

## Development of a Passive Solar Vegetable Dryer

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**ABSTRACT** Solar dryers are devices that dehydrate items with high moisture content by harnessing solar energy for its operation. The solar dryers generate heated air for removing inherent moisture in the products in contrast to open air drying, which although cheaper, exposes products to contamination from animals, insects, and dust from the environment. This study was focused on the key objective of developing a cost-effective, 4 kg capacity solar dryer that is affordable to the average Nigerian rural farmer by applying standard mechanical engineering principles and using locally available materials. The performance of the developed dryer was evaluated through practical testing, where a test sample of 0.3 kg of pepper and 0.5 kg of okra were dried using the unit and compared to open sun drying of similar quantities of the vegetables as a control experiment. The comparison aimed to assess the effectiveness of the solar dryer in terms of preservation of the aesthetic quality of the samples and drying times achieved compared to open sun drying. The results of the study showed that the solar dryer outperformed the traditional open sun drying method in both the quality of end products and the drying time. Energy consumed for drying the batch sizes using the dryer was found to be 13,110.3 kJ per kg and 8,353.8 kJ per kg for pepper and okra, respectively. The drying efficiency for these batches were determined to be about 19% and 36% for pepper and okra, respectively. The dryer attained a maximum temperature of 70 °C.

**KEYWORDS:** Passive Solar Dryer; Moisture Content; Moisture Removal Rate, Collector Efficiency, Drying Efficiency

### I. INTRODUCTION

A solar dryer is a device developed for the dehydration of items with high moisture content such as fruits, vegetables, meat, fish, spices and other categories of perishable goods as well as materials like textile products. Dehydration is achieved by harnessing solar energy to heat air which is then made to move over and across the item to be dried thereby removing moisture from the products as required. Solar dryers are presently not very accessible to the average Nigerian farmer due to the fact that they are expensive to acquire, especially the commercial size drying units. The key objective of this work is the development of a cost-effective, medium capacity solar dryer that is affordable to the average Nigerian rural farmer. The rationale behind drying of crops is mainly for preservation to extend the shelf life, and thereby minimize post-harvest losses [1]. Removing the moisture from crops also eases handling and transportation. The concept of drying crops with energy from the sun has existed for hundreds of years but as a crude method which is simply open-air drying in the sun by the direct exposure of the products to sunlight. Although it may be cheaper to sun-dry food items, that process exposes the food to contamination and attack from animals, dust and insects, with the higher possibility infestation and growth of microorganisms due to non-uniform drying [2]. There is also the limitation of the demand for more intensive labour required to protect the produce at night and during poor weather. Over time the necessity for a better means of drying became apparent as the drawbacks of sun drying outweighed the benefits. Solar drying systems are more efficient and hygienic with improved standard of dried product since the drying process takes place within an enclosure that offers higher drying temperature and protection from the mentioned limitations of open sun drying [2]. This will lead to improved agricultural productivity and better food security [3]. Agricultural sector contribution to the Nigerian economy is reported to be about 24.2% of the GDP [4]. Challenges related to food preservation and post-harvest losses are on global scale, hence development of sustainable technologies like passive solar dryers has become imperative.

This study was focused on the key objective of developing a cost-effective, 4 kg capacity solar dryer that is affordable to the average Nigerian rural farmer by applying standard mechanical engineering principles and using locally available materials. Determination of energy consumption for drying the batch sizes using the developed dryer to be 13,110.3 kJ per kg and 8,353.8 kJ per kg for pepper and okra, respectively and the drying efficiencies for these batches were determined to be about 19% and 36% for pepper and okra, respectively, represent key

contribution of this study to the existing body of knowledge in the field of passive solar drying technology. This provides additional resource for researchers and policy makers for possible implementation that leads to improved agricultural contribution to Nigeria's gross domestic product (GDP). This article is structured into 5 main sections: introduction laying the background of the study; a section on literature review that gives an update on trends of development in solar drying technology; the methodology section sets forth the research methods employed in the study; while there is a section that presents results of the study and the relevant discussions. The conclusion section rounds off the article.

## II. RELATED WORKS

Energy generated by the sun is a product of nuclear fusion of hydrogen nuclei at high temperatures at the sun's core to form helium atoms. This energy from the sun is the primary source of all other naturally occurring sources of energy such as wind, water (waves and tides) and formation of fossil fuels. Energy can be categorized by type: renewable and non-renewable. Solar energy is renewable and considered to be the cleanest and most abundant energy source available on earth. This energy manifests in the form of light and thermal energy and is transmitted by radiation across the void of space to the earth's surface through the atmosphere. Not all the energy is absorbed when solar radiation impinges on a surface. About 30% of solar energy is reflected back into the atmosphere after reaching the earth's surface with most of the remaining 70% available for harnessing [6]. The intensity of radiation from the sun varies from one location to the other on the earth as explained by the "Inverse Square Law" [7]. The amount of energy obtainable from the sun at any given moment is also dependent on the time of day, season and location. Such dependencies present a limitation that can be mitigated using energy storage technologies. Fig. 1 shows the varying global horizontal irradiation for Nigeria from North to South, showing values for Abuja to be within 5.0 – 5.4 kWh/m<sup>2</sup>/day [8].

Current trends suggest that application of solar energy is gaining ground globally including in the agricultural industry because of its sustainability and eco-friendliness, especially in comparison to non-renewable energy sources like fossil fuels. Solar energy is considered sustainable not only because it is self-replenishing but also due to the fact that its use has negligible harmful impact on the environment. Solar radiation is typically harnessed using a collector, which is simply any device capable of absorbing solar energy. The energy can then be utilized actively, passively or through a combination of both methods. A passive system will not require any mechanical assistance for its successful operation while active systems depend on other devices to generate forced convection for their operation [6]. Passive systems are therefore less expensive than active systems. Solar energy is readily available for exploitation as the sun radiates energy at a rate of  $3.8 \times 10^{23}$  kW but only about 60% of this (i.e.,  $1.74 \times 10^{14}$  kW) reaches the earth's surface [9]. There is, therefore, an evident need for its efficient exploitation because it is free, abundant and unregulated.



Figure 1: Global Horizontal Irradiation for Nigeria [8]

### A. INSOLATION IN NIGERIA

In the development and design of solar systems, knowledge of insolation values or solar radiation levels is imperative in determining the viability of any such endeavours before the system is designed. Solar energy is best quantified in terms of the available average irradiation, hours of sunshine and frequency of overcast. Areas in the world which lie within the latitudes 35°N and 35°S of the equator and experience more than 200 hours of sunshine a year are ideal for the utilization of the sun's energy [10]. Nigeria, lying between latitudes 4° and 14° N, falls within this geographical zone, clearly showing potential for the use of solar energy. Values for average sunshine hours in Nigeria have been variously determined to be 6.25 hours daily, [11]. Also, a study using the Angstrom prediction model estimated solar radiation levels over Makurdi, Nigeria, to be about 4.2 kWh/m<sup>2</sup> daily during the dry season and 3.28 kWh/m<sup>2</sup> daily during the rainy season [12]. This value falls slightly below the corresponding values for Abuja (5.4 and 5.0 kWh/m<sup>2</sup>). A similar work in [13], obtained average levels of solar irradiation over Maiduguri to be 7.5 kWh/m<sup>2</sup> daily in the dry season and 6.11 kWh/m<sup>2</sup> daily in the rainy season of the year. Authors in [14] provided values for daily solar radiation levels in Nigeria with a mean of 5.5 kWh/m<sup>2</sup>, ranging from 4 kWh/m<sup>2</sup> in the coastal zones, to 7.0 kWh/m<sup>2</sup> in the north. Taking the available data into consideration, it can be opined that Nigeria is a prime example of a country with untapped potential for the use of solar energy resource. The average of about 6 hours of sunshine daily [11] gives a yearly amount of 1885 hours of sunshine, which for an area within the tropical region, is ideal for solar energy exploitation.

### B. SOLAR DRYERS

A dryer, also referred to as a dehydrator, is any device designed to be used for the primary purpose of removing inherent moisture as desired from a given product. A solar dryer removes moisture from products such as vegetables by harnessing the energy of the sun, while conventional dryers depend on other energy sources such as fossil fuels with their known negative effects of global warming and climate change. The main concept of using a solar dryer is to increase the efficiency of the drying process under ambient conditions while ensuring a more controlled and sanitary drying environment compared with open sun drying. Solar Dryers can be classified according to the properties of the dryer, mainly its operating principles. Authors in [15] highlights the primary means of classification of solar drying systems as being on the basis of their operating airflow modes as either passive or active. Solar dryers can also be classified on the basis of operating temperature as either high-temperature solar dryers or low-temperature dryers. Authors in [16] stated that solar dryers for agricultural produce can be classified based on size, system design and means of solar energy utilization. Focusing on classification by means of air movement, systems may be classified as natural or forced convection systems. Focusing on the method of heat transfer, the systems can be categorized as direct or indirect [16].

### C. PASSIVE SOLAR DRYERS

A passive solar dryer is also conventionally termed natural-circulation solar drying system. Passive dryers are mainly of cabinet form with glass cover. This type of dryer most often depends on the greenhouse and thermo-siphon effects as working principles [17]. There is an inlet to the solar collector where air enters and is heated up by the greenhouse effect, the hot air rises through the drying chamber passing through the trays and around the food, removing the moisture content and exits through the air vent near the top of the shadowed side. The hot air acts as the drying medium, it extracts and conveys the moisture from the item being dried to the atmosphere under natural convection, thus the system there is no mechanical device required to control the intake of air into the dryer. There are 2 basic types of passive dryers: the direct and indirect solar dryer. For the direct solar dryer, the item to be dried is put in the chamber with the collector, while there are 2 chambers for the indirect dryer: the solar collector compartment, also referred to as the air heating compartment and the drying chamber, designed to accommodate layers of drying trays made of net meshes on which the items can be spread for drying. Passive solar dryers (PSD) are generally cheaper than active solar dryers [18]. They will therefore be more suitable for low-income rural farmers as in Nigeria and other parts of sub-Sahara Africa. They also have been demonstrated as achieving high thermal efficiency, up to 38.3% [19] and achieving drying temperatures of about 45 - 75 °C [20].

#### D. SOLAR DRYING IN NIGERIA

Drying of agricultural products and consumables is a general practice in Nigeria. Vegetables are often sold fresh, but drying is still practiced for some varieties for preservation and also for value addition. In Nigeria, solar drying is mostly practiced as open sun drying. Although examples of use of engineered solar drying exist, these are not widespread and are often government or non-governmental organization (NGO) led projects to provide solar drying support to impoverished farming communities, as was the case in 2018 where the WEP funded the construction of a greenhouse dryer for the Adogo community in Benue State [21]. According to [22], solar energy has become a prime energy source for the agricultural sector [22]. Many researchers have been involved in the design and fabrication of solar dryers for agricultural use. A direct active solar dryer was designed in [23] and fabricated for use in cooking banana within less than 16 hours. According to the research carried out, the forced convection dryer yielded results of greatly reduced drying times for the item by 60%.

### III. MATERIALS AND METHODS

#### A. METHODOLOGY

The underlying philosophy for this work is to design and fabricate a passive solar dryer that will not only be effective but also affordable for an average Nigerian rural farmer. The approach was to conceptualize a relatively robust and modular unit, enabling it to be built using locally available materials. Dove tail joints were utilized in this work supported with adhesive binding, applying wood glue and silicone for covering gaps and ensuring an airtight fit. This is as a result of the design philosophy which utilizes joinery, a technique that replaces the need for external fasteners for woodworking designs. Technical consideration was given to the issue of improving airflow through the device since this has been identified as a major factor in the drying process. Construction of the solar dryer required very few materials. Plywood was selected as the principal material for the drying cabinet in this work due to the fact it is readily available, not too costly and it is environmentally friendly [24]. It is also a mature technology for insulation, therefore the need for further insulation is avoided. Additionally, the plywood sheets can be profiled into almost any flat wall shape. It also allows easier in-board profile cuts that help the use of joinery which reduces the need for metal fasteners. The glazing of a solar thermal collector is the transparent sheet that provides physical protection as well as a medium through which the radiation from the sun can energize the components within the collector. For this, any of glass, transparent plastic or acrylic sheets, may be used. Consideration must be given to the most important factors for this design, which are; cost, durability and functionality. Taking these into account, acrylic sheets were selected because they are quite affordable, durable and easily accessible.

In order to achieve temperatures much higher than ambient, a heat sink of appropriate material must be designed. This can be made of galvanized iron (GI), aluminium or copper, each having its advantages compared to the others. Of the options listed, aluminium is the most readily available and affordable and can be sourced from used/discarded aluminium cans which can aid in reducing cost while recycling usable materials.

The crop drying trays were also made from plywood boards. The frames of the tray were made from cut-offs of the boards used for the main unit. The mesh of the tray was made from a nylon net sheet. Net sheets allow air movement across and through the material. Other options for this are metal net meshes, which are costlier than the nylon nets. The design utilized available meteorological data for general weather conditions in Abuja, as well as average daily sunshine hours. This ranges from about 9:00 am to 5:00 pm, approximately a 9-hour window. A downdraft design was implemented in the design for allowing even distribution of heat within the chamber before the moist air is pulled from the base through a chimney. Performance evaluation tests were carried out on the fabricated solar dryer with results presented below.

## B. RESEARCH DESIGN

### a) Design Assumptions

The following are the design assumptions made for the governing parameters and the equations and subsequent calculations for the dryer design:

- i. Insolation values for Abuja are taken to be the following:
- ii. Global horizontal irradiance: 5.2 kWh/m<sup>2</sup>/day [8].
- iii. Diffuse normal irradiance: 1.01 kWh/m<sup>2</sup>/day [25].
- iv. Average daily radiation: 717.66 W/m<sup>2</sup> [26].
- v. Average daily temperature is assumed to be 31.4°C, [27].
- vi. Air density is assumed constant at 1.15697 kg/m<sup>3</sup>. This was derived using Omni calculator by inputting ambient atmospheric data corresponding with the weather conditions in Abuja.
- vii. Daily sunshine hours between 9:00 am – 5:00 pm (i.e., a drying period of 8 hours).
- viii. Specific heat capacity of pepper determined as 1.65 kJ/kg. K [28] and 1.77 kJ/kg. K for okra [29], respectfully. Pepper and okra are commonly grown vegetables in Nigeria and are traditionally dried in the open and are used as the design specimens for this work.
- ix. Dryer operating temperature: The operating temperature for this is 65°C with air inlet ambient temperature of 30°C [30].
- x. Batch size: Design batch size of 4 kg of specimen was used. This quantity can easily be handled manually and will also give a reasonable spread area within the dryer chamber.
- xi. Collector glazing: This serves as the roof of the unit. It is required to be relatively sturdy as it will experience extended exposure to heat and the elements (varying weather conditions) and possibility of damage from impact, while also allowing maximum penetration of light through the medium. The general practice is to utilize glazing material of about 4 – 5mm thickness [24], hence 5mm thick acrylic sheets were used in this work.
- xii. Drying requirements: Initial and final moisture content for test crops - Pepper (87% & 10%) and Okra (88.7% & 15%), respectively [30].
- xiii. Insulation: The insulating material which also is the main construction material is decided as plywood of 1.5 cm. It is a good insulator as well as an environmentally friendly option, also having no carcinogenic effects nor corrosive qualities, hence having no negative impacts on the product being dried [24].
- xiv. Air movement: Being a passive design, the process is mostly controlled by a natural convection achieved by the use of a chimney which ensures air movement during periods of higher ambient temperatures and reduces air movement in cooler temperatures.
- xv. Assumed drying time: 6 days of 8 hours for pepper and 4 days of 8 hours for okra.

### b) Design Calculations

a. Solar Collector Tilt Angle ( $\beta$ ) is obtained by using Equation 1 [24]:

$$\beta = 10^\circ + \text{Lat } \phi \quad (1)$$

where Lat  $\phi$  = Latitude of location (Abuja; 9.0765°)

b. Insolation on Collector Surface Area ( $I_c$ ) is calculated from Equation 2 [24]:

$$I_c = H \times R \quad (2)$$

where H is the average daily radiation for the location (for Abuja,  $H = 717.66 \text{ W/m}^2$ ) and R is the ratio of solar energy on tilted surface to energy on energy on horizontal surface obtained from Equation 3 [24]:

$$R = \left(1 - \frac{D}{G}\right) r_b + \frac{D}{G} \left[ \frac{1 + \cos \beta}{2} \right] + \frac{\rho(1 - \cos \beta)}{2} \quad (3)$$

where:

$r_b = 1.375$  (Beam Radiation Direction Factor, [24],  $\rho = 0.2$  (Ground Reflectance),  $G = 5.2 \text{ KWh/m}^2/\text{day}$  (Global Horizontal Irradiation),  $D = \frac{1.9 \text{ KWh}}{\text{day}}$  (Diffuse Horizontal Radiation),  $H = 717.66 \text{ W/m}^2$  (Average Daily Radiation),

c. Collector area is obtained using Equation 4 [31]

$$A_c = \frac{M_a \times c_p \Delta T}{I_c \eta_c} \quad (4)$$

where  $\Delta T = T_o - T_a = 65 - 30 = 35^\circ\text{C}$

$T_o = (\text{Operating Temperature})$

$T_a = (\text{Ambient Temperature})$

$C_p = 1.005 \text{ KJ/Kg} \cdot \text{K}$  (Specific Heat Capacity of Air)

$\rho_a = 1.15697 \text{ Kg/m}^3$  (Air Density)

$\eta_c = 80\%$  (Assumed collector efficiency)

$V_a = 1.67 \text{ m/s}$  (Average Air Speed)

$\Phi_a = \text{Volumetric Flow Rate}$

$$\Phi_a = V_a \times \text{Air gap} \times \text{Collector width} \quad (5)$$

$M_a = \text{Mass Flow Rate (kg/s)}$

Air Gap is the space between the cover glazing and absorber plate and Collector Width are dimensions used to determine the air intake cross-sectional area.

$$M_a = \Phi_a \times \rho_a \quad (6)$$

$$A_c = W \times L$$

$$L = \frac{A_c}{W}$$

d. Dryer efficiency ( $\eta_d$ ) is calculated from Equation 7 [32]

$$\eta_{Dryer} = \frac{Q_m + Q_{vap}}{E_{Th}} \quad (7)$$

Where:  $Q_w = \text{Energy for moisture evaporation from sample (kJ)}$ ,

$Q_m = \text{Energy for sample sensible heating (kJ)}$

$E_{TH} = \text{Thermal energy (kJ)}$

e. Amount of Moisture to be removed ( $M_R$ ) is determined using Equation 8:

$$M_R = M_i(S_1 - S_2) \quad (8)$$

Where:

$M_i$  is mass of wet sample

$S_1$  is the initial moisture content (88.7 and 87% for okra and pepper, respectively).

$S_2$  is the final moisture content (15 and 10% for okra and pepper, respectively).

f. Average Drying Rate ( $d_R$ ) is obtained using Equation 9 [33]

$$d_R = \frac{M_R}{t_d} \quad (9)$$

g. Energy required to heat drying air ( $E_{HD}$ ) is calculated using Equation 10, [24] 018):

$$E_{HD} = (M_a \times C_p \times \Delta T) \quad (10)$$

Where:

$M_a$  is the mass flow rate of drying air (0.011 kg/s)

$C_p$  is the specific heat capacity of air (1.005 kJ/kg. K)



$$\Delta T = \text{Collector temp} - \text{Ambient temp. (35 K)}$$

h. Energy for sample sensible heating is determined from Equation 12 [32]:

$$Q_m = M_{wet} \times C_m \times (T_{m,o} - T_{m,i}) \quad (11)$$

Where:

$$M_{wet} = 4 \text{ Kg (Mass of wet sample)}$$

$$C_m = \text{Specific Heat Capacity of Specimen (KJ/Kg.K)}$$

$$T_{m,o} = \text{Outlet Material Temperature}$$

$$T_{m,i} = \text{Inlet Material Temperature}$$

i. Energy for Moisture Evaporation from sample ( $Q_w$ ) is obtained from Equation 12, [32]

$$Q_w = h_{fg} \times m_w \quad (12)$$

$$h_{fg} = 2345 \text{ KJ/Kg @ } 60^\circ\text{C (Latent Heat of Vaporisation of water)}$$

$$m_w = \text{Mass of water removed (kg)}$$

j. Quantity of air required for sample drying is estimated using Equation 13 [30]:

$$Q_a = \frac{M_R \times H_D}{c_a \times \rho_a \times (T_f - T_i)} \quad (13)$$

Where:

$$M_R = 2.95 \text{ Kg and } 3.08 \text{ Kg (Amount of Moisture to be Removed)}$$

$$H_D = 8507.76 \text{ KJ (Sensible Heat for Pepper)}$$

$$H_D = 8704.5 \text{ KJ (Sensible Heat for Okra)}$$

$$C_a = 3.81 \text{ KJ/Kg} \cdot ^\circ\text{C (Specific Heat Capacity of Pepper)}$$

$$C_a = 3.54 \text{ KJ/Kg} \cdot ^\circ\text{C (Specific Heat Capacity of Okra)}$$

$$T_i = 30^\circ\text{C (Initial Drying Temperature)}$$

$$T_f = 65^\circ\text{C (Final Drying Temperature)}$$

## IV. RESULTS AND DISCUSSION

### A. SPECIMEN DATA

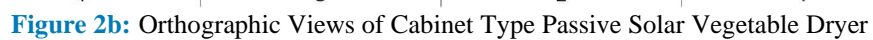
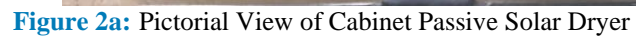
Specimen data for this work are presented in Table 1 with okra having a slightly higher initial moisture content of 88.7%. Test mass of 382 and 522g were used for pepper and okra samples, respectively which were dried to final moisture content of 8 and 6% for pepper and okra, respectively, by the solar dryer within 8 days. The control experiment with open sun drying gave final moisture contents of 16 and 12%, respectively, for pepper and okra, after 8 days, as shown in Table 3. These results compare excellently well with results obtained in other similar studies. The different works of authors in [34] and [35] on drying of vegetable obtained 20% for pepper and 10% for okra final moisture content, respectively. Final moisture content for good shelf life should be less than 10% for vegetables [36].

**Table 1:** Specimen Data

Specimen Initial Conditions	Pepper	Okra
Test mass (g)	382	522
Moisture content (%)	87	88.7

### B. SOLAR DRYER PARAMETERS

Figure 2a shows the pictorial view of the solar dryer. The orthographic views are as shown in Figure 2b while Table 2 presents the summary of the dryer's key design values.





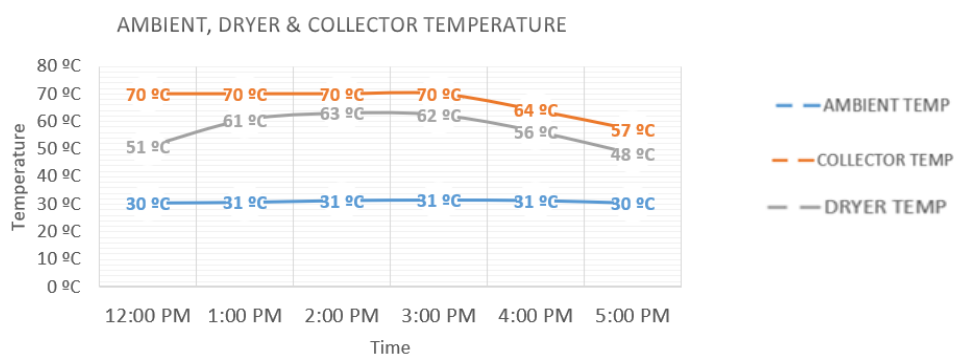
**Table 2:** Key Design Values for Solar Dryer

S/N	Design Component	Specifications
1	Solar Collector Dimensions	(1.04 x 0.80) m
2	Solar Collector Area	0.834m <sup>2</sup>
3	Drying Chamber Dimensions	(1.10 x 0.39 x 0.80) m
4	Glazing Thickness	5mm
5	Insulating Material	Plywood
6	Insulating Material Thickness	15mm
7	No. of Trays	4
8	Drying Tray Dimensions	(1.0 x 0.75) m
9	Drying Tray Area	0.75m <sup>2</sup>
10	Collector Tilt Angle	19°
11	Air Gap Height	0.05m
12	Air Vent Area	(0.05 x 0.8) m <sup>2</sup>
13	Selected test vegetables	Pepper & Okra
14	Batch Size	4kg
15	Drying temperature	65°C

The cabinet profile designed allows for drying of specimens in trays thereby improving space management and drying efficiency.

### C. SOLAR DRYER PERFORMANCE

The performance of the solar dryer compared with open sun drying of the specimens are shown in Table 3 while the operational temperatures are presented in Fig.3. The solar dryer had final specimen mass of 53 g of pepper and 54g of okra compared to 125g and 65g for pepper and okra, respectively, for open sun drying. Wet mass of specimens was 382g of pepper and 522g of okra, respectively, for the tests. This shows that the solar dryer delivered products with lower moisture content than open sun drying. Maximum performance of the collector was often achieved within the hours of 12 noon to about 3:00 pm daily, from which point it begins to drop off along with observed temperatures. This was likely due to the varying solar intensity with time of day. Additionally, efficiency seemed to increase in direct relation to temperature difference between ambient and the collector which is consistent with heat transfer processes. The collector achieved an average temperature of 66°C while maximum temperature attained was 70°C. Temperatures within this range 65°C – 75°C are appropriate for drying most types of fruits and vegetables [37].

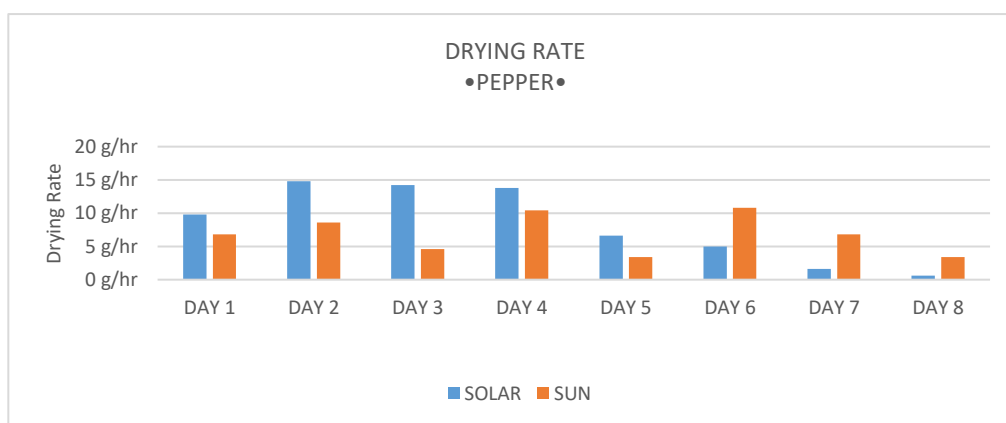
**Figure 3:** Daily Average Recorded Temperatures

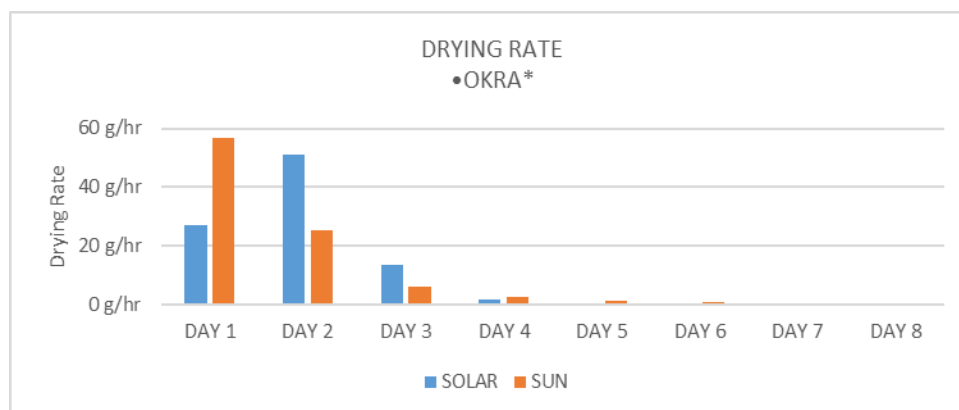
**Table 3:** Comparison of Solar Dryer Performance with Open Sun Drying

Specimen Conditions	Pepper	Okra
Initial Test mass (g)	382	522
Initial Moisture content (%)	87	88.7
Final moisture content after 8 days (solar dryer, %)	8	6
Final moisture content after 8 days (open sun drying, %)	16	12
Moisture removal rate (g/hr.)	15	51
Energy for drying (kJ/kg)	13,110.3	8,353.8
Dryer efficiency (%)	19	36

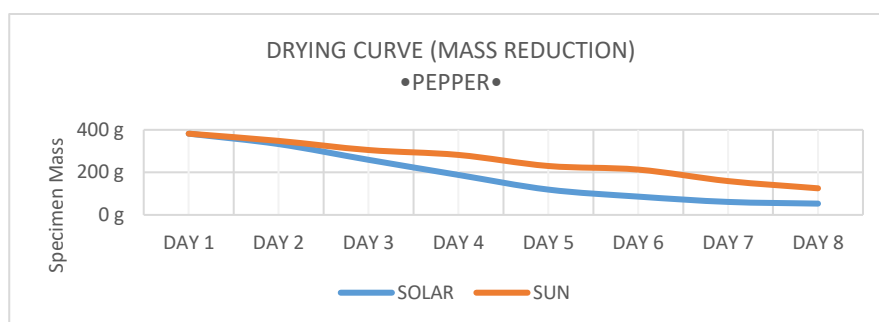
#### D. MOISTURE REMOVAL AND DRYING RATES

The removed moisture data presented in Fig. 4 were gathered through testing by recording daily the initial and final mass of the dried specimens and comparing this data against time to determine the value of the drying rates achieved over the period of the load testing phase. The moisture removal drying charts for pepper and okra displayed in Figs. 5 and 6, respectively, depict the drying characteristics of the solar oven versus the open sun drying, with regards to the mass of moisture removed each day. Overtime, the mass of removed moisture drops as there is less moisture to heat off after every drying session. The superiority of the drying oven over the open-sun drying is clearly demonstrated by the curves. From the data collected from the pepper specimens, the unit consistently outperformed open sun drying till it reached levels close to producing adequately dried products of 8% moisture content. The drying process for okra on the other hand showed the open sun initially leading the solar dryer but is overtaken on the 2nd day of drying by the solar oven which achieved adequately dried products of 6% moisture content within the first 3 days. The open sun specimen became adequately dried on the 6th day, reaching the acceptable moisture content of 16%. The average efficiency of the collector over the testing period was determined to be 77% with a peak efficiency of 94%. This average collector efficiency is almost equal to the assumed design value and compares well with results obtained by other researchers, ranging from 30 - 79% [38]. From Fig. 3, the dryer temperature is seen to be proportional to the collector temperature as expected with a fairly constant temperature difference between the collector and dryer of about 12°C. Tests showed that the temperatures within the dryer unit remained reasonably steady without major temperature fluctuations leading to good thermal performance of the dryer. The average temperature difference between ambient and collector was 36°C which points to the collector's capability of raising the ambient temperature to levels twice its value.

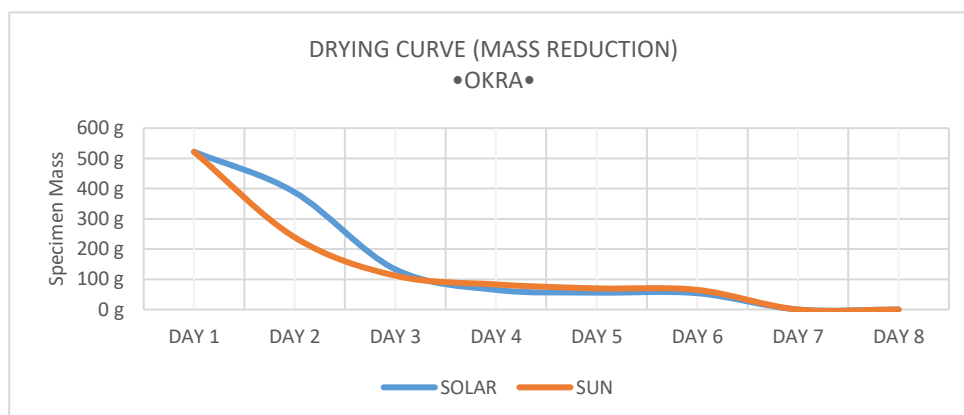
**Figure 4a:** Daily Drying Rates of Pepper (solar dryer vs open sun)



**Figure 4b:** Daily Drying Rates of Okra (solar dryer vs open sun)



**Figure 5:** Drying Curves of Pepper (Solar Dryer vs Open Sun)



**Figure 6:** Drying Curve of Okra (Solar Dryer vs Open Sun)

Fig. 7a. shows samples of okra dried in the solar dryer took 3 days to reach optimal dryness value while the sample for open sun drying shown in Fig 7b took 6 days. Similarly, Fig. 8 a & b show the final dried pepper specimens. The oven dried pepper specimens shown in Fig. 8b achieved optimal dryness within 6 days of testing while 8 days were required for open sun drying shown in Fig. 8a. Taking into account data gathered from the testing, the difference between solar oven drying and open air drying observed in the experiments for okra were minimal in terms of aesthetic quality of dried products, but for pepper the aesthetic quality from the solar oven drying was much better than for the open air drying with final moisture content of 15%. The okra on the other hand was visually superior in the sun dried than the solar dried.



**Fig. 7a:** Final Open Air-Dried Okra Specimen



**Fig. 7b:** Final Solar Oven-dried Okra Specimen



**Fig. 8a:** Final Open Air-Dried Pepper Specimen



**Fig. 8b:** Final Solar Oven-dried Pepper Specimen

The total cost of the solar dryer unit developed was about seventy thousand naira (₦70,000) or US\$109.60, at the prevailing rate of 638.7 to the US\$ in 2023. The production cost translates to US\$ 27.25/kg for the unit of 4 kg capacity, which makes it very competitive compared to fossil fuel and electrically operated dryers costing about US\$71.11/kg [16]. An indirect forced convection solar dryer developed by Alonge et al (2014) [39] had a total cost of ₦40,550 for a 2 kg capacity, which if adjusted for inflation would cost about ₦120,000 as at 2023, i.e., US\$93.94/kg.

## V. CONCLUSION

This paper presents the detailed design and fabrication of a 4kg capacity solar vegetable dryer for the use rural farmers in Nigeria and in other similar economies in order to reduce post-harvest losses. Tests showed that the built unit dried pepper and okra effectively and efficiently. The developed unit meets the operational requirements of the selected vegetables and has also been engineered to be affordable for the target population, with a production cost of ₦70,000. Testing of the unit yielded positive results as the collector and dryer consistently achieved temperature difference above ambient of about 23°C. The collector achieved an average efficiency of 77%, while overall dryer efficiency is 19% for pepper and 36% with okra. In operation, the unit achieved a moisture removal rate of 51g/hr for sliced okra specimens, and 15g/hr for uncut peppers. It produced dried peppers with a calculated 8% moisture content and okra with 6% moisture content. The technical and economic performance of the device positions it for commercial production in order to better improve national food security. As a recommendation, similar future works may achieve higher performance indices by improving the airways for better venting of moisture driven out of the specimens being dried.

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