# Evaluation of a Passive Solar Chimney Dryer for Rural Farmers Using *Arachis Hypogea* at Uyo, Nigeria

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**Abstract:** The performance of a passive solar chimney dryer for rural farmers using *Arachis hypogea* (groundnut) has been evaluated and the results compared with the traditional open-sun drying. The solar chimney dryer consists of the solar collector and the chimney drying chamber with five trays with dimensions of 100 x 70 x 20 cm$^3$ and 100 x 70 x 50 cm$^3$ respectively. The experiment was carried out at Uyo (Latitude 5°2'60N and Longitude 7°55'60E). The results show a reduction in mass from 20.00kg to 2.30kg and from 20.00kg to 2.50kg for solar chimney dryer and open-sun drying respectively. The results obtained also reveal that the moisture content left in *Arachis hypogea* after three days was 11.5% in the dryer and 12.50% in the open-sun. The passive solar chimney dryer efficiency using *Arachis hypogea* at Uyo was about 7.3%.
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**Keywords:** Passive solar chimney dryer, open-sun drying, solar collector, dryer efficiency

## 1. Introduction

Open-sun drying was virtually the only method of cereals preservation until recently when solar drying technology was developed in Nigeria; this method of crop preservation is the most effective, particularly in the rural areas where poverty is highly prevalent. Drying is an excellent way to preserve food that can add variety to meals and provide delicious and nutritious snacks like *Arachis hypogeal* (ground nut). Drying *Arachis hypogea* by solar energy is of great economic importance especially in rural areas where most of the crops harvested are lost due to fungal and microbial attacks (Eze and Chibuzor, 2008; Arun *et al.*, 2014a). These wastages could be prevented by proper drying which enhances storage (Twidell and Weir, 1986). Preserving *Arachis hypogea* by solar drying requires only the heat of the sun. Dried *Arachis hypogea* also requires no energy to maintain it while stored, also dried food is more delicious and remains nutritious. Solar crop drying using passive solar dryers has been studied (Ajao and Adedeji, 2008; Hassanain, 2011; Adeaga *et al.*, 2014; Arun *et al.*, 2014a; Arun *et al.*, 2014b; Chaudhari and Salve, 2014; Singh *et al.*, 2014; Uddin *et al.*, 2014).

In rural localities farmers dry *Arachis hypogea* by the open-sun method. The practice has some obvious disadvantages (Twidell and Weir, 1986). The method of open-sun drying is unhygienic since *Arachis hypogea* is easily contaminated by flies and birds droppings and consequently infected by fungi and bacteria. Human health is thus endangered as a result of food poisoning. This method also prolongs drying and may result in the deterioration of the quality of *Arachis hypogea*. Moreover this is labour intensive as *Arachis hypogea* is moved frequently in and out during the day and night and from rain. In rural areas, conventional sources of energy are totally absent for the development of active dryers which have higher rates of performance. In this study, a low temperature passive solar chimney dryer was used for drying *Arachis hypogea* at low temperature and high relative humidity period of the year. One obvious advantage of low temperature drying is that it enables *Arachis hypogea* to be dried evenly without cracking and burning and hence minimizes the exposure of *Arachis hypogea* to fungal and bacterial infection and wastages (Forson *et al.*, 2007). This method is very suitable for bulk drying for long-term storage. In the process of drying, heat is necessary to evaporate moisture from the food item and a flow of air helps in carrying away the evaporated moisture. There are two basic mechanisms involved in the drying process; the migration of moisture from the interior of individual food items to the surface and the evaporation of moisture from the surface to the surrounding air (Youcef-Ali *et al.*, 2001). The drying of a product is a complex heat and mass transfer process which depends on external variables such as temperature, humidity and velocity of the air stream and internal variables which depend on parameters like surface characteristics (rough or smooth surface); chemical composition (sugars, starches, etc); physical structure (porosity, density, etc.); and size and shape of product (Gatea, 2011). The objective of this study is to evaluate the performance of a low temperature passive solar chimney dryer for rural farmers using *Arachis hypogea* at high relative humidity.

## 2. Calculations Considered

**Declination ($\delta$):** This is the angle between the sun's direction and the equatorial plane and is given by (Duffie and Beckman, 1974; Twidell and Weir, 1986; Forson *et al.*, 2007; Eze and Chibuzor, 2008) as,

$$\delta = 23.45\sin\left[0.9863\,(284 + n)\right] \quad (1)$$

where $n$ is the day number of the year from $n$ = 1 to $n$ = 365.

**Length of the Day ($N$):** The length of the day is given by (Duffie and Beckman 1974; Twidell and Weir, 1986; Henry and Price, 1999) as

$$N = \left(\frac{2}{15}\right)\cos^{-1}\left(-\tan\varphi\tan\delta\right) \quad (2)$$

**Optimum Collector Slope ($\beta$):** The optimum collector slope, $\beta$ is determined from

$$\beta = \delta + \varphi \quad (3)$$

where $\delta$ is the angle of declination for Uyo and $\varphi$ is the latitude of the Uyo, Nigeria.

**Collector Efficiency ($\eta$):** The collector efficiency ($\eta$) is computed from

$$\eta = \frac{\rho V c_p \Delta T}{A I_c} \quad (4)$$

where $\rho$ is the density of air (kgm$^{-3}$); $I_c$ is the insolation on the collector; $\Delta T$ is the temperature elevation; $c_p$ is the specific heat capacity of the air at constant pressure (Jkg$^{-1}$K$^{-1}$); $V$ is the volumetric flow rate (m$^3$s$^{-1}$); and $A$ is the effective area of the collector facing the sun (m$^2$).

**Dryer Efficiency ($\eta_d$):** The dryer efficiency $\eta_d$ is given by

$$\eta_d = \frac{w\Delta H_L}{I_d A_c} \quad (5)$$

where $w$ is the moisture evaporated (kg), $\Delta H_L$ is the latent heat of vaporization of water (2320kJkg$^{-1}$), $I_d$ is the total hourly insolation on the collector and $A_c$ is the area of collector (m$^2$).

**Rate of Heat Flow into the Dryer:** This is the sum of the convective heat $q_c$, conductive heat $q_k$ and radiative heat $q_r$ transfers (Twidell and Weir, 1986; Research and Education Association, 1996), i.e.,

$$q = q_c + q_k + q_r \quad (6)$$

$$\frac{q}{A} = \frac{T_a - T_d}{\frac{1}{h_a} + \frac{\Delta x}{k} + \frac{1}{h_d}} + \varepsilon\sigma\left(T_a^4 - T_d^4\right) \quad (7)$$

where $q/A$ is the rate of heat transfer per unit area, $h_a$ is the heat transfer coefficient for the ambient, $h_d$ is the heat transfer coefficient for the dryer chamber, $T_a$ is the ambient temperature, $T_d$ is the drying chamber temperature, $\sigma$ is Stefan-Boltzmann constant, $\Delta x$ is the thickness of the glass cover, $A$ is the effective area of the collector, and $\varepsilon$ is the emissivity and $k$ is the thermal conductivity.

**Heat Energy ($Q$)** needed for Crop Drying at Moderate Temperature: This is given by

$$Q = M_w L = \rho c_p V(T_a - T_b) \quad (8)$$

where $L$ is the latent heat of vaporization of water, $M_w$ is the mass of crop before drying, $\rho$ is the density of water, $c_p$ is the specific heat capacity of air at constant pressure ($J/kgK$), $V$ is the volumetric flow rate ($m^3/s$), $T_a$ is the ambient temperature and $T_b$ is the dryer temperature (K).

**Wet Basis Moisture Content ($M_w$):** The wet basis moisture content ($M_w$) is given by (Ajao and Adedeji, 2008; Hassanain, 2011) as

$$M_w = \frac{M_i - M_f}{M_i} \times 100\% \quad (9)$$

where $M_w$ is the wet basis moisture content, $M_i$ is the initial mass of dried samples, $M_f$ is the final mass of the dried samples.

**Dry Basis Moisture Content ($M_d$):** The dry basis moisture content ($M_d$) is given by (Ajao and Adedeji, 2008; Hassanain, 2011) as

$$M_d = \frac{M_i - M_f}{M_f} \times 100\% \quad (10)$$

where $M_d$ is the dry basis moisture content, $M_i$ is the initial mass of dried samples, $M_f$ is the final mass of the dried samples.

**Average Drying Rate ($R_d$):** The average drying rate ($R_d$) is given by (Ajao and Adedeji, 2008; Hassanain, 2011) as

$$R_d = \frac{M_i - M_f}{t} \quad (11)$$

where $M_i$ is the initial mass of dried samples, $M_f$ is the final mass of the dried samples and $t$ is the drying time.

**Moisture Content ($MC$):** The moisture content is given by

$$MC(\%) = \frac{M_i - M_f}{M_i}\ x\ 100\% \quad (12)$$

where $M_i$ is the mass of sample before drying and $M_f$ is the mass of sample after drying.

**Moisture Loss ($ML$):** The moisture loss is given by

$$ML = \left(M_i - M_f\right)(g) \quad (13)$$

where $M_i$ is the mass of the sample before drying and $M_f$ is the mass of the sample after drying.

## 3. Materials and Method

The passive solar chimney dryer used was made of four lengths of single iron bars, two lengths of 5.08m steel pipe, two sheets of 1.5mm steel plate, Perspex glass of 1.00 x 0.70m$^2$ and 1.00 x 0.50m$^2$, wire mesh, five racks of 1.00 x 0.50m$^2$ each and a solar collector of 1.00m x 0.70m x 0.20m tilted 45$^\circ$ facing South with gray black gravel bed heat storage system, Fig. 1.

Pilled wet *Arachis hypogea* of about 20.00kg was washed and soaked in a 5M solution of common salt for 5 to 10 minutes. Salt was used only as a seasoning, not as a preservative. The *Arachis hypogea* was weighed and placed on the racks and dried for three days. During drying the *Arachis hypogea* was turned over occasionally to maintain uniform drying. One thermocouple was positioned at the inlet and another at the outlet portion of the solar collector and chimney dryer to measure the air temperature. The ambient temperature was recorded using a mercury thermometer. The experiment was conducted from 10:00am to 4:00pm daily for three days. The experiment was carried out at Uyo, Nigeria (Latitude $5^{\circ}2'60$N, Longitude $7^{\circ}55'60$E) (Anon., 2013). The finished product was hard, brittle, dry and of the same colour.

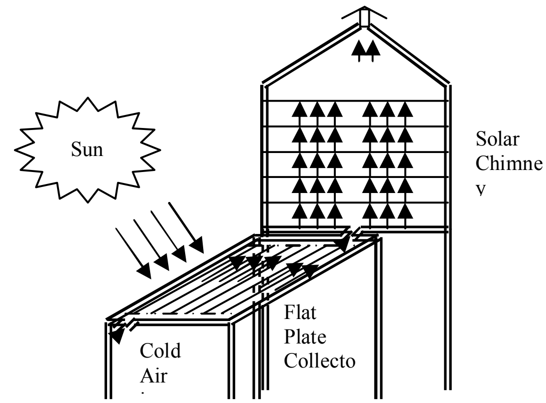


Fig. 1: Solar Chimney Dryer

Table 1: Temperature and Mass of *Arachis hypogea* (Groundnut) in Dryer and Open-sun

| Time (hrs) | Dryer temp ($^{\circ}$C) | Ambient temp ($^{\circ}$C) | Mass of Ground nut in Dryer (kg) | Weight Loss in Dryer (kg) | Mass of Ground nut in Open–Sun (kg) | Weight Loss in Open-sun (kg) |
|---|---|---|---|---|---|---|
| 1 | 39.0 | 36.0 | 20.00* | 0.00 | 20.00* | 0.00 |
| 2 | 41.0 | 38.0 | 17.00 | 3.00 | 17.70 | 2.30 |
| 3 | 45.0 | 39.0 | 15.00 | 5.00 | 15.80 | 4.20 |
| 4 | 42.0 | 34.0 | 12.40 | 7.60 | 15.60 | 4.40 |
| 5 | 40.0 | 33.0 | 12.00 | 8.00 | 14.40 | 5.60 |
| 6 | 35.0 | 31.0 | 11.20 | 9.80 | 12.40 | 7.60 |
| 7 | 46.0 | 34.0 | 9.00 | 11.00 | 9.70 | 10.30 |
| 8 | 47.0 | 35.0 | 8.80 | 11.20 | 9.40 | 10.60 |
| 9 | 54.0 | 35.0 | 8.50 | 11.50 | 8.70 | 11.30 |
| 10 | 48.0 | 36.0 | 8.10 | 11.90 | 8.30 | 11.70 |
| 11 | 50.0 | 34.0 | 7.30 | 12.70 | 7.80 | 12.20 |
| 12 | 38.0 | 32.0 | 6.00 | 14.00 | 7.20 | 12.80 |
| 13 | 50.0 | 35.0 | 3.10 | 16.90 | 3.80 | 16.20 |
| 14 | 52.0 | 40.0 | 2.80 | 17.20 | 3.50 | 16.50 |
| 15 | 54.0 | 42.0 | 2.60 | 17.40 | 3.10 | 16.90 |
| 16 | 55.0 | 43.0 | 2.50 | 17.50 | 2.80 | 17.20 |
| 17 | 54.0 | 41.0 | 2.30 | 17.70 | 2.50 | 17.50 |
| 18 | 47.0 | 39.0 | 2.30 | 17.70 | 2.50 | 17.50 |

* Initial Mass

**4. Results and Discussion**

The results obtained from drying *Arachis hypogea* in the solar chimney dryer and open-sun are presented in Table 1 and Figs. 2 - 10. From Table 1, the results indicate that the dryer temperature was higher than the ambient temperature during the three days, the minimum and maximum temperatures were $35^{\circ}$C and $55^{\circ}$C for the dryer, $31^{\circ}$C and $43^{\circ}$C for the ambient respectively. The average drying temperatures were $40.3^{\circ}$C, $47.2^{\circ}$C and $52.0^{\circ}$C for day 1, day 2 and day 3, respectively. The average insolation was 445Wm$^{-2}$. This was very good for adequate drying as seen from the monthly mean global radiation for Uyo (Wansah *et al.*, 2014). The highest temperatures occur at 2:00 PM. The average weight loss for *Arachis hypogea* in the dryer and open-sun were 9.80kg and 7.60kg for day 1; 4.20kg and 5.20kg for day 2; 3.70kg and 4.70kg for day 3 respectively. The results obtained also reveal that the moisture content left in *Arachis hypogea* after three days was 11.5% in the dryer and 12.50% in the open-sun. Properly dried food has a moisture content which varies from 5.0% to 25.0% depending on the food (Whitefield, 2000), so the *Arachis hypogea* was properly dried for long term storage. The passive solar chimney dryer efficiency was about 7.3%. This is low because the dryer was opened at the top of each hour to collect the sample for weighing (Ojiki *et al.*, 2011; Wansah *et al.*, 2011). The final mass of the *Arachis hypogea* was 2.30kg. Figures 2-4 show temperature changes during the drying period, while Figures 5-7 show reduction in weight for the three days and Figures 8-10 show the weight loss for the three days. The *Arachis hypogea* in the dryer attained a smaller final mass than that in the open-sun.

Figures 2-4 show temperature changes during the drying period.

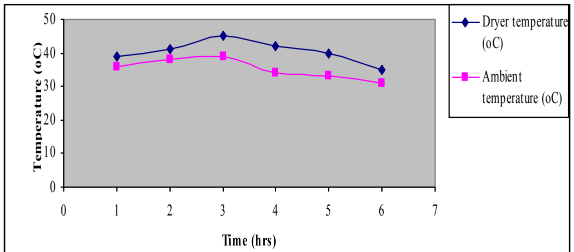

Fig.2: system Temperature - Day 1

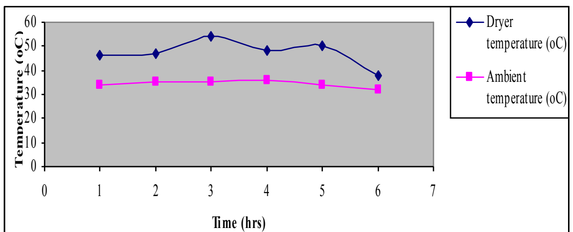

Fig.3: System Temperature - Day 2

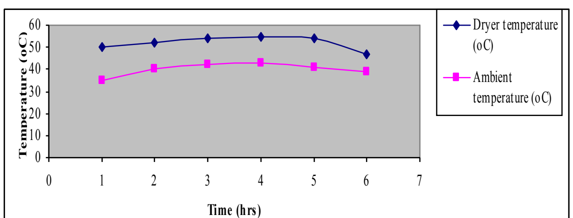

Fig.4: System Temperature - Day 3

Figures 5-7 show reduction in weight for the three days

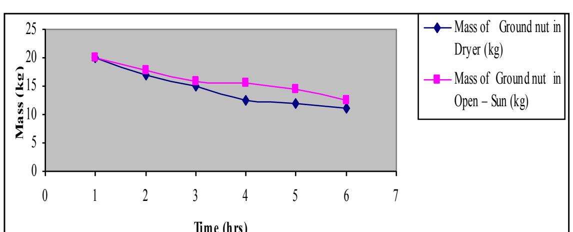

Fig.5: Reduction in Weight - Day 1

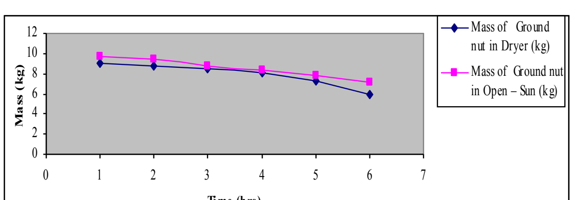

Fig.6: Reduction in Weight - Day 2

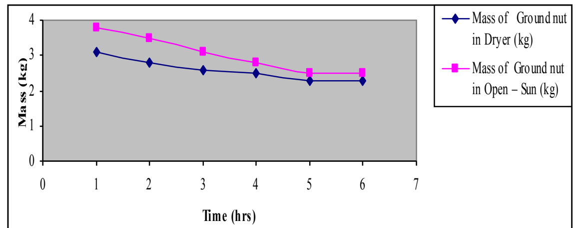

Fig.7: Reduction in Weight - Day 3

Figures 8-10 show the weight loss for the three days.

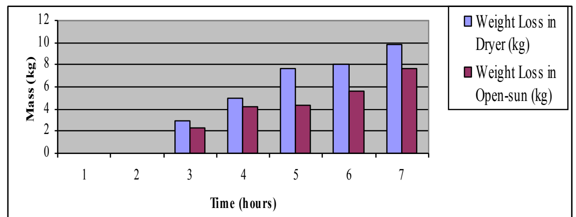

Fig.8: Weight Loss - Day 1

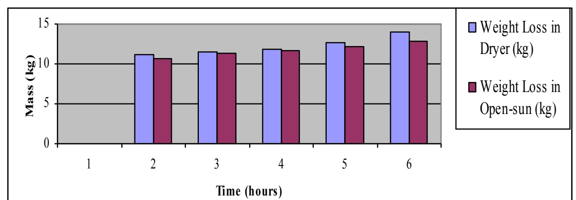

Fig.9: Weight Loss - Day 2

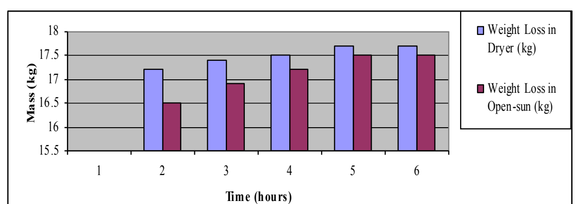

Fig.10: Weight Loss - Day 3

## 5. Conclusion

The performance of a passive solar chimney dryer for rural farmers at Uyo using *Arachis hypogea* has been evaluated. The study shows a passive solar chimney dryer as a better alternative technology in rural locations in order to avoid disadvantages of conventional open-sun drying method. The amount of moisture content decreased progressively to a minimum in the dryer in three days due to the flow of dry warm air and the amount of insolation on the solar collector. The passive solar chimney dryer efficiency was not very good as it was opened regularly. The colour of dried *Arachis hypogea* in the solar chimney dryer was unchanged with the taste and flavour enhanced. The passive solar chimney dryer is therefore recommended for drying to rural farmers to enhance and utilize the free solar energy resource found abundantly in Uyo, Nigeria which is within the tropics.

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