Performance of a Passive Mixed-Mode Solar Dryer in Owerri, Nigeria

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Abstract

This manuscript delineates the architectural framework and empirically assessed efficacy of a passive mixed-mode solar dryer fabricated from readily accessible materials within the locale of Owerri. The apparatus encompasses a solar collector and drying chambers, with respective dimensions of 0.11 m x 0.4 m x 0.6 m and 0.9 m x 0.4 m x 0.6 m. Empirical evaluations were undertaken in March 2019 during the temporal window of 08:00 to 18:00 hours local time. The results indicated that maximum temperatures of 51°C were attained within the solar dryer during the interval from 11:00 am to 2:00 pm, while thermal efficiency and dryer efficiency were computed at 57.38% and 43.40%, correspondingly. The drying chamber of the solar dryer exhibited enhanced drying efficiency in comparison to conventional open-air drying techniques. The apex drying efficiencies of 21.28%, 37.33%, and 14.48% were ascertained for yam, plantain, and pepper, respectively.

Key words: Solar dryer, transparent top cover, farm produce, temperature variation, aluminum foil

Introduction

Agriculture contributes to the economy of most African countries through the supply of food for the teeming population, and providing adequate raw material for industrial growth thereby creating employment and generating foreign exchange. Large quantities of farm produce are harvested yearly in Sub Saharan Africa but they are lost before utilization due to poor processing and storage techniques (Musa-Makama et al. 2005). Drying of Farm produce is an essential means of preserving food after harvest. It is a process of heating and dehydration that uses thermal energy to eliminate moisture, thereby preventing microbial growth, inhibiting enzymatic changes, and avoiding undesirable odors, flavors, and spoilage.

The use of solar energy is the oldest means of drying farm produce and most farmers in Sub Saharan African still depend on this means for preservation of their farm produce before next planting season. In most rural areas, farmers still depend on the use of open solar drying technique for drying their farm produce. The open drying technique is a process where the farm produce is spread directly under the sun to dry. This technique has a lot of drawbacks which include exposure to dust and sand particles, prolonged drying process which could result to loss in nutrient value and possibly microorganism infestation plus exposure to animals and birds and unexpected rainfall Muhammadu & Adebayo (2012) and Muunir et al. (2013).

In other to mitigate these problems, solar dryers are used. Solar dryers can be classified according to the mode in which air flows into the solar dryer as either active or passive system. In active system, a fan is used to force air through the solar dyer. The passive, air movement is achieved by the natural flow of air as a result of buoyancy effect into the solar dryer. Solar dryers can also be classified according to the method used in harvesting solar energy. These are the direct method, the indirect method and the mixed mode method. In the direct method, the farm produce to be dried is placed in a transparent enclosure of glazing material and sunlight heats it directly (Ching et al. 2006). Heat energy for drying the farm produce is built up within the dryer. In the indirect method, solar energy does not contact the farm produce directly. Instead, an absorber plate captures the solar energy, and air—moved either passively or actively—transfers the collected heat to the drying chamber. Solar drying methods differ in how they apply heat. The indirect method shields the produce from direct sunlight entirely. It works by using an absorber plate to collect solar energy, then transporting that heat to the drying chamber via air circulation, which can be active (using fans) or passive (using natural convection). The mixed-mode dryer, however, uses a hybrid approach: it gets heat from both direct solar radiation striking the produce and a flow of preheated air from a solar collector.

Numerous researchers have worked to enhance solar dryer performance. Gatea (2011), for instance, developed a mixed-mode solar dryer for beans, noting collector efficiencies of 61.82% and 45.40% at 11:00 and 9:00, respectively. Ikem et al. (2016) conducted a thermodynamic analysis on a mixed-mode dryer, reporting its energy efficiency, exergy efficiency, and exergy destruction. Focusing on a different application, Topic et al. (2013) created a small-scale, mobile dryer for medical plants and non-timber forest products. Pardhi and Bhagoria (2013) also developed a mixed-mode dryer, but with forced circulation; their 1.03 m² unit reduced the moisture in 3kg of grapes from 81.4% to 18.6% in four days. Abdullahi et al. (2013) built an adjustable, natural convection dryer that could process 16.52 kg of fresh groundnuts with 35% moisture. Finally, Kangade (2012) designed a solar tunnel dryer in Zimbabwe for tomatoes, which lowered the moisture from 94.09% to 20.50% (dry basis) in 15 hours using air temperatures of 32.6-56°C, yielding 6.28% dry matter.

The objective of this project is to design and construct a passive solar food dryer that is capable of using mixed mode drying method, using metrological parameters of Owerri for design purpose and locally available materials for construction. The performance evaluation of the passive mix-mode dryer is carried out using three different types of farm produce. Design Analysis

During steady state, energy incident on the collector is equal to energy absorbed by the collector and materials plus energy lost to the surrounding. It is given as

$$I_T(\tau\alpha)A_c = Q_u + Q_L \qquad (1)$$

where I_T is the rate of total solar radiation incident on the collector surface, $(\tau\alpha)$ is the transimittance-absortance product of the glazing material, A_c is the surface area of the collector, Q_u is the useful energy gained by the collector and Q_L is the energy loss by the collector

The rate of energy loss by collector is given by Duffie and Beckman (2013) as

$$Q_L = U_L A_C(T_c - T_a) \qquad (2)$$

where T_c is the collector temperature, T_a is the ambient air temperature. The overall heat transfer coefficient (U_L) is the effective combination of all losses out of the collector and is given as

$U_L = U_{top} + U_{bottom} + U_{edge}$ (3)

where U_{top} is the top heat loss coefficient from the solar collector, U_b is the bottom heat loss coefficient from the solar collector, U_{edge} is the edge loss coefficient from the solar collector which is assumed to be negligible in this work.

The top heat loss coefficient is given by Duffie and Beckman (2013) as

$$U_{top} = \left[\frac{N}{\frac{C}{T_{pm}}\left[\frac{T_{pm}-T_a}{(N+f)}\right]^e} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma\left(T_{pm}+T_a\right)\left(T_{pm}^2+T_{pm}^2\right)}{\frac{1}{\varepsilon_p+0.00591Nh_w}+\frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g}-N} \quad (4)$$

where

$f = (1 + 0.089h_w - 0.1166h_w \quad _p)(1 + 0.07866N$ (5)

$C = 520(1 - 0.000051\beta^2) for\ 0^0 < 70^0; for\ 70^0 < \beta < 90^0, use\ \beta = 70^0$ (6)

$e = 0.430(1 - 100/T_{pm})$ (7)

$h_w = 5.7 + 3.8$ (8)

The bottom heat loss coefficient of a flat plate collector is given as

$$U_{bottom} = \frac{K_{ins}}{\delta_{ins,bottom}} \quad (7)$$

where K_{ins} is the thermal conductivity of the insulator material, $\delta_{ins,bottom}$ is the thickness of the insulation material at the bottom of the solar collector

Substituting equation (2) into (1), the useful energy gain by the solar dryer is given as

$Q_u = A_c[I_T(\tau\alpha) - U_L(T_c - T_a)]$ (10)

In the same vein, the actual rate of extraction of heat from the collector may also be measured by means of the change in temperature leaving the collector. It is given as

$Q_u = \dot{m}\, C_p(T_o - T_a)$ (11)

where T_o is the temperature of air leaving the collector, C_p is the specific heat capacity of air at constant pressure and $\dot{m}$ is mass of air leaving per unit time

At the inlet air temperature, the maximum possible useful energy gain in a collector occurs. Consequently, by establishing a correlation between the genuine useful energy output of the collector and the theoretical useful output assuming the collector operates at the ambient air temperature, the collector heat removal factor (FR) is defined.

$$F_R = \frac{\dot{m}C_p(T_o - T_a)}{A_C[I_T(\tau\alpha) - U_L(T_c - T_a)]} \qquad (12)$$

Reformulating equation (12), the actual useful energy captured by the solar dryer is expressed as

$$Q_u = F_R A_c[I_T(\tau\alpha) - U_L(T_c - T_a)] \qquad (13)$$

Hence, the thermal efficiency of the solar dryer is given as

$$\eta = \frac{Q_u}{A_c I_T} \qquad (14)$$

The method provided is used to estimate the agricultural produce's moisture content percentage. by Tiwari (2002) as

$$MC\ (\%) = \left(\frac{M_i - M_f}{M_i}\right) x\ 100\% \qquad (15)$$

The mass of farm produce before drying (Kg) is represented by Mi, and the mass of farm produce after drying (Kg) is represented by Mf.

The relationship provided by Bannout and Ehl (2010) is used to estimate the dryer efficiency (ηD) for a natural convection drier.

$$\eta_D = \frac{(M_i - M_f)L}{A_c I_T t}$$

(16) where L is latent heat of vaporization of water (2320 KJ/Kg) and t is the time of drying. Owerri is a city in south-east of Nigeria with two major climatic conditions namely rainy and dry seasons. The average monthly insolation level in Owerri ranges between 13.02 and 16.16 MJm^{2}day (Anyanwu and Oteh, 2003), with the least occurring during the wet season. Since the solar dryer is expected to operate under all the weather conditions,

it is best to choose as the design month that with the lowest average monthly insolation level. From Anyanwu and Oteh (2003), it is the month of July with a value of 13.02 $MJm^{-2}day$.

Construction Procedure

The inexpensive materials used to build the solar dryer are easily found in the neighborhood market. The drying chamber and the solar collector are its two main parts. The solar dryer's walls are made of 6 mm thick seasoned wood, which is very resistant to termite infestation in addition to being a poor heat conductor. Figure 1 shows a picture of the solar dryer.

The solar collector is composed of a 1.125 m2 sheet of 0.45 mm thick aluminum that has been coated black to enhance solar absorption, a 0.03 mm thick transparent glass that acts as glazing, and 0.1 m thick insulation constructed of wood chip of K = 0.17 W/m.K. on the underside of the collector. To prevent rats entering, the intake to the solar collector is enclosed with fine steel chicken wire mesh. The lower section of the drying chamber is where the solar collector is connected.

Figure 1 - Side and interior view of solar dryer.

Three evenly spaced drying trays constructed of wood and fine steel chicken mesh wire, as well as a transparent top measuring 0.005 mm, make up the drying chamber. Two holes of diameter 0.05 m at the top of the drying chamber allow moisture to escape from the farm produce inside. An access door on the side of the drying chamber allows products to be loaded or unloaded. In order to achieve maximum solar energy harvesting, Okonkwo (1993) suggested that solar collector should be titled to local latitude plus 15^{O}. As a result, the drying chamber's clear top and solar energy collector are built to incline at 20 degrees.

Experimental Rig Set Up

The efficacy of the solar dryer was systematically assessed utilizing yam, plantain, and pepper during the month of March in the year 2019 at the Federal Polytechnic Nekede, located in Owerri, Imo-State, Nigeria, from 8:00 am to 6:00 pm. Throughout the duration of the day, the agricultural products were meticulously weighed, appropriately labeled, and sliced prior to their introduction into the drying chamber. In the evening, the agricultural products were subjected to reweighing to ascertain the extent of moisture loss. A similar category of agricultural product was processed using the open drying methodology as a control to facilitate a comparative analysis of moisture loss between the solar dryer and the open drying technique. As illustrated in Figure 2, temperature probes were strategically positioned at designated locations labeled a through f to monitor temperature fluctuations within the solar dryer. The probes were strategically arranged with a separation of 0.35 meters within the drying chamber and a separation of 0.3 meters in the solar collector segment. Data acquisition was conducted at hourly intervals. Utilizing a maximum insulation temperature of 260°C, a type K thermocouple, which is insulated with Teflon and metal gauze wire, was employed to assess both the ambient temperature and the temperature within the solar dryer. The probe exhibited an accuracy of ± 2.2°C or ± 0.75% of the reading within the range of 0°C to 800°C and was connected to a digital thermometer possessing a measuring range of -50°C to 1300°C, alongside a high resolution of 0.1°C and an accuracy range of 18°C to 28°C. Meanwhile, insolation was quantified utilizing the Daystar solar meter, which employs a polycrystalline silicon photovoltaic cell as a sensor, thereby providing a precise reading with an accuracy of 3% over the range of 0.0 to 1200 watts, and possessing a resolution of 1 W/m^2.

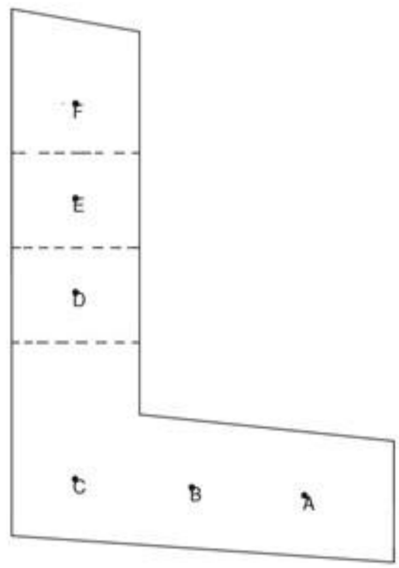

Fig 2 – Points of temperature measurement

Result and Discussion

Each day of the experimental procedure encompassed the collection and documentation of temperature fluctuations both within the solar dryer and in the external environment. The alterations in temperature occurring inside the solar dryer alongside the external temperature during the drying process of yam, plantain, and pepper are illustrated in Figures 3, 4, and 5, respectively. Conversely, Figure 6 presents the solar intensity recorded on the day the experimental study was executed.

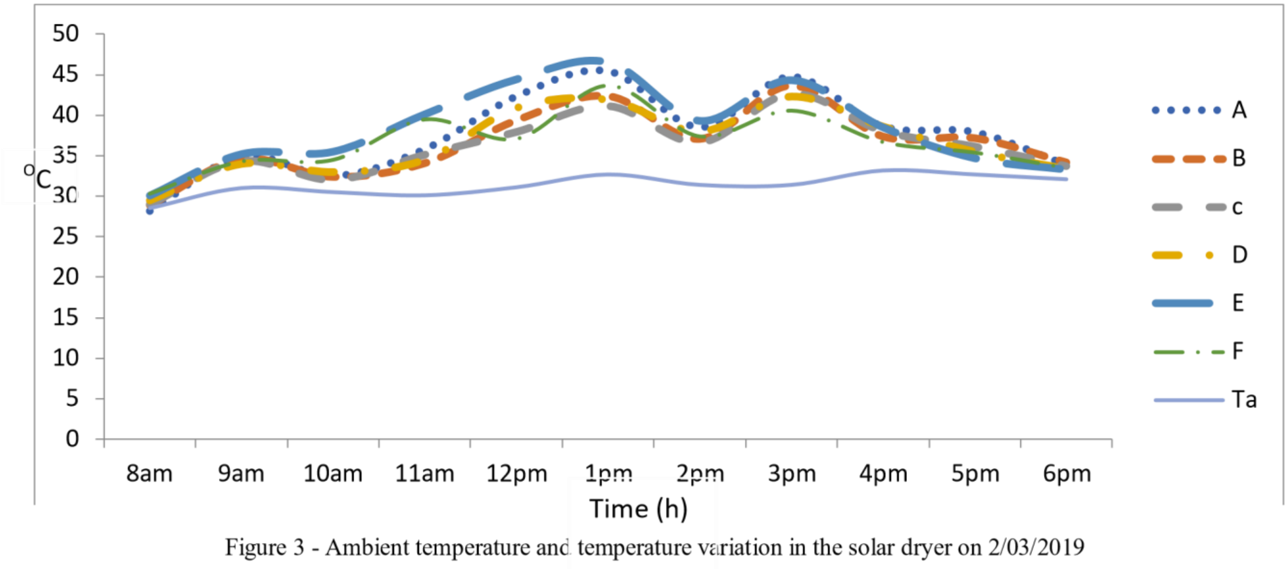

Figure 3 - Ambient temperature and temperature variation in the solar dryer on 2/03/2019

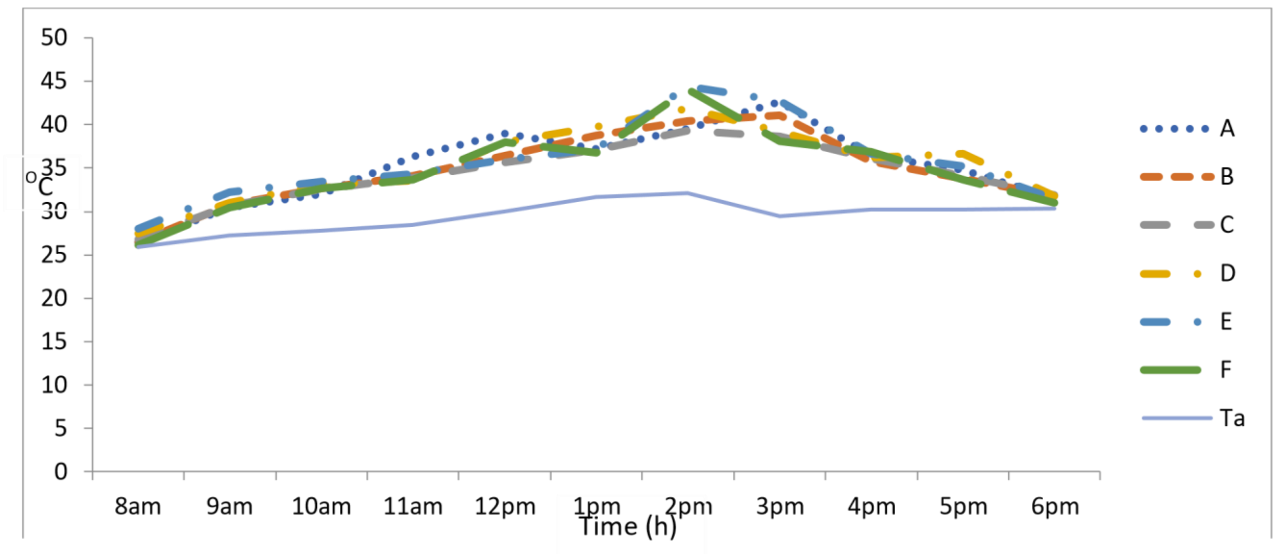

Figure 4 - Temperature fluctuations in the solar dryer and the surrounding air temperature on March 5, 2019

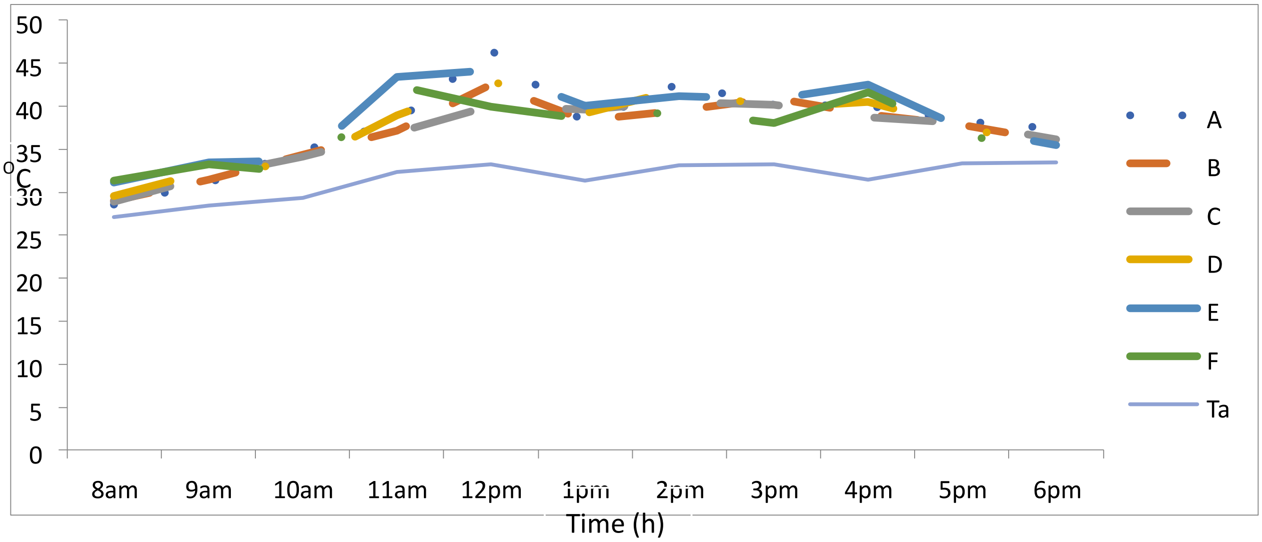

Figure 5 - Ambient temperature and temperature variation in the solar dryer on 8/03/2019

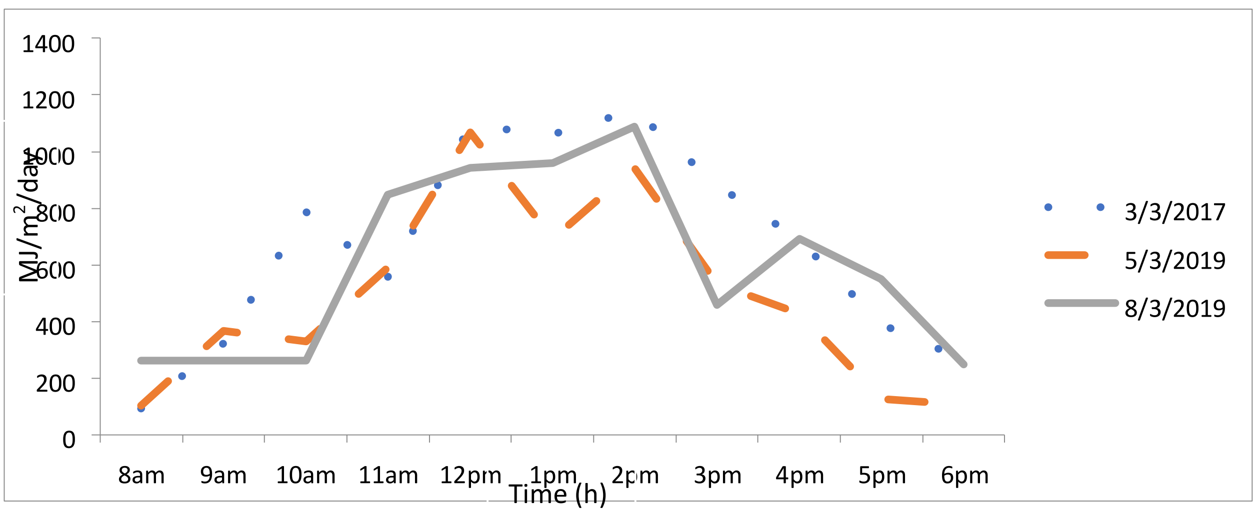

Figure 6 - Solar Intensity

Figures 3 to 5 demonstrate that the solar dryer's interior temperature was higher than the ambient temperature on the day the experiment was conducted. Due to the drying chamber's translucent upper portion, air heating takes place partially on the drying chamber and partially in the solar collector area. Due to higher reported levels of solar radiation intensity, higher temperature readings were obtained inside the dryer chamber between 11 a.m. and 3 p.m.

From the Figures, point A which is first chamber recorded the highest temperature which ranges from 51^{O}C to 46.5^{O}C. For yam, plantain, and pepper, the solar dryer's thermal efficiency was determined to be 54.77%, 52.38%, and 57.38%, respectively. Tables 4, 5, and 6 provide the percentages of moisture content for pepper, plantains, and yams, respectively.

Table 1 - Moisture content percentage for yam on 2/03/2019

Farm Produce: Yam	M_i (Kg)	M_f (Kg)	$M_i - M_f$ (Kg)	MC (%)
Chamber 1	178.2	142.4	35.8	20.09
Chamber 2	206.0	166.2	42.2	20.78
Chamber 3	169.2	133.3	35.9	21.22
Control	203.0	167.7	33.3	16.41

Table 2 - Moisture content percentage for plantain on 5/03/2019

Farm Produce: Plantain	M_i (Kg)	M_f (Kg)	$M_i - M_f$ (Kg)	MC (%)
Chamber 1	64.0	50.6	13.4	20.94
Chamber 2	64.9	50.0	14.9	22.96
Chamber 3	70.0	55.7	14.3	20.43
control	74.5	60.0	14.5	19.46

Table 3 - Moisture content percentage for pepper on 8/03/2019

Farm Produce: Pepper	M_i (Kg)	M_f (Kg)	$M_i - M_f$ (Kg)	MC (%)
Chamber 1	87.6	75.8	11.8	13.47
Chamber 2	94.4	77.8	16.6	17.59
Chamber 3	89.8	76.8	13.0	14.47
control	94.9	83.5	31.4	33.09

The findings of calculating the moisture content percentage for the three farm products utilized to test the solar dryer using equation (15) are shown in Tables 1–3. For all of the farm produce, it was found that chamber 2 experienced a greater loss of water content. This indicates the heat energy absorbed by the collector is pushed into the chamber by convection and heat energy transmitted through the topside of collector chamber is concentrated more at chamber 2. It is not possible to dry pepper using the solar drier, as Table 6 shows. Even though Figure 5 indicates that the recorded ambient temperature for that day was lower than the temperature in the sun dryer, it is evident that the control pepper, which was dried using the direct technique, lost more water than the pepper dried using the solar dryer. Figure 6 shows a sample of dried slices of plantain by the solar dryer.

Figure 7 - Sample dried sliced plantain by the solar dryer

Conclusion

A basic passive mixed-mode solar dryer that was built in Owerri, Imo State, using easily accessible materials has had its performance evaluated. It was noted that:

1. The temperature that was reported within the drying cabinet was 13.3 OC greater than the outside temperature. The cabinet's chamber that received direct sunlight from the clear top cover, however, reached its peak temperature of 51 OC between 11 a.m. and 2 p.m.

2. The dryer can achieve a maximum drying efficiency of 43.40% and a maximum thermal efficiency of 57.38%. These figures are greater than those of open-air drying, which have drying efficiency of 21.65% and thermal efficiency of 32.52%.
3. For yam, plantain, and pepper, the solar dryer recorded maximum moisture content percentages of 21.22%, 22.96%, and 17.59%, respectively.

Thus, since solar dryer is capable of reducing the moisture content of yam and plantain to an appreciable level, this reveals that the solar dryer can be used effectively for drying farm produce such as yam and plantain within Owerri.

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