DEVELOPMENT OF DIRECT MODE NATURAL CONVECTION SOLAR DRYER FOR HIGH MOISTURE CONTENT CROPS

BY

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ABSTRACT

Farmers find it extremely difficult and in most cases impossible to process and preserve high moisture content crops by normal open sun drying. In order to ameliorate this identified problem, five direct mode natural convection flat plate high moisture content solar dryers were designed and constructed with locally available materials. Sliced fresh ripened Ronita Cultivar tomato and mango as well as fresh okra, carrot and onion were used to test run the solar dryers. While the samples of the same crops dried in open sun were used as control. The tests were conducted in the months of January, February, March and April, 2005 and the average ambient values 31.4 °C, 16.11 %, 1.32 m/s and 570.9 W/m² for temperature, relative humidity, wind speed and solar energy radiation respectively, were used in the analysis. Evaluation of drying systems’ performances indicated that over 50 percent savings in drying time was achieved with the solar dryers as compared to the open sun drying. Also the system drying efficiencies of the dryers revealed that tomato, onion, okra, mango and carrot dried in solar dryers attained 105.85, 66 60, 64.25, 100.00 and 93.97 percent respectively higher than the system drying efficiencies of the same samples dried in open sun. Each of the dryers generated an average daily drying air temperature of over 49°C and less than 55°C.

KEYWORDS: Solar, Energy, Moisture content, Dryers, Drying, Efficiency.
INTRODUCTION

Nigerian farmers lost about 20 to 60 percent of vegetables such as tomato, okra, onion, mango, carrot and others yearly due to inadequate processing and preservation methods (Karikari, 1989). Olajide et al. (2003) estimated food loses due to spoilage and mishandling in the lesser and underdeveloped countries to fall between 25 and 40%. Samaila et al. (2008) stated that harvested fruits are of high moisture content which under tropical conditions of high temperature and relative humidity are prone to rapid post-harvest deterioration and losses of up to 30 – 69%. Hence the convectional abundant supply of vegetables at give-away prices and great wastage during their peak period have persisted. The scarcity or non-availability of these crops in their off seasons has continued to be a common and ugly experience of the poor farmers. Eke, (1991) stated that, the length of time an agricultural product can be preserved is a direct function of its moisture content, chemical and physical compositions as well as the environmental conditions of the crop in question. Tomato, okra, onion, mango and carrot are highly perishable crops which naturally deteriorate few days after harvest. To keep these crops for some months in their fresh quality, so as to retain the actual nutrients, taste and colour, has remained a problem yet unsolved.

The crops in question, which are produced in large quantities in Sub-Saharan northern part of Nigeria, serve as a rich source of vitamin C to the farmers. Fargna (1985) reported that tomato contains about 50 mg of vitamin C in every 100 gm. Ihekoronye and Ngoddy (1985) found that vitamin C is very essential in healing body wounds. Luh and Woodroff (1975) showed that raising the temperature of these crops over 60°C for more than a few minutes in the presence of much air can cause destruction of vitamin C.
**Traditional method of drying vegetables**

Farmers generally dry their grains in thin-layer, that is the depth at which all the drying crop samples are exposed to equal amount of heated air flowing through the product layer. Sahay and Singh (2005) stated that the thickness of grains in thin-layer drying is normally up to 15 cm. Farmers equally dry some vegetable crops as a means of processing and preserving them for off season use. However, this method is associated with many problems. Olukosi et al. (1990) detailed on how farmers in Kaduna State, Nigeria, dry their vegetables (tomato and okro) and the problems they normally encounter. They explained that small and medium size ripen tomato are sliced into halves, while those of big size are cut into four parts, slicing of okro has no pattern, it is decided based on the farmers’ choice. The Researchers further stated that farmers had no knowledge of drying onion, mango and carrot. Lutz and Hardenburg (1967) gave the initial moisture content wet basis of tomato as 94 percent, while Peter and Raymond (1964) presented 4 percent moisture content wet basis as the safe storage moisture content of tomato.

Farmers leave the drying sliced tomato outside, in the dry season, until they are completely dried before packing them out. It takes about eight to ten days to dry a batch of sliced tomato in the dry season, while it takes about six to eight days in the raining season to dry a batch of sliced okra. During such a long drying time, the dried vegetables are usually contaminated with dirt, plant and animal remains, attacked by bacteria, fungi and rodents. Also, the colour of tomato changes to black or dirty colour. The farmers admitted that these drying problems are beyond their control.

Researchers have worked on solar dryers for drying grains and lower moisture content crops which farmers equally dry in open sun (John 2005 and Gbaha et al.,2007). Arinze et al (1990 and 1992 ) presented prototype solar dryers. Eke (1995) and Akani (1990) reported that the industrial
methods of preserving vegetables, tomato in particular, involve high skilled technology, which is capital-intensive and out of reach of the local farmers.

In this work the researcher had a major concern on high moisture content crops which farmers produce in large quantities but processing and storage remain insurmountable problems. Hence the main aims of this work are; to fabricate simple natural convection solar dryers for vegetables and fruits, which are high moisture content crops and to conduct preliminary tests on the dryers’ performances by the dryer system drying efficiencies.

MATERIALS AND METHODS

Locally available and affordable materials to the local farmers were employed in fabrication and test running of the solar dryers. Materials used were, wood, sawdust, corrugated roofing zinc, black oil paint, water–colour glass, hinges and staples, nylon netting, local kitchen knife and fresh ripened Ronita Caltvar tomato.

Design of the solar dryers based on the already existing models and the use of system drying efficiency were employed in fabrication and performance evaluation of the solar dryers.

Selection of experimental crop

Olukosi et al, (1990) asserted that farmers found it very difficult to preserve high moisture content crops, by open sun drying. The report further indicated that tomato harvested firm but ripen at 90 to 94 percent moisture content wet basis, would deteriorate after 3 to 5 days. Therefore it can rightly be assumed that tomato is a high moisture content and highly perishable crop. Hence tomato was chosen for design consideration of direct mode natural convection solar dryer in this work, the dryer will as well dry any other high moisture content crop.

Dryer Capacity
Eke (1995) reported that farmers in Hunkuyi, Marabadanja, sabon-gari and Samaru villages in Zaria and the suburbs, produce tomatoes, okra, onions, carrots and mangoes in large scale and they normally process tomatoes and okra for storage by drying in open sun. The farmers slice ripen small to medium sizes of tomatoes into two halves, while the large sizes are cut into four parts longitudinally. Similarly okra is sliced crosswise to a thickness of about 10mm. The sliced crops are arranged in single layer on surface of mats, rocks, ground, mud roof or road sides and left to dry naturally in the open sun. The quantity dried at a time varies, based on the available drying spaces and the quantity a farmer has. On the average they dry 2kg to 15kg of sliced tomatoes per batch drying. Using this as a basis to develop the capacity of a prototype solar dryer, 10kg of fresh ripened but firm Ronita Cultivar tomato sliced crosswise to a thickness of 15mm and arranged in single layer on crop tray in the drying chamber was chosen.

**Solar Dryer Design Consideration**

Based on the assumed capacity of 10kg fresh ripened sliced Ronita cultivar tomato, a rectangular direct mode natural convection solar dryer was designed. The solar dryer consisted of a square collector section and a square drying chamber section.

**Solar Energy Collector Section**

The collector section is a square box like structure, constructed with wood of 25mm thick by the sides. The wood equally served as the collector side insulator. Flat absorbing surface was made of corrugated roofing zinc painted with black oil paint, framed with wood and sandwiched with sawdust which served as the base insulator.
Water-colour glass, framed with wood, was mounted as the top cover. The space between the top cover and the absorber plate is the air plenum. This section is presented in figure 1.

**Figure 1:** Schematic of the solar collector section

A= water colour glass top cover, B= Air inlet space (Air plenum)
C= Sawdust (Insulator), D= Corrugated roofing zinc

**Drying Chamber Section**

The sides and the base housing of the drying chamber section were made with corrugated roofing zinc framed with wood, sand wished with saw dust and painted black. The top cover was made of water-colour glass framed with wood and hinged with staples, for easy opening and closing while loading or unloading a crop to and from the dryer. Crop tray constructed with nylon netting framed with wood, was positioned in the drying chamber. Air plenum under and above the crop tray were created for free circulation of air inside the dryer. Exhaust opening for transporting moisture out of the drying product was provided as the air outlet space at the upper end of the drying
chamber. The drying chamber section was also of a square shape but deeper than the collector section. This is shown in figure 2

![Figure 2: Schematic of the drying chamber section](image)

E= Drying chamber air outlet space, F= Crop tray in drying chamber

A= remains as defined earlier

The solar collector and drying chamber units were joined together to form a complete dryer, as indicated in figure 3.
Figure 3: Schematic of the assembled direct mode natural convection solar dryer

Determination Of Solar Collector Area

Duffie and Beckman (1980) and Holdman (1980) gave a model equation for calculation of solar energy collector.

\[ A_c = \frac{Q}{F_R t[I + U_R(T_c - T_o)]]} \] ........................................ (1)

Where

\( A_c \) = Solar collector area, m\(^2\)

\( Q \) = Collector useful heat energy gain required to dry a given quantity of agricultural product (J)

\( t \) = Drying time (seconds)

\( F_R \) = Collector heat removal factor (dimensionless)

\( I \) = Total solar radiation incident on the dryer (W/m\(^2\))

\( T_c \) = Glass transmissivity (dimensionless)

\( T_c \) = Collector air outlet temperature (°C)
\( T_a = \) Ambient temperature ( \(^{\circ}\)C)

\( U_L = \) Overall heat transfer coefficient. W/m\(^2\)\(^{\circ}\)C

**Collector Useful Heat Energy Gain**

The collector useful heat energy gain required to dry a given quantity of agricultural product, was obtained by using the procedure detailed by \( \text{Eke, 2003} \).

\[
Q = \left[ C_p W_p (T_c - T_a) + L_v D_m \right] \tag{2}
\]

where

\( C_p = \) Specific heat capacity of the product \((\text{J/kg}^{\circ}\text{C})\)

\( W_p = \) Initial weight of product before drying \((\text{kg})\)

\( L_v = \) Heat of evaporation of moisture from the product \((\text{J/kg})\)

\( D_m = \) Dry matter of product. \((\text{kg})\)

**Quantity Of Moisture Removed From The Product.**

Equation 3, a model given by \( \text{Henderson and Perry (1980)} \), was employed to determinate the quantity of water removed to dry the product from initial moisture content to safe storage (final) moisture content.

\[
W_w = \frac{MC_i - MC_f D_m}{100} \tag{3}
\]

But

\[
D_m = \left( W_p - \frac{W_p M_{wi}}{100} \right) \tag{4}
\]

where

\( M_{wi} = \) Initial moisture content of product (percentage wet basis)

\( MC_f = \) Final moisture content of product (percentage dry basis)
MCᵢ = Initial moisture content of product (percentage dry basis)

Wₚ = Quantity of water removed (kg)

The values of Fr, Uᵢ, I, Te of glass and Tc were obtained from (Eke, 2003)

Other values such as Cp and Lv were obtained from product thermal table, given by (Heldman and Singh 1980) and Ta was obtained from IAR meteorological unit. The parameter were used to calculate the collector area of the solar dryer as 1.0 m²

**Dryer insulation thickness**

To maximise the energy generation of the collector unit, the base of the collector was insulated with saw dust and optimum thickness of the insulator was determine using equation for heat transfer energy through a thin slab presented by (ASHREA 1977) in equation 5 and 6

\[
Q = \frac{T_c - T_a}{1/A \left[ \frac{1}{h_1} + \frac{\Delta X}{K} + \frac{\Delta X_1}{K_1} + \frac{\Delta X}{K_1} \right]}
\]

......................... (5)

Thus

\[
\Delta X_1 = \frac{AK_1}{Q} (T_c - T_a) \left( \frac{1}{h_1} + \frac{2\Delta X}{K} + \frac{1}{h_a} \right)^{-1}
\]

............... (6)

Where

h₁ = heat transfer coefficient at collector air outlet temperature (w/m²°C)

ΔX = Thickness of corrugated roofing zinc (0.0005m)

K = Thermal conductivity of zinc (112.1 w/m°C)

Dₓ₁ = Thickness of saw dust (insulation), m

K₁ = Thermal conductivity of saw dust w/m°C

hₐ = heat transfer coefficient at ambient air temperature, w/m²°C
The values of $K$ and $K_1$ were obtained from Holman 1980 as well as equations for calculation of $h_1$ at 45°C and $h_a$ at 29°C. The values of $\Delta X_1$ (thickness of insulator) obtained by calculation was multiplied by a factor of two to realise a thickness of 10mm.

**Fabrication of Five Solar Dryers**

The design specifications were followed to fabricate five similar direct mode natural convection solar dryers in the Department of Agricultural Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria. They were mounted on a wooden stand and inclined at an angle 15° at a horizontal position sloping toward south. The inclination enhanced trapping of maximum solar radiation on the dryer and free convection flow of air from the collector unit to the drying chamber where moisture is picked from the crop and carried out naturally through the drying chamber air outlet opening. Figure 4 showed the five solar dryers.

![Five Solar Dryers with some measuring instruments](image)

**Figure 4:** Five Solar Dryers with some measuring instruments
Drying Test

Tomato, okra, onion, carrot, and mango were used to evaluate the performance of the dryers. Each of these crops were sliced at the thickness of 15mm and each sliced sample loaded in single layer in a particular dryer and dried at the same time. Samples of each of the crops were spread in single layer to dry in open sun as controls.

Instrumentation

Ambient air, collector and drying chamber air outlet temperature for the five dryers were measured with a digital type - T- thermocouple of a 24- channel outlet, omega digital thermometer and mercury–in–glass thermometer. Solar radiation at the inclination of the dryer was measured with Haenni solar 118 Delta radiometer with digital read out. Relative humidity was monitored with digital omega hygrometer. A wind vane anemometer was used to measure the wind speed outside the dryer at the height of one meter above the ground. The drying sliced crops in the dryer and open sun were sampled out periodically and the moisture content in wet basis was measured by oven drying method. Measurements were done at two hours intervals in the day time for each batch drying. The data collection was replicated three times. The drying took place in the month of January, February March and April. In each of these months three batches of samples were dried and the average values of the parameters of the drying samples in the five dryers and the corresponding open sun drying were taken under the same ambient weather conditions for the analysis presented in this work.

Solar Dryer Drying Efficiency

The system drying efficiency of the dryer was one of the basis for assessing the performance of the solar dryer and the control. System drying efficiency free convection
solar dryer \( \int_{sd} \) was obtained from the following relationship (Brenndorfer et al 1987 in Akani 1990)

\[
\int_{sd} = \frac{M_w L_v}{I T A t} \quad \text{................................. (7)}
\]

RESULTS AND DISCUSSION

Figure 5, 6, 7 and 8 showed the results of the drying curves of average values of collector (Tc)-°C and drying chamber (Td)-°C air outlet temperatures, Weather factors monitored during drying test, (solar radiation (I)-W/m², ambient (Ta)-°C, ambient relative humidity (Rh)-% and wind speed (wsp)-m/s) and the moisture contents (M)-% of the drying products.

Figure 5: Curves of average values of TcTo, TcOn, TcOk, TcMa and TcCa solar collector air outlet temperatures for collectors drying tomato, onion, okro, mango and carrot respectively.
Figure 6: Curves of average values of TdTo, TdOn, TdOk, TdMa and TdCa solar drying chamber air outlet temperatures for dryers drying tomato, onion, okro, mango and carrot respectively.
Figure 7: Curves of average values of weather factors during solar and open sun drying of crops (ambient temperature (Ta), wind speed (Wsp), relative humidity (Rh), solar radiation (I)).
Figure 8: Average values of moisture contents – wet basis (%) of tomato (Mtod) / (Mtos), onion (Mond) / (Mons), okro (Mokd) / (Moks), mango (Mmad) / (Mmas) and carrot (Mcad) / (Mcas) dried with solar dryer and open sun respectively.

Table 1 is generated from the analysis of results in figure 5 to 8. Hence, results on the effect of solar and open sun drying of the crops in question are summarised in tables 1 and 2.
**Table 1**: Effect of solar and open sun drying on tomato, onion, okra, mango and carrot.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Crop</th>
<th>Nature of crop</th>
<th>Method of drying</th>
<th>Thickness of slices (mm)</th>
<th>Total drying time (hr)</th>
<th>Effective drying time (hr)</th>
<th>Moisture content (MC) wet basis (%)</th>
<th>Colour rated on 5-point scale</th>
<th>Pungent aroma rated on 5-point scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tomato</td>
<td>Fresh</td>
<td>Solar dryer</td>
<td>15</td>
<td>76</td>
<td>34</td>
<td>93</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dried</td>
<td>Open sun</td>
<td>15</td>
<td>154</td>
<td>70</td>
<td>93</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Onion</td>
<td>Fresh</td>
<td>Solar dryer</td>
<td>15</td>
<td>58</td>
<td>30</td>
<td>87</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dried</td>
<td>Open sun</td>
<td>15</td>
<td>106</td>
<td>50</td>
<td>87</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Okra</td>
<td>Fresh</td>
<td>Solar dryer</td>
<td>15</td>
<td>56</td>
<td>28</td>
<td>88</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dried</td>
<td>Open sun</td>
<td>15</td>
<td>102</td>
<td>46</td>
<td>88</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Mango</td>
<td>Fresh</td>
<td>Solar dryer</td>
<td>15</td>
<td>78</td>
<td>36</td>
<td>88</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dried</td>
<td>Open sun</td>
<td>15</td>
<td>170</td>
<td>72</td>
<td>88</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Carrot</td>
<td>Fresh</td>
<td>Solar dryer</td>
<td>15</td>
<td>77</td>
<td>35</td>
<td>88</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dried</td>
<td>Open sun</td>
<td>15</td>
<td>152</td>
<td>68</td>
<td>88</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

The system drying efficiencies of the samples dried with solar dryers and open sun drying methods are presented in Table 2.
Table 2 : System drying efficiencies of the dried products

<table>
<thead>
<tr>
<th>S/N</th>
<th>Crop</th>
<th>Nature of crop</th>
<th>Method of drying</th>
<th>System drying Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tomato</td>
<td>Fresh</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dried</td>
<td>Solar dryer</td>
<td>21.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Open sun</td>
<td>10.59</td>
</tr>
<tr>
<td>2</td>
<td>Onion</td>
<td>Fresh</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dried</td>
<td>Solar dryer</td>
<td>21.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Open sun</td>
<td>12.71</td>
</tr>
<tr>
<td>3</td>
<td>Okra</td>
<td>Fresh</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dried</td>
<td>Solar dryer</td>
<td>24.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Open sun</td>
<td>15.19</td>
</tr>
<tr>
<td>4</td>
<td>Mango</td>
<td>Fresh</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dried</td>
<td>Solar dryer</td>
<td>19.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Open sun</td>
<td>9.68</td>
</tr>
<tr>
<td>5</td>
<td>Carrot</td>
<td>Fresh</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dried</td>
<td>Solar dryer</td>
<td>19.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Open sun</td>
<td>10.29</td>
</tr>
</tbody>
</table>

The sliced samples of tomato, onion, okra, mango and carrot dried with solar dryers, achieved 54.55, 52.88, 50.98, 57.65 and 55.26 percent gain in drying time respectively, over the open sun drying method. Figure 5 to 8 equally indicated that tomato, onion, okra, mango and carrot were dried at average daily solar dryer temperature of 49.9°C, 51.17°C, 52.29°C, 50.5°C and 49.9°C respectively. These average daily solar dryer temperatures are within the limit of the recommended 60°C drying
temperatures for vegetables (Ihekoronye and Ngoddy, 1985). All the crops dried were of high moisture content, however, air outlet temperature of the drying chambers were not the same, although the dryers were similar in size and of the same quantity of samples by weight. These differences in temperature of the drying chambers might be due to the crops, thermal properties as well as the quantity of moisture evaporated from the product. Thus the higher the quantity of moisture removed the lower the dryer outlet temperature.

Generally the system drying efficiencies are characterized with low percentage values. This is because single layer drying of sliced crops require large drying area. Hence a given drying area can only contain relatively small quantity of the drying sliced crop.

Equation 7 was employed to analysis the system drying efficiencies and this revealed that tomato, onion, okra, mango, and carrot dried in solar dryers attained 105.85, 66.6, 64.25,100.00 and 93.97 percent respectively higher than the system drying efficiencies of the same sample dried in open sun. This showed that drying of tomato, mango and carrot and such like products can best be achieved by solar dryer than open sun drying. Although system drying efficiency of onion is comparatively low, the crop cannot be dried in open sun because the pungent aroma is usually lost when exposed to unconfined space environment.

**CONCLUSION**

Five similar natural convection direct mode solar vegetable dryers were designed and constructed with locally available materials. Evaluation of the dryers’ drying performances on the given crops indicated that over 50 percent savings in drying time can be achieved with the use of solar dryers.
Based on the data analysis of the dryer and the traditional open sun drying, it is concluded as follows:

System drying efficiencies of tomato, onion okra, mango and carrot dried in solar dryers were determined.

Colour changes of the dried vegetables is a function of their period of exposure to solar radiation and the dust contamination.

Onion dried with solar dryer retains most of its pungent aroma.

The overall average solar dryer temperature was not higher than 60°C and heat flow was by natural convection.

In the rural areas where there is no scientific instrument to measure moisture content of the drying crop, it can be determined when tomato, onion and okro are dried to safe storage moisture content by squeezing the products in the palm and texture is brittle.

Drying samples in the open sun were rewetted over the night.

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Westport


