DEVELOPMENT AND PERFORMANCE EVALUATION OF A MEDIUM SCALE DIRECT MODE PASSIVE SOLAR DRYER FOR FARMERS IN NIGERIA

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ABSTRACT
Huge losses of vegetables due to inadequate processing systems are obvious among farmers in South-Eastern Nigeria. In order to abate this problem a medium scale direct mode passive solar dryer of capacity 50 kg of sliced okra was developed and evaluated at Michael Okpara University of Agriculture, Umudike between July and October 2014. A cabinet solar dryer housed with plastic corrugated transparent material was constructed for this study. Fresh okra sliced to a thickness of 15 mm was spread in single layer to dry in a solar dryer and in open sun as a control. Results obtained showed that the solar dryer raised the drying air temperature 31.82 °C to 45.54 °C, which was 30.11 percent above the average ambient air temperature during the drying period. The ambient relative humidity was reduced from 73 % to 23.5 % in the solar dryer drying chamber where the sliced product was loaded. The moisture content of sliced okra reduced from 88% wet basis to 5% wet basis at 28 hours solar dryer effective drying time. The dryer achieved 40.1% drying efficiency based on the effective drying time. Sliced okra samples dried in the solar dryer were of high qualities when compared with the sample dried in open sun.

Keywords: Solar, energy, passive, dryer, okra, plastic sheet.

1 INTRODUCTION
According to KNOEMA (2014), Nigeria is endowed with a large area of arable land mass which covers 750,474.48 sq. km. The available land resources encourages agricultural activities, engaging approximately 70 percent of Nigerian population in agriculture and the small farms produce about 80 percent of the total food (Encyclopedia, 2014). Therefore, Nigerian farmers produce most of the needed food for the teeming population of 187,158,009 as at 13th July, 2016 (www.geohive.com). Farming in Nigeria is all year round, in the rainy season, water supply is by rains, while in the dry season water supply is through irrigation. This results in abundant harvest of grains, cereals, root crops, seeds, nuts, fruits and vegetables. Nigeria is the second largest producer of okra all over the world with average production rate of about 1,060,620 tonnes of okra in 2011 (OAN, 2014). Burkil (1997) asserted that okra production worldwide is estimated at six million tonnes per year. Non indigenous dryers, imported into the country, are costly, which makes them out of reach to the farmers, who really need the dryer to process their farm products. However, the major constrain of Nigerian farmers is preservation of crops. Samaila et al. (2008) reported that harvested fruits are of high moisture content which under tropical conditions of high temperature and relative humidity is prone to rapid post-harvest deterioration and losses of up to 30 to 69 %. Adetuyi et al. (2008) worked on nutritional value of okra and indicated that okra contains 46.28 mg/100g of vitamin C and equally serves as a plasma replacement for ‘blood –volume expander’. Okra provide just 30 calories per 100g, it contains no saturated fats or cholesterol. It is rich in vitamin A and is an excellent source of anti-oxidant vitamin such as ascorbic acid or vitamin C (Umesh, 2009).
Okra farmers and marketer experience a lot of annual post-harvest losses caused by poor handling, inadequate storage facilities and high perishable nature of fresh okra fruits. Thus, drying the commodity is needed to preserve its quality and enhance long shelf life. Wankhade et al. (2013) opined that in order to reduce losses and derive maximum utilization and economic gain, okra should be sliced and dried at 1 m/s constant air velocity and drying air temperature of 40°C. Yadav et al. (2005) stated that okra has specific heat capacity of 3.54 kJ/kg°C. Olukosi et al. (1990) reported that farmers in Nigeria majorly preserve their crops by traditional open sun drying system. The survey conducted on traditional open sun crop drying system in Nigeria as reported by (Olukosi et al., 1990; Kaul et al., 1995 a,b) revealed that Nigerian farmers normally dry their crops in small scale in open sun. The farmers spread their crops in thin layer; particularly okra sliced into even thickness and spread out in single layer.

Nielson (2005) and Susan (2011) asserted that solar energy which is renewable is commonly available and affordable for consumption in rural areas at no cost. Kaul and Egbo (1985) stated that solar radiation floods Nigeria all the year round at about 490 to 522.2 W/m². Nigeria lies within a high sunshine belt of the world, receiving between 3.5 and 7 kW/m²/day from the coastal Latitude to the far North (Iwe, 1998). This radiation provides enough free solar energy source that can be harnessed by heliothermal process to raise the ambient temperature to a sufficient level that can efficiently dry sliced okra.

Imported dryers used in the country today are costly, sophisticated and unavailable to farmers who are currently still facing crop drying problems. Several indigenous solar dryers built for drying grains and vegetables had been reported by (Esper and Muhlbauer, 1996; Alonge and Hammed, 2007; Iwuoha, 2003). However, their works were on small scale level which have not really solved the drying problems of the farmers. Therefore, this research aims at developing a medium scale direct mode passive solar dryer of nothing less than 45 kg capacity of sliced fresh okra and evaluating the dryer’s performance.

2 MATERIALS AND METHODS

2.1 Selection of crop for design consideration
Research on crops produced and dried by Nigerian farmers showed that okra has high moisture content and is widely produced in Nigeria by the local farmers. Okra has as high as 84 to 88 percent moisture content wet basis and need to dry down to a safe storage moisture content of 4 percent wet basis (Akoy, 2000; Ismail and Ibrahilliss, 2013). Therefore, okra was chosen as the crop for design consideration on the assumption that any solar dryer that dries okra effectively will equally dry other crops of such high or lower moisture content.

a. Design Calculations

2.2.1 Collector useful heat energy gain
The dryer’s performance depends largely on its ability to generate sufficient useful thermal energy gain. The prediction equation for the dryer performance is given in equation 1 using moisture content wet basis data (Sahay and Singh, 2005).

\[ Q = \left[ C_p W_p (T_c - T_a) + L_v W_w \right]^{\frac{1}{t}} \]

where, \( Q \) is collector useful thermal energy gain (W), \( C_p \) is specific heat of okra before drying (J/kg°C), \( W_p \) is weight of okra before drying (kg), \( T_c \) is collector air outlet temperature (°C), \( T_a \) is ambient temperature (°C), \( L_v \) is heat of vaporization of moisture at the drying air temperature (J/kg), \( W_w \) is weight of water to be removed in order to dry the product from the initial moisture content to self-storage moisture content (kg) and \( t \) is total or effective drying time (s).

\( L_v \) is expressed in equation 2 (ASAE, 1998) and also reported by ABD EI-Wahab et al. (2011). Equation 3 is given by (IRRI, 2014).
\[ L_v = 2,502,535.26 - 2,385.76 (T_c - 273.16) \] at 
\[ 273.16 < T_c < 338.72 \]

where, \( T_c \) is temperature of the drying air (°C).

\[ W_w = W_p - \left( \frac{100 - M_{cw}}{100 - M_{cfw}} \right) W_p \]

where, \( M_{cw} \) is initial moisture content of agricultural material in wet basis (%), \( M_{cfw} \) is final moisture content of agricultural material in wet basis (%).

### 2.2.2 Determination of Solar collector area

Duffie and Beckman (2006) and Holdman, (1981) gave a model equation for the calculating solar collector area as:

\[ Q = hA(T_c - T_a) \]

where, \( A \) is solar collector Area (m²), \( Q \) is collector useful heat energy gain required to dry a given quantity of agricultural product (W), \( h \) is heat transfer coefficient (W/m² °C). For natural convection solar dryer, \( h \) in equation 4 can be calculated from equation 5 (Holdman, 1981).

\[ Nu = \frac{hx}{k} \]

where, \( Nu \) is Nusselt number (Dimensionless), \( k \) is thermal conductivity (W/m °C), \( x \) is length of the collector section (m). Also \( Nu \) can be expressed as given in equation 6 for an inclined solar collector flat plate (Holdman 1981)

\[ Nu = 0.14 \left[ (G_r P_r) \frac{1}{3} - (G_c P_c) \frac{1}{3} \right] + 0.56 (G_r P_r \cos \phi) \frac{1}{3} \]

where, \( G_r \) is Grash of number (dimensionless), \( G_c \) is critical Grash of number (dimensionless) with the value as 5x10⁹ for solar collectors inclined at an angle (\( \phi \)) not exceeding 15°. \( G_r \) can further be expressed as:

\[ G_r = \frac{g \beta x^3 (T_c - T_a)}{\nu^2} \]

where, \( g \) is acceleration due to gravity (m/s²), \( \beta \) is temperature coefficient of thermal conductivity (1/°C), \( x \) is length of solar collector (°C), \( \nu \) is kinematic viscosity (m²/s).

Likewise \( Pr \) (Prandtl number - dimensionless) can also be expressed as:

\[ Pr = \frac{C_p \mu}{k} \]

where, \( \mu \) is dynamic viscosity (kg/ms)

Thus:

\[ A = \frac{Qx}{Nu(T_c - T_a)} \]

According to Yadav et al. (2005), the specific capacity \( (C_p) \) of okra is given as 3.54 kJ/kg °C. The dynamic viscosity \( (\mu) \), kinematic viscosity \( (\nu) \), thermal conductivity \( (k) \) at the drying air temperature \( (T_c) \) of 45°C solar collector were obtained from thermal table given by Holdman, (1981) and \( T_a \) was obtained from the meteorological units, National Root Crop Research Institute, Umudike, Abia State 29.5 °C. The medium scale dryers was design to dry 50 kg of sliced okra of thickness 15 mm at a time. The parameters were used to calculate the collector area of the solar dryer as 2.6 m².

### 2.2.3 Fabrication of the Solar Dryer

The design specifications were followed to fabricate a cabinet direct mode passive solar dryer in the Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umudike, Umuahia, Nigeria. The dryer was fabricated with a 2.08 by 5.08 cm angle iron, flat metal sheet, corrugated transparent plastic sheets, crop trays and black oil paint. The area of the collector section was 2.6 m² and was mounted on a metallic stand inclined at an angle of 15° to the horizontal. The inclination
enhanced trapping of maximum solar radiation on the dryer and natural convection flow of hot air from the collector section to the drying chamber where moisture is picked from the crop and carried out naturally through the drying chamber air outlet opening. The features of this solar dryer indicated that it is direct mode passive solar cabinet dryer, and it is simple to construct with locally available and affordable materials. The dryer is presented in Plate 1.

Plate 1: A Medium Scale Cabinet Direct Mode Natural Convection Solar Dryer.
Where; A is chimney, B is crop tray, C is transparent housing, D is drying chamber section, E is solar collector section, F is transparent collector top cover and G is collector air inlet space.

2.2.4 Performance Evaluation of the Solar Dryer
The dryer was evaluated by considering the overall thermal system drying efficiency of the dryer and savings in drying time, using open sun drying as a control measure for the experiment. Duffie and Beckman, (2006) expressed overall thermal system drying efficiency as:

$$\int sd = \frac{Qt}{A_c} \frac{1}{I vR_t}$$

(10)

where, \(\int sd\) is system drying efficiency, \(I\) is solar radiation intensity flooding on dryer surface, \(v\) is collector top cover material transmissivity, \(A_c\) is collector surface area (m\(^2\)), \(t\) is drying time (s) and \(R\) is ratio of total radiation on tilted surface to that on plane of measure. \(Q\), remains as earlier defined. But \(R\) is defined as:

$$R = \left[\frac{\cos(L - b) \cos d + \sin(L - b) \sin d}{\cos L \cos d + \sin L \sin d}\right]$$

(11)

where, \(L\) is latitude of location, \(b\) is optimum dryer tilt angle from the horizontal, \(d\) is declination angle of the sun. But \(d\) is as given in equation 12 (Rao and Parulekar, 2004)

$$d = 23.45 \sin \left(\frac{360}{365} \left(284 + n\right)\right)$$

(12)

\(n\) is day of the year counted from 1st January

2.2.5 Drying Test
Okra was used to evaluate the performance of the dryer. Fifty (50) kg of okra was sliced to a thickness of 15 mm and dried in the solar dryer while same sample were dried in open sun serving as a control for the experiment. The drying sliced okra in the solar dryer and open sun was sampled out periodically at 2 hours intervals for moisture content determination using the oven drying method. The temperature of the dryer was equally monitored using open sun drying as control. Measurements were taken at two hours intervals in the day time for each batch drying. Data collections were replicated three times. The drying took place between August and October of 2014 which is the peak period of okra production in South-Eastern part of Nigeria. This period is equally the peak of rains and most difficult time for open sun drying. Hence most of the harvested crops are lost within this period. In each of
these months, three batches of sliced okra samples were dried and the average values of the parameters of drying samples in the dryer and their corresponding open sun drying method were taken under the same ambient weather conditions. The average moisture content of the samples was determined using method given by (ASAE, 1996).

3.0 RESULTS AND DISCUSSION

3.1.1 Effect of Time on Solar Radiation and Relative Humidity

![Figure 1: Effect of time on solar radiation (W/m²) and relative humidity (Rh)].

Figure 1 showed that during the drying period the relative humidity was generally high in morning hours with average value of 82.2 % relative humidity at 8.00 a.m. and solar radiation intensity of 241.8 W/m². The average value of solar radiation intensity increased to 897 W/m² and relative humidity decreased to 65.3 % at 2.00 p.m. Also the average value of solar radiation intensity decreased to 387.6 W/m² and the relative humidity increased to 67 % at 6.00 p.m.

3.1.2 Effect of Time on Temperatures Utilized in Drying Process

![Figure 2: Effect of time on ambient temperature (°C), Collector air outlet temperature (°C) and drying chamber air outlet temperature (°C)].

From figure 2 it was observed that the ambient temperature, collector air outlet and drying chamber air outlet temperatures generally increased from morning to afternoon and thereafter decreased in the evening.
On the average the ambient temperature were 26.2 oC, 34.3 oC and 30.2 oC at 8.00 a.m., 2.00 p.m. and 6.00 p.m. respectively. Also the average collector air outlet temperatures were 26.7 oC, 53.7 oC and 37.0 oC at 8.00 a.m. In the same order the drying chamber air outlet temperatures were 28.3 oC, 62.7 oC and 44.5 oC.

### 3.1.3 Effect of Time on Wind Flow Rate

![Figure 3: Effect of time on ambient wind flow rate Wsp (m/s).](image)

Figure 3 showed that the ambient wind flow rate generally decreased from to afternoon and increased from afternoon to evening. Figure 3 further indicated that the average values of wind flow rate were 1.5 m/s, 0.5 m/s and 1.1 m/s at 8.00 a.m., 2.00 p.m. and 6.00 p.m. respectively.

### 3.1.4 Drying rate of the Samples dried with the Solar Dryer and Open sun

![Figure 4. Drying performance of medium scale solar dryer for rainy season okra drying.](image)

In figure 4, Mcd is moisture content gradient of okra dried with the solar dryer (%), and Mcs is moisture content gradient of okra dried in open sun (%).
Table 1. Results of performance of medium scale solar dryer for drying okra at slice thickness of 15 mm.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Nature of crop</th>
<th>Nature of Drying</th>
<th>Total drying time (hr)</th>
<th>Edt (hr)</th>
<th>MCwb (%)</th>
<th>Rh_a (%)</th>
<th>I_a (W/m²)</th>
<th>w_sa (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh</td>
<td>Okra</td>
<td>Solar dryer</td>
<td>88</td>
<td>56</td>
<td>28</td>
<td>5</td>
<td>73.4</td>
<td>656.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open sun</td>
<td>124</td>
<td>54</td>
<td>54</td>
<td>5</td>
<td>72.0</td>
<td>622.2</td>
</tr>
<tr>
<td>Dried</td>
<td></td>
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</table>

Edt = Effective drying time; MCwb = Moisture content wet basis, Rh_a = Average relative humidity; I_a = Average solar radiation intensity; w_sa = Average wind speed.

3.2 Discussions

Results in Figures 1 to 5 as contained in Table 1 showed that the average collector useful thermal energy gain generated per batch drying for the three months was 1,063.1 W. The sliced okra samples dried with solar dryer, achieved 54.84 percent gain in drying time, when compared with open sun drying method. Figures 2 and 3 equally showed that okra was dried at average daily solar dryer temperature of 45.53°C. The solar dryer raised the drying temperature from 31.82°C to 45.53°C which is 30.11 percent above average ambient air temperature. These average daily solar dryer temperatures obtained were within the limit of the recommended 60°C drying temperatures for fruits and vegetables. This conforms to the report of (Pendre et al., 2011). The ambient relative humidity reduced from 73% to 23.5% in the solar dryer drying chamber where the sliced product was loaded for drying. Reduction of the relative humidity in the drying chamber and the increase in temperature enhance the quick drying and good quality of the sliced okra. Okra is a high moisture content crop, therefore this dryer is suitable to dry high and low moisture content crops.

Generally the system drying efficiencies are characterized with low percentage values. This is because single layer drying of sliced crops requires large drying area. Hence, a given drying area can only contain relatively small quantity of dried sliced crop. Equation 10 was employed to analyze the system drying efficiencies and this revealed that for effective drying time the system drying efficiencies of the solar dryer was 40.1 percent. On the other hand the same sample of okra dried in open sun achieved 20 percent system drying efficiency. Thus, the solar dryer constructed performed twice better than the open sun drying system. Besides, okra samples dried in open sun grew mould before it could dry down to safe storage moisture content. This showed that drying of okra and such like products can best be achieved by this medium scale solar dryer than open sun drying. It will equally be noted that this solar dryer can be effectively used in any part of the world that receives solar radiation.

4 CONCLUSION

Based on the results obtained from this solar dryer and the traditional open sun drying, it can be concluded that:

i. A medium scale 50 kg capacity passive direct mode cabinet solar dryer with transparent corrugated plastic material for the dryer top cover was designed and constructed with locally available materials.

ii. Evaluation of the solar dryer performance using okra as a test crop showed that over 50 percent savings in drying time was recorded when compared with open sun drying.
iii. The overall average solar dryer temperature obtained was not higher than 60°C and the heat flow was by natural convection.

iv. In rural areas where there are no scientific instrument to measure moisture content of the drying crop, this work have shown that when okra is dried to safe storage moisture content; squeeze the drying sample in the palm, brittleness of the texture indicates dryness.

v. This solar dryer achieved 40.1 percent system drying efficiency while the open sun drying method achieved 20 percent, showing that the medium scale passive solar dryer generally performed twice more efficient than the open sun drying method.

vi. The solar dryer dried okra from initial moisture content of 88 % to 5 % wet basis within 28 hours effective drying time.

REFERENCES


