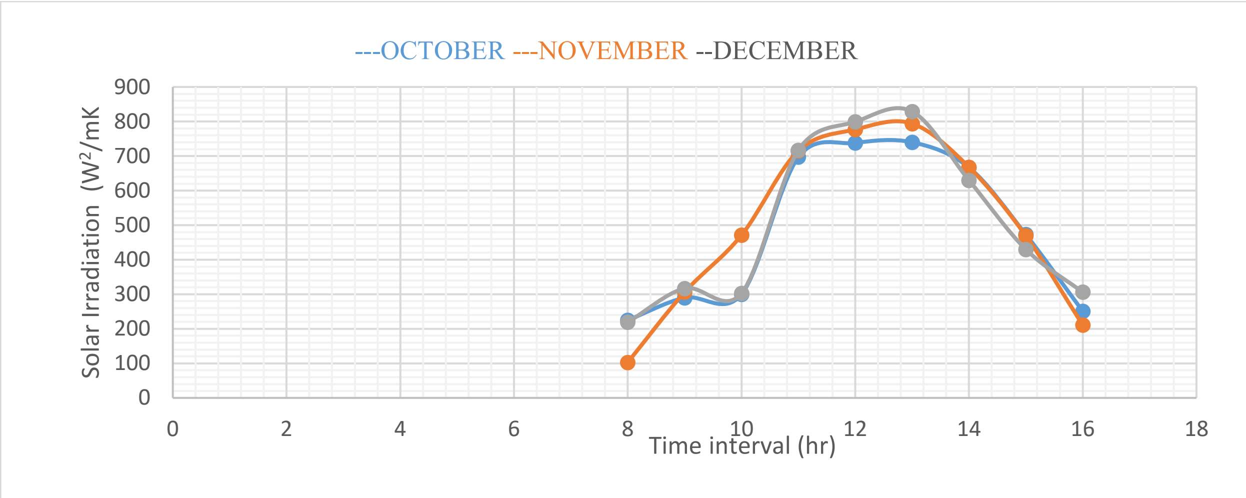

Fig. 4. Solar Irradiation against Time.

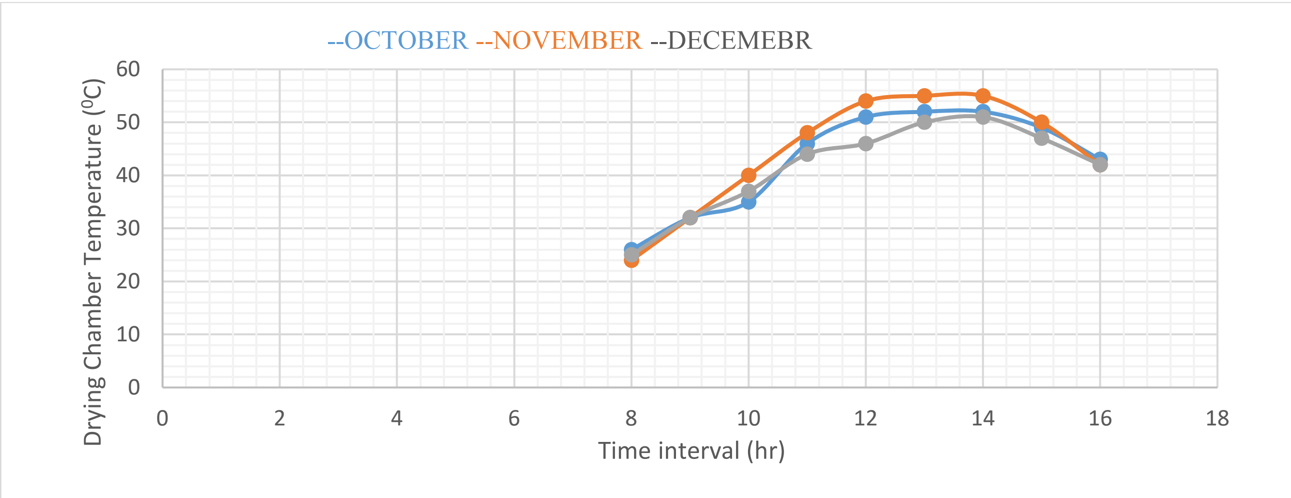

Fig. 5. Drying chamber temperature against time.

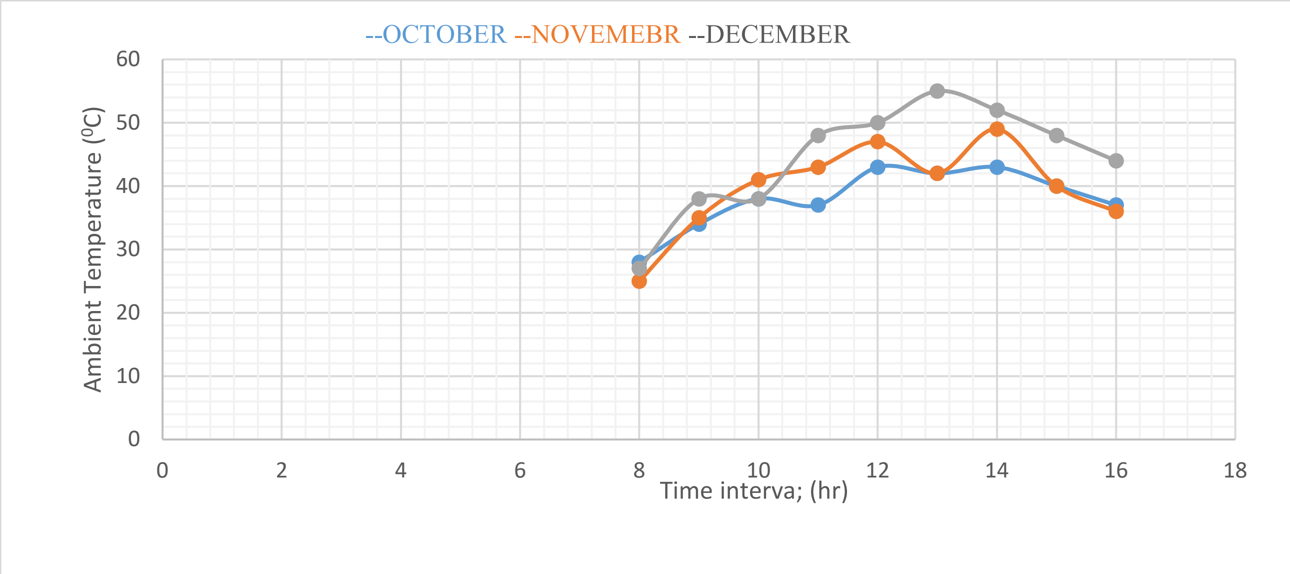

Fig. 6. Average ambient temperature against time.

The weather conditions during the testing of the solar dryer were measured and tabulated as shown in Tables 2and 3. with comparative graphs of key variables as shown in Figures 2 to 6 which compared the averaged weather conditions for the three-months drying period under review. From the graph in Figure 2, it can be inferred that the relative humidity is highest in the early hours (morning) of the day making the ambient air more saturated with moisture. With a decrease in the relative humidity during mid-day the drying process takes place rapidly. From figure 3, it can be inferred that the wind speed fluctuates unpredictably. However, an average wind speed of 1.426 m/s is inappreciable and inadequate for open sun drying. This is mitigated in the solar dryer by the use of a forced draft to create higher volume flow rate of air at entry into the drying chamber with a consequential effect of rapid moisture lost and drying. Figure 4 shows the relationship between solar irradiation and time. From the graph, it was observed that the highest solar irradiation occurred at midday between 12pm and 1pm. The drying chamber temperature therefore peaked at midday as evident from the peak of the curve. One may therefore assert that the drying chamber temperature is directly affected by the amount of solar irradiation. The variation of ambient and dryer temperatures with time is represented in Figures 5 and 6 respectively. It was observed that both temperatures rise through the day as the sun rises and tends to drop as the sun sets during evenings. However, from a direct comparative curve between dryer temperatures and ambient temperatures shown in Figures 7, 8 and 9 for the months of October, November and December, 2019 respectively, it was observed that ambient temperatures are usually lower than the temperature in the drying chamber beginning from periods of the days when the sun rises. The magnitude of the ambient and dryer average temperature difference was noticeably not very high, which may be due to losses in the drying chamber arising from convection current leakages, conduction through metal walls without adequate lagging and radiation loses.

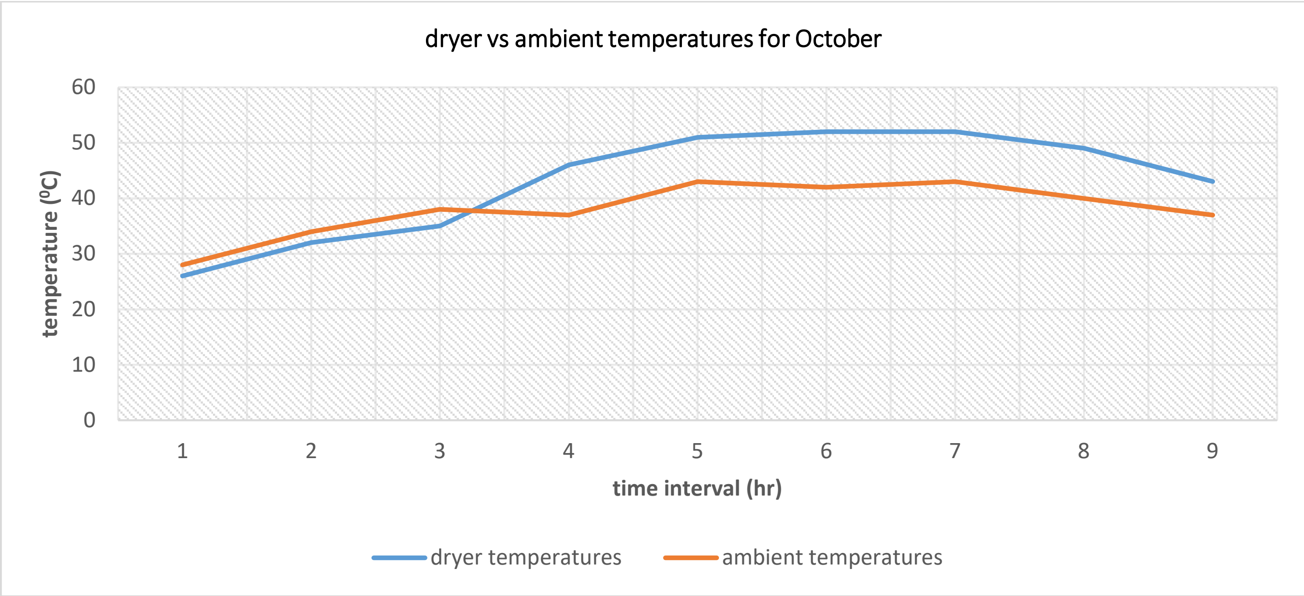

Fig. 7. Average dryer/ambient temperature comparison for October 2019.

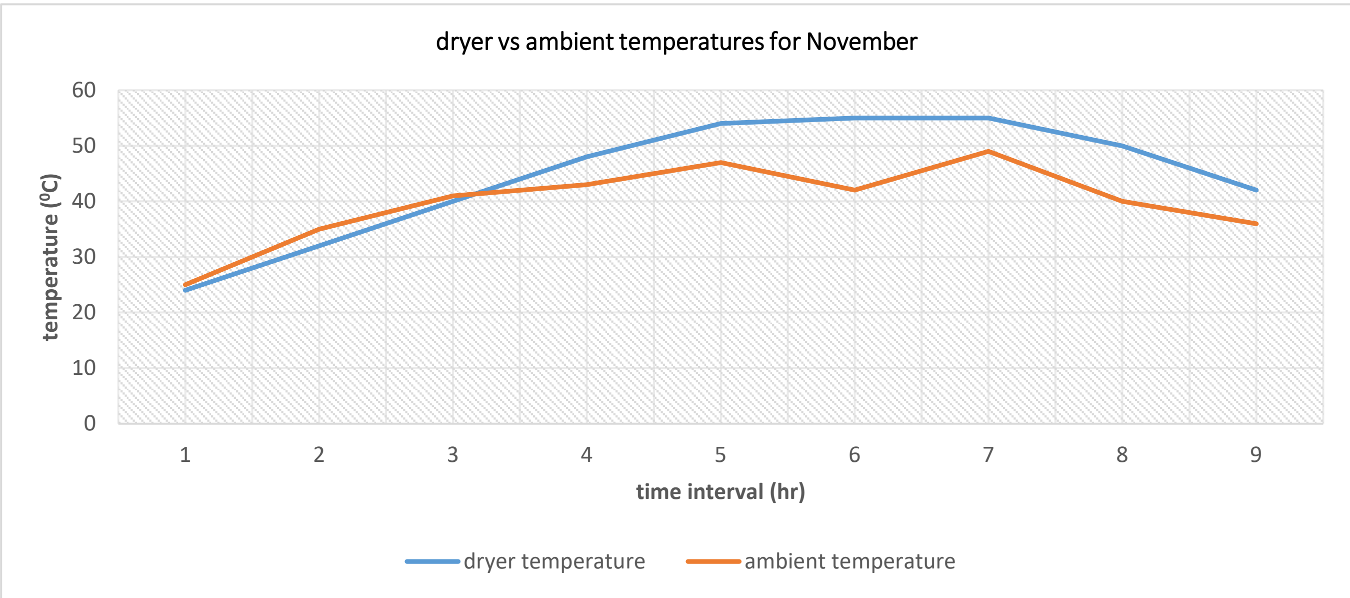

Fig. 8. Average dryer/ambient temperature comparison for November 2019.

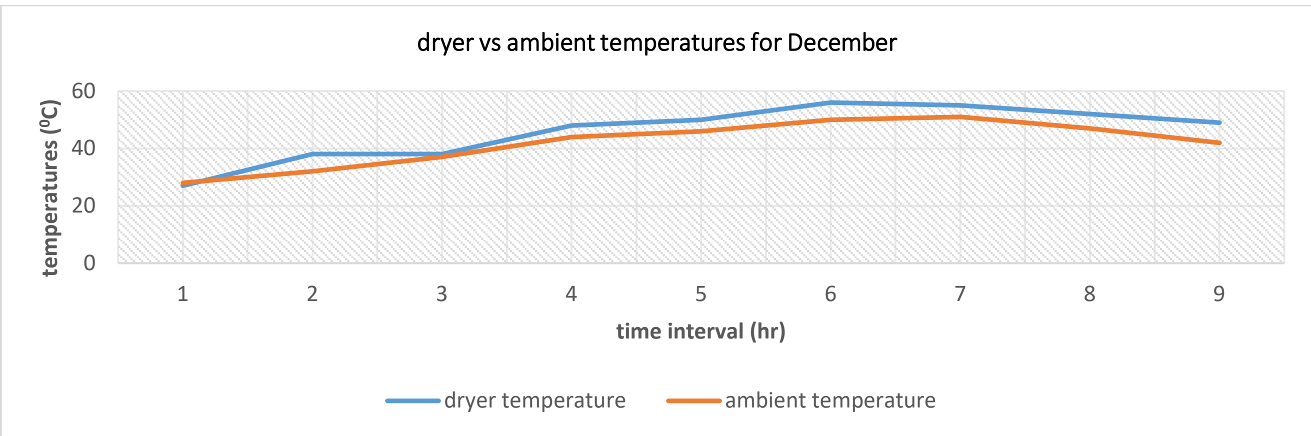

Fig. 9. Average dryer/ambient temperature comparison
for December 2019.

4.1. Daily Mass Readings

Tables 4.9 and 4.10 show the mass readings taken at the beginning and at the end of each day for the open sun drying and solar dryer respectively. It can be observed from the tables that little or insignificant drying occurred on the third day.

Table 5. Daily Mass Readings for Open Sun Drying.

Period (days)	Day 1	Day 2	Day 3	Day 4	Day 5
Weight (g) Before drying	1101	791	622	552	483.2
Weight (g) after drying	790	620	552	483	483

Table 6. Daily Mass Readings for Solar Dryer.

Period (days)	Day 1	Day 2	Day 3
Weight (g) Before drying	1101	543	464
Weight (g) after drying	544	464	464

4.2. Mass of Water Lost

Total weight of water lost

Open sun drying: 1102- 483 = 619g

Solar Dryer: 1101 – 464 = 637g

Percentage of moisture content removed

Open sun drying: 619/1102 ×100 = 56.17%

Dryer: 637/1101 ×100 = 57.86%

4.3. Drying Time

The drying was carried out over a period of 3 days. It was observed that most of the drying was done in the first day for both open sun drying and the solar dryer. The drying process was completed in two days in the dryer for agro materials with lower initial moisture content such as unripe plantain and three days with agro materials with higher water content such as old yam and cassava. The open sun drying was completed in minimum of five days under the same prevailing weather conditions for the concurrent drying process with the solar dyer. This further explains and proves that the solar dryer was more efficient for agro material drying.

5. Conclussion

The fabricated solar dryer shown in Figure 10 was effective in the drying of agricultural food produce such as plantain, yam and cassava chips. Its use has various advantages compared to the conventional outdoor sun drying. Its hygienic, safe from invading animals and has a better holding temperature to ensure rapid drying. Fabrication and testing of the machine was successfully carried out by measuring the solar irradiance and other weather conditions that influence the rate of drying of the produce. The topography, direction, and maximum solar irradiance impinging on the solar collector were determined by measuring the angle of tilt which was a major factor in the drying process. Fabrication and testing of the machine was carried out in a given planting and harvesting period (October to December) in the Midwest southern region of Nigeria hence, data recorded for the period under review will be helpful to farmers in forecasting weather trends and enable them carry out agro operations effectively. Locally sourced materials were sourced for the production of the device which makes it easy to produce and affordable to the rural farmers.

Fig. 10. The fabricated solar dryer.

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