Investigation of low cost solar collector for drying vegetables in rural areas

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Abstract: Despite the numerous solar dryers reported by researchers in Nigeria, farmers in Zaria Nigeria continue to dry tomato by traditional open sun drying method, the inherent problems associated with this method notwithstanding. Therefore this research is aimed at investigating suitable solar collector material that is available, affordable and can easily be worked on by rural farmers. Metal, wood, cement and mud which are commonly available local materials were used to fabricate four types of solar dryers and the dryers were mounted truly facing south. Sliced tomato samples were used for performance test of the dryers. Moisture content of the samples, dryer temperature, wind speed, relative humidity and solar radiation were monitored at 2 hours intervals. From the analysis, the dryers' savings in drying time over the open sun drying for wood, cement, mud and metal dryers were 131.25%, 131.25%, 136.17% and 192.11% respectively. Average ambient wind speed during the drying period was 0.98 m/s, while that of relative humidity was 23.85%. The metal dryer dried sliced tomato 18 hours ahead of mud dryer, while cement and wood dryers dried the sliced tomato 2 hours longer than the samples dried in the mud dryer. Temperature, energy generation, saving in drying time and cost effectiveness, of mud dryer when analysed at F-test at 0.01 and 0.05 degree of freedom indicated statistical significant difference when compared with wood and cement dryers. The dryers equally indicated 7.38%, 19.56%, 20.25%, 20.91% and 27. 24% system drying efficiencies, for open sun, wood, cement, mud and metal in that order. This work revealed that mud solar dryer is available, affordable and can easily be worked on by rural farmers. Results from this work indicated that mud direct mode natural convection solar dryer is best suited for Zaria and Zaria related geographical locations.

Keywords: solar, energy, collector, crop, drying, drying efficiencies

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1 Introduction

Energy supply is one of the important but scarce commodities to the rural farmers in Nigeria. However energy usage is inevitable in processing and preservation of biomaterials. Energy from the firewood which is mainly employed in domestic food processing courses deforestation. Also firewood pollutes the environment with smoke and creosote which enhances global warming. The effect of smoke on individual over time leads to partial or permanent lost of sight (Collins, 2001). Therefore majority of elderly people in Nigeria particularly women have eye – problems, which normally advances to partial or total blindness. This is because wood smoke contains many chemical products, including carcinogens, carbon monoxide, and hydrocarbons that are detrimental to human health (Tony, 1997). This greatly affects the economy of the country, because much is spent on recycling problems.

Solar energy which is renewable is commonly available and affordable to local farmers. Zhiqiang (2000) asserted that introduction of solar energy technology in the rural areas of China will help to abate

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the excessive deforestation which is already causing ecological deterioration. Kaul and Egbo (1985) and Abdulsalam et al. (2012) opined that about 490 – 522.2 W/m^2 of the solar radiation floods Nigeria as monthly average daily horizontal solar radiation intensity. This radiation provides a potential energy source, released at no cost, but wasted because of lack of adequate technology to harness it. Solar energy is renewable and available for sustainability of any project in Nigeria that is dependent on solar energy as source of power supply (Adejumo and Bamgboye, 2004). Drying is one of the oldest techniques of preserving agricultural products. Drying as a process for food conservation and preservation seems to be an adequate method under most conditions in the developing economies (Ali and Sakr, 1981). The farmers normally preserve their agricultural products by drying down to shelf storage moisture content. National supply of electricity to the rural dwellers, mainly farmers, is erratic and in many places not available. On the order hand, fossil fuel is very costly and unaffordable to the farmers (Itodo et al., 2002). The only commonly available and affordable energy supply to the rural dwellers is solar energy.

Farmers in Zaria and her neighboring villages traditionally preserve their vegetables such as tomato, okra, pepper and others by spreading the crops in single layer, for drying on surface of rock, on top of mud roof, road sides and on local raffia baskets. Agricultural materials spread on these surfaces are left to dry in the open sun at ambient weather conditions; therefore, the products usually take a long period to dry. Farmers reported that during the rainy and dry seasons, maize took eight days and five days respectively to dry to shelf storage moisture content, while okra took six days and four days to dry in rainy and dry season respectively to safe storage moisture content (Eke, 1991). After this long period of drying the product are contaminated, deteriorated or completely spoilt. Taiwo (2013) asserted that Nigerian farmers currently lose as high as 30% - 50% of vegetables, fruits and some tuber post harvest crops in spite of their age-long open sun drying practice. However the abundant solar energy the farmers normally use in open sun drying can be harnessed by a solar collector for effective crop drying.

Solar collector is the essential item of equipment which transforms solar radiant energy to some other useful energy form (Duffie and Backman, 1980). A flat-plate thermal solar collector consists of an absorber, a transparent cover, a frame and insulator. Many researchers have designed flat plate surface thermal solar collector with different materials. Wikipedia (2011) reported that new polymer temperate silicones flat plate collectors are now being produced in Europe. In a wider usage of solar collector, Yasser et al. (2009) used 9, 10-diphenylanthracene for solar cell collector which indicated an improvement in light harvesting and charge carrier transfer. Ryu et al. (2010) stated that polymer treated with fullerene and a UV absorbing film performed well when used as organic solar cells. Angewandte (2010) indicated that fulvalene diruthenium oercome when used as solar collector material was able to store thermal energy and released same when direct solar radiation was not available. Kruidhof and Vander (1979) reported that Cobalt oxide on bright nickel-electroplated steel was used as a spectrally selective material in solar collector with a good result. Plastic can equally be used as a low temperature solar collector, but it deteriorates quickly due to ultra-violet radiation effect (AMECO, 2009). John (2005) stated that plastic was successfully used as solar collector for solar swimming pool, where the water was heated up to 27^{0}C during the cold period. Wood, metal and Galvanically applied selective coating, such as black chrome, black nickel and aluminum oxide with nickel were used as natural convective heat flow solar collectors for solar dryers (Gbaha et al., 2007 and Heindl 2010). Parker (1978) investigated the effect of plane and vee-corrugated surfaces made of zinc chromate and painted black on solar energy absorption and found it to be highly efficient. Arinze et al. (1990), Akani (1990) and Eke (1991) used mild, galvanized metal sheets, cement plastered surface, corrugated roofing zinc and plywood as collector surfaces for solar thermal collector. All indicated that these materials can be used as solar collectors. Despite the numerous solar dryers reported by researchers in Nigeria, farmers in Zaria Nigeria continue to dry tomato by traditional open sun drying method, the inherent problems associated with this method notwithstanding. Therefore this research is aimed at investigating suitable solar thermal energy collector material that is available, affordable and can easily be worked on by rural farmers.

2 Materials and methods

The farmers spread their crops on the ground, rock surfaces, roadsides, mud roofs, flat surfaces like raffia tray and metal trays. Therefore sheet metal, cemented surface, wood and mud are selected as material for consideration. The design considerations and material selections in this work are based on thermal properties, resistance to weather effects, availability, affordability and workability of materials.

2.1 Capacity of the solar dryers

Interview conducted in the north west zone of Nigeria, where Zaria is located, revealed that farmers have the greatest problems in drying tomato (Olukosi et al., 1990). This is because tomatoes have high moisture content with soft tissue and need to be dried at a short time in order to avoid spoilage. The difficulties in drying tomatoes forced the farmers to dry less than 1 to 10 kg of fresh sliced tomato at a time in open sunlight, the quantity dried at a time depends on available drying space. The drying operation takes about 13 to 15 days for a batch drying. Therefore the capacity of each of the prototype solar dryers in this work was chosen to be 10 kg of fresh sliced tomato. Hall (1986) gave the shelf storage moisture content of dried tomato as 4% moisture content (wet basis). Quantity of water to be removed from 10 kg fresh tomato to dry from 93% to 4.5% moisture content wet basis was calculated by equation given by (Henderson and Perry, 1980) as;

$$W_w = \frac{MC_i - MC_f}{100}\left(W_p - \left[\frac{W_p M_{wi}}{100}\right]\right) \quad (1)$$

The collector useful heat energy gain Q, required to dry 10 kg of tomato from 93% to 4.5% Moisture content wet basis was obtained using the procedure detailed by (Eke, 2003), which is expressed as:

$$Q = \left[C_p W_p (T_c - T_a) + L_v\left(\frac{MC_i - MC_f}{100}\right)W_p - \frac{W_p M_{wi}}{100}\right]\frac{1}{t} \quad (2)$$

where, Q = collector useful thermal energy gain, W; C_p = specific heat of tomato (cv. Ronita), 3680 J (kg °C)$^{-1}$ (Heldman and Singh, 1980); W_p = weight of fresh tomato before drying, kg; MC_i = initial moisture content of tomato (fresh sliced tomato) in dry basis, %; MC_f = final moisture content of tomato (safe storage moisture content of sliced tomato) in dry basis, %; M_{wi} =initial moisture content of tomato (fresh sliced tomato) in wet basis, %; W_w = weight of moisture to be removed from the tomato to effect drying from the initial to final moisture content, kg; t = drying time, s; L_v = heat of vaporization; of moisture at the drying air temperature obtained from Equation (3) (ASAE, 1998 reported in Abd EI-Wahab et al., 2011) , J/kg.

$$L_v = 2{,}502{,}535.259 - 2{,}385.76424(T_d - 273.16); \quad \text{at } 273.16 \# T_d \quad 338.72 \quad (3)$$

where, T_d = drying air temperature, K.

2.2 Determination of the solar dryer size configurations

Duffie and Beckman (1980) gave the model equation as:

$$A_c = \frac{Q}{F_R}\left[IT_r - U_L(T_c - T_a)\right] \quad (4)$$

where, A_c = solar collector Area, m^2; Q = collector useful heat energy gain required to dry a given quantity of agricultural product, kg; F_R = collector heat removal factor of value 0.45 (Duffie and Beckman 1980); I = total solar radiation incident on the dryer 450 W/m^2 (measured with solar Radiometer placed at the same inclination with the dryer); T_r = polythene transmissivity (0.83); U_L = overall heat transfer coefficient, 8.5 W (m^2 °C)$^{-1}$ as worked out by Eke (2003); T_c = collector air outlet temperature, °C; and T_a = ambient temperature, °C. The area A_c of solar collector was calculated to be 0.56 m^2 while the drying chamber was 0.93m^2.

2.3 System drying efficiency

Performances of the four types of solar crop dryers were evaluated by considering their system drying efficiencies, available, affordable, workability and dried product quality. Brenndorfer et al. (1987) reported in Akani (1990) gave the expression for System Drying Efficiencies (E_{Sd})as the ratio of the heat required to evaporate a given quantity of moisture from the product to useful heat gain generated by the solar dryer. Thus;

$$E_{sd} = {W_w L_v}/{A_c t I T_r} \quad (5)$$

The terms remained as already defined.

2.4 Feature of the solar dryers

Equations (1) to (4) were employed to achieve the size configuration of the direct mode, free convection metal-type, wood-type, cement-type and mud-type solar dryers, in the Department of Agricultural Engineering, Ahmadu Bello University, Zaria. Each of the four types of dryers consisted of a solar collector of 0.61 m wide, 0.92 m long and a drying chamber of 1.53 m long with same width as the collector, as well as air plenum of 0.065 m. The inlet and outlet air plenum provided free convection air flow through the dryer. Transparent glass sheet of thickness 5 mm was used as the collector and drying chamber top cover material.

Metal, wood, cement and mud type dryers solar collector (absorber surface) were made of sheet metal, plywood, cement and mud materials respectively. They were painted black with black oil paint, while polystyrene board was used to insulate the bottom and side parts of the metal and wood collectors. The dryers were mounted at an angle of 15^o to the horizontal and truly facing south. The dryers were similar in size and shape but only differ from each other in the materials used for their solar collector construction. Hinged cover was attached to aid in loading and unloading the drying crops. Basically, UC-B80 variety of tomato was used to evaluate the solar dryers. Fresh ripened but firm tomato at 90% moisture content wet basis, of the cited variety was sliced into average thickness of 15 mm and spread in a single layer on the crop trays in the drying chamber was dried. A set of the sliced tomato was spread in a single layer in open sun, which served as control. Market surveys on prices of materials used to fabricate the dryers were conducted in Zaria and the environs. The dryers are shown in Figures 1 to 4.

Figure 1 Solar dryer with metal plate solar thermal collector

Figure 2 Solar dryer with wood solar thermal collector

Figure 3 Solar dryer with cement thermal solar collector

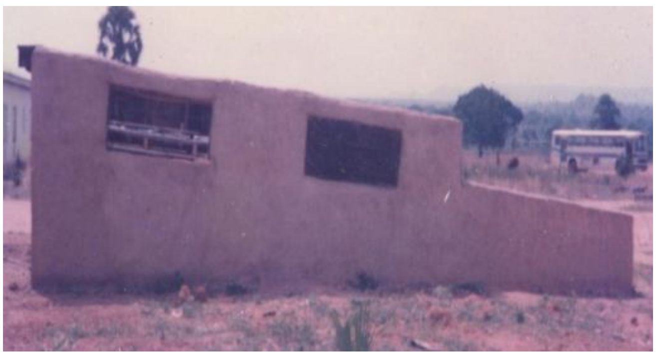

Figure 4 Solar dryer with mud solar thermal collector

2.5 Instrumentation

Ambient air, collector and drying chamber air outlet's temperatures for the four dryers were measured with type T-Thermocouples of a 24–channel outlet and Omega digital Thermometer. Solar radiation at the inclination of the dryers was measured with Haenni solar 118 Delta Radiometer with digital read out. Relative humidity was monitored with digital Omega Hygrometer. A vane anemometer was used to measure ambient wind speed, at the height of one meter above the ground. The drying sliced tomato in the dryers and open sun were sampled out periodically and the moisture content in wet basis was measured by oven drying method.

3 Results and discussion

Figures 5, 6, 7 and 8 showed the results of the curves of average values of ambient temperature (Ta), wind speed (Wsp), relative humidity (Rh), solar radiation (I) which are weather factors during solar and open sun drying and evaluation of the dryers. Curves of average values of wood, cement, mud and metal for collectors (Tc)-^{o}C and drying chamber (Td)-^{o}C air outlet temperatures respectively, and the moisture contents (Mc-%) of crop dried with wood, cement, mud and metal dryers.

Figure 5 shows the air outlet temperatures for Wood, Cement, Mud and Metal collector as attaining 24.66%, 25.03%, 26.01% and 30.13% respectively, higher than the ambient air temperature. The metal collector indicated the highest increase in temperature. This can be mainly attributed to the fact that the lactic structures of the metal is easily excited to vibrate at a higher frequency than wood, cement and mud, when exposed to the same solar radiation intensity. Therefore the frictional force that occurred during the high frequency vibration in the

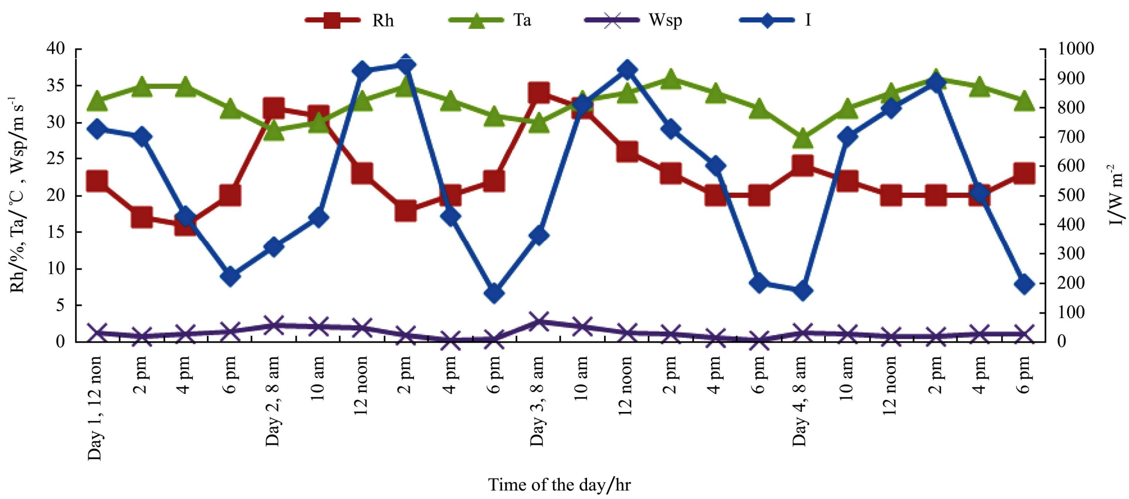

Figure 5 Curves of average values of weather factors during solar and open sun drying of crops (ambient temperature (Ta), wind speed (Wsp), relative humidity (Rh), solar radiation (I))

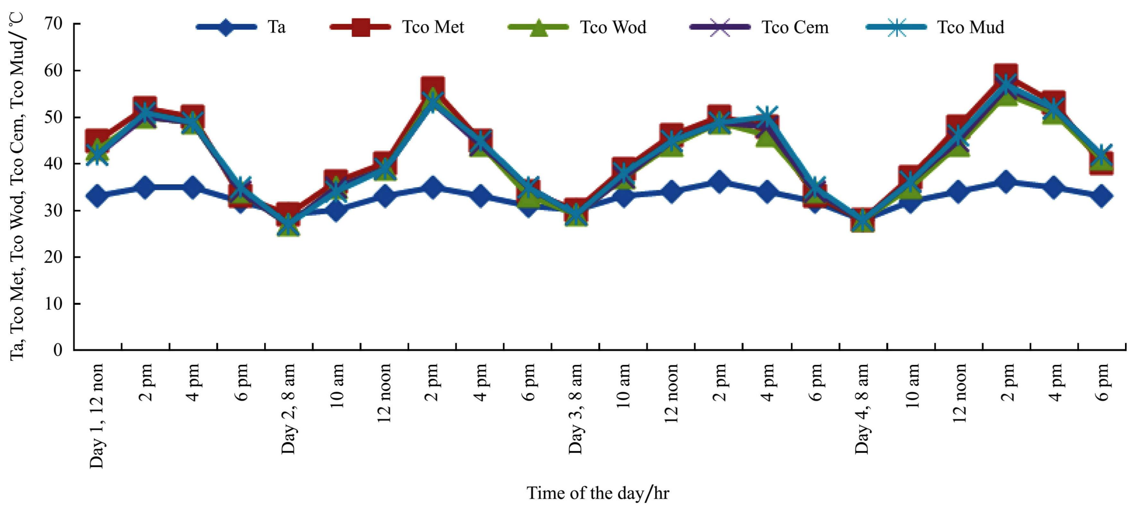

Figure 6 Curves of average values of temperature generated by metal (Tco Met), wood (Tco Wod), cement (Tco Cem), mud (Tco Mud) collectors and of ambient temperature (Ta)

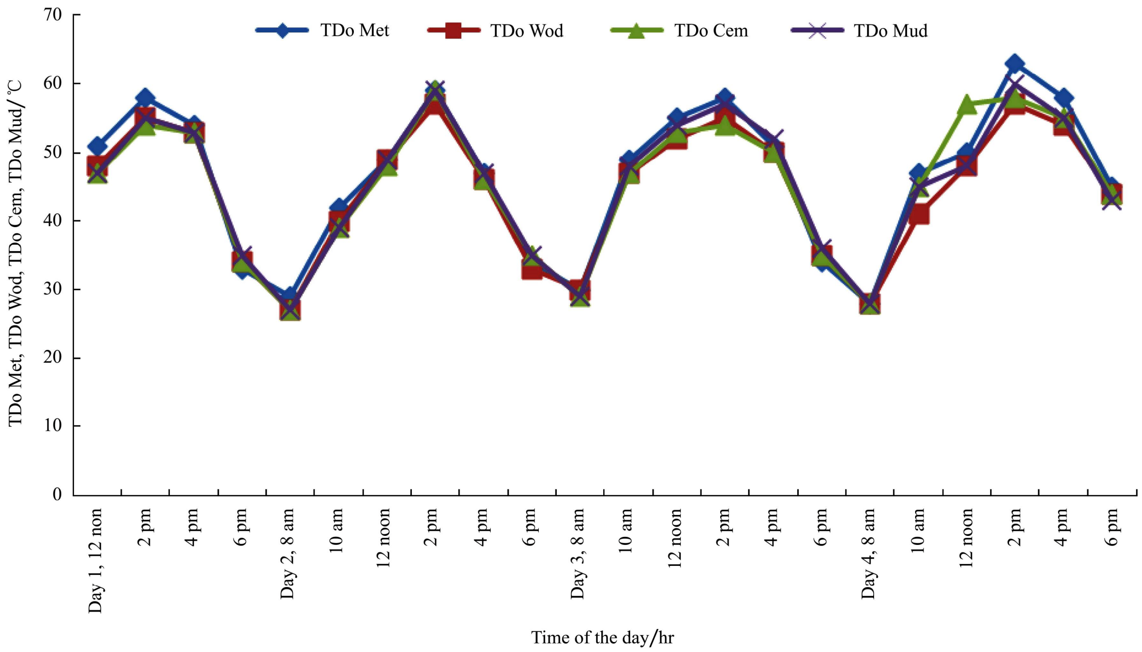

Figure 7 Curves of average values of temperature generated by metal (TDo Met), wood (TDo Wod), cement (TDo Cem) and mud (TDo Mud) drying chamber sections

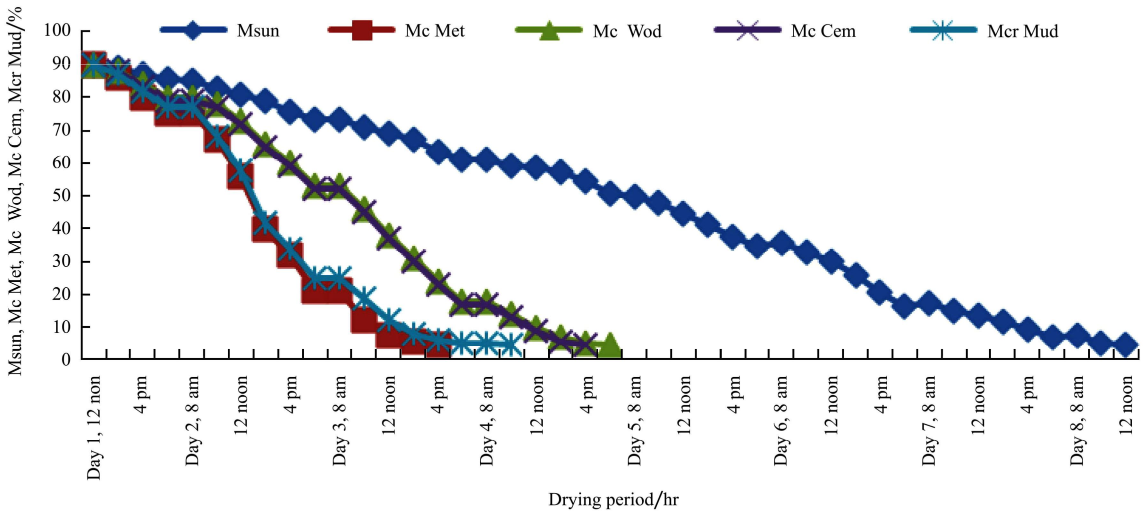

Figure 8 Curves of average values of the moisture content (wet basis, %) for the product dried in (Msun – open sun; McMet-metal dryer; McWod-wood dryer; McCem-cement dryer and McMud-mud dryer)

metallic lactic produced higher thermal energy, which resulted to higher temperature more than the other collectors, when exposed to the same solar radiation intensity. The temperature in the drying chamber was generally increased as indicated in Figure 3 because the dryers were direct mode; this enhanced the drying rate of the product.

Table 1 was generated from Figures 2 and 3. It also indicated the production cost of the four dryers.

The moisture levels, duration of drying of tomato and temperature generated by various dryers and open sun drying were analyzed from Figures 1 and 2 and Table 1. From the analysis, the dryers' savings in drying time over the open sun drying for wood, cement, mud and metal dryers were 131.25%, 131.25%, 136.17% and 192.11% respectively. Moisture from the sliced tomato was driven out by natural convection which resulted in long drying time, the samples dried from initial moisture content of 90% (wet basis) to 4.0% (wet basis). The average ambient wind speed during the drying period was 0.98 m/s, while that of relative humidity was 23.85%. The metal dryer dried the sliced tomato 18 hours ahead of mud dryer, while cement and wood dryers which dried the crops at same time took 2 hours longer than the tomato slices dried in the mud dryer. It was observed that the metal dryer consistently exhibited higher performance in the drying operation. However, there was no statistical significant difference in the crop drying rate and collector heat generation from the four types of dryers. Equation (4) was employed to calculate System Drying Efficiencies of the dryers which were 7.38%, 19.56%, 20.25%, 20.91% and 27.24%, for open sunlight, wood, cement, mud and metal in that order. The system drying efficiency is generally low because tomato can only be effectively dried in slices spread in single layer and that makes it occupy a large area of space.

Table 1 Dryers' performances while drying tomato and the dryers' production cost

N/S		Metal Dryer	Wood Dryer	Cement Dryer	Mud Dryer	Open Sun Drying
1	Average temperature generated by solar collector units of these dryers during the drying test, °C	42.43	40.64	40.76	41.08	30.00
2	Average temperature generated by solar drying chambers of these dryers during the drying test, °C	46.62	42.52	43.10	44.08	30.00
3	Initial tomato moisture content-Wet basis, %	90.00	90.00	90.00	90.00	90.00
4	Final tomato moisture content- Wet basis, %	4.00	4.00	4.00	4.00	4.00
5	Total drying time, hr	76.00	96.00	96.00	94.00	222.00
6	Production cost, ₦	15,000.00	8,860.00	10,470.00	5,000.00	-

The collectors indicated 41.43%, 35.47%, 35.87% and 36.93% increase in temperature over the ambient temperature for metal, wood, cement and mud collectors respectively. The dryers generated higher heat energy at the drying chambers because they were direct mode natural convection solar dryers and the drying principle was non-adiabatic.

Analysis of the market survey revealed that mud solar dryer has the lowest production cost of five thousand naira, while the percentage increase in prices of cement, wood, and metal dryers against the mud dryer were 109.40%, 77.20% and 200% respectively. The performance of mud dryer in temperature and energy generation as well as saving in drying time and cost effectiveness, when analysed at F-test at 0.01 and 0.05 degree of freedom indicated statistical significant difference result when compared with wood and cement dryers. However the metal dryer performed better in terms of savings in drying time and high thermal energy generation, at the period of solar radiation in day time. The mud solar dryer stored thermal energy longer than all the other solar collector materials; this might have been one of the reasons for the better performance of the mud solar dryer. It was also observed that farmers normally use mud for erecting structures. Thus out of these local materials, mud is most commonly available, easiest to work on and affordable to farmers. The overall performance of the dryers indicated that the mud solar dryer can be rightly suggested to be the most suitable local material for fabrication of natural convection direct mode solar dryer in rural areas.

4 Conclusions

Direct mode passive solar dryers made of metal, wood, cement and mud which are commonly available and local materials were used to construct four similar solar thermal dryers. Analysis of these dryers revealed that the dryers' savings in drying time over the open sun drying for wood, cement, mud and metal dryers were 131.25%, 131.25%, 136.17% and 192.11% respectively. The dryers equally indicated 7.38%, 19.56%, 20.25%, 20.91% and 27. 24% system drying efficiencies, for open sun, wood, cement, mud and metal in that order. The performance of mud dryer in temperature, energy generation, saving in drying time and cost effectiveness, when analysed at F-test at 0.01 and 0.05 degree of freedom indicated statistical significant difference when compared with wood and cement dryers. Based on tomato drying performance and cost of production mud was identified as commonly available, affordable and most suitable material for the construction of direct mode natural convection solar dryer for rural farmers in Zaria and Zaria related geographical locations

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