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(RESEARCH ARTICLE)

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# Development and performance evaluation of a dual energy source solar dryer for tomatoes

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## Abstract

Solar energy is the most promising of the renewable energy sources in view of its apparent limitless potential. A Dual energy Source Solar Dryer was developed under Bauchi weather at latitude 9°14′ N and longitude 12°26′ E using locally available materials and the performance was evaluated. The essence of the dryer was to achieve the effective method of tomato preservation and eliminate the drudgery and product deterioration associated with traditional methods of open sun drying of tomatoes. This is in view of alleviating the weather limitation experienced by farmers in crop drying especially for tomatoes. The solar dryer consists of tray, reflective walls and glass roof, a preheating air absorber plate, inner panels for removal of moisture and chimney through which air stream passes across the dryer. Evaluation of the dryer showed a raised temperature of about 47 °C attainable in the drying chamber. The dryer temperature and drying rate was found to be higher than the natural open sun drying method. The dryer was able to reduce moisture content of tomato from initial moisture content of 94% wet basis to 4% in three days with effective drying time of 24 h, efficiency of 64%, air mass flow rate of 0.025 kg s-1 and drying rate of 0.03906 kg h-1. The results showed a considerable advantage of solar dryer over the traditional open sun drying method in terms of drying rate and less risk for spoilage.

**Keywords:** Solar; Solar Dryer; Tomatoes; Quartz Amethyst

## 1. Introduction

Solar thermal technology is a technology that is rapidly gaining acceptance as an energy saving measure in agricultural application. It is proffered to other alternative sources of energy such as wind and shale, because it is abundant, in exhaustible and non-polluting [1]. Solar energy has numerous applications when it is converted to heat, electricity or biomass. The technologies for conversion of solar energy into heat and electricity can be classified into solar thermal systems and photovoltaic (PV) or solar electricity. The unique advantages of solar energy which includes; readily availability, cost free, pollution-free, make it a very attractive source of energy [2].

Preservation of human and animal food by open air drying was presumably one of the first conscious and purposeful technological activities undertaken by man [3] over the last few decades, open air drying has gradually become more cumbersome because of the acquirement for a large area, quality degradation, contamination from rodents, air, birds and insects that makes it unhygienic [3].

[4] 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 %. [5] Stated that this affects the economy of about 60 to 70 percent of the nation's population who are engaged in agriculture and agro-based

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industries. Tomato is highly perishable and preservation for off season use is really a great problem to farmers. [6] Stated that the initial moisture contents of tomatoes range from 90 to 94% wet basis and must be dried to 4.5% moisture content for safe storage. [7] Asserted that farmers utilized direct solar radiation in traditional method of tomato drying, in which case sliced tomatoes are spread in the sun on mats, surface of rocks, mud roofs and on road sides. Considerable percentage of the drying tomatoes deteriorates due to slow rate of drying. It takes 13 days and 8 days in high humid and low humid weather respectively to dry tomatoes in open sun. Generally, the qualities of open sun-dried tomatoes are hygienically of low standard.

## 2. Material and methods

Materials used in the construction of the intermittent tomatoes solar dryer were selected based on their properties. Such properties are physical, thermal and isolative. The dryer is made up of five components.

- The Solar collector
- The Drying chamber
- The quartz amethyst chamber
- Storage chamber
- The frame of the Dryer

### 2.1. The solar dryer

Transparent glass was used as the cover of the solar collector compartment, the glazing is 3 mm thick transparent glass sheet as suggested by [8], it do not allow heat radiation to pass through them but absorb heat and get them heated (Altermanoul substance), the glass also provide a greenhouse effect. The heat absorber (inner box) of the solar air heater was constructed using 2 mm thick aluminium plate, painted black mounted in an outer box of the collector built from well-seasoned wood timber (plywood) as shown in Figure 1. The space between the inner box and the outer box is filled with a foam material of about 45 mm thickness and thermal conductivity of 0.044 W/mK. The collector assembly consists of air flow channel enclosed by transparent cover and the absorber back plate provides effective air heating so that solar radiation that passes though the transparent cover is then absorbed by both the mesh and black-plate. Air inlet vent is covered by a galvanized wire mesh to prevent entrance of rodents while the other end opens to the plenum chamber.

**Figure 1** Constructed Solar Dryer

The solar collector is tilted and oriented at an angle of ($b = 10° + lat.\theta$) in such a way that it receives maximum solar radiation during the desired season of use. The best stationary orientation is due south in the northern hemisphere and due North in southern hemisphere. This inclination is also to allow easy run off of water and enhance air circulation.

### 2.2. The Drying Chamber

The drying chamber is also a wooden box and was dimensioned based on the bulk density of tomatoes [9]. Thermal energy balance was computed considering the useful energy required for drying, and the thermal losses of the system. The heat required to evaporate the moisture and keep the tomatoes at the dryer temperature. The drying cabinet was made up of mild steel wire mesh of 3 mm diameter, its perforation allows air to pass through the tomatoes, this which promotes the drying process.

The frame of the dryer was built from a well-seasoned wood (plywood) which could withstand termite and atmospheric attacks, see Figure 2. An outlet vent was provided towards the upper end at the back of the cabinet to facilitate and control the convection flow of air through the dryer. The four opposite side walls of the cabinet are covered with plywood sheets of ¾" thick, which provides additional insulation and the drying cabinet was covered (roof) with a glazing material of 3 mm thick glass.

**Figure 2** Inner view of the solar dryer

### 2.3. The Quartz amethyst chamber

The Quartz Amethyst stones were used instead of marble stones, this is because of their strong heat absorption and long heat retention as heat absorbers, they were painted black which makes them good heat absorbers and emitters of heat to the samples but bad reflectors of heat while absorbing from the sun.

**Figure 3** Constructed solar collector

### 2.4. The drying tray

This is constructed from a well-seasoned wood (plywood) and a layer of wire mesh with a partly opened structure to allow drying to pass through the tomatoes. It uses the sun energy rays entering through the collector glazing and the drying chamber glazing cover. The trapping of rays is enhanced by the internal surfaces of the collector that was painted black and the trapped energy heats the air within the collector. The greenhouse effects achieved through the collector drives the air current into the drying chamber. If the vents are opened, the hot air rises and escapes through the upper vent in the drying chamber while cool air at ambient temperature enters through the lower vent in the collector, therefore, an air current is maintained, as cooler air at a temperature Ta enters through the lower vents and hot air at a temperature Te leaves though the upper vent.

**Figure 4** Coupling the collector & drying chamber

When the dryer is empty i.e. contains no sliced tomatoes to be dried, the incoming air at temperature Ta has a relative humidity Ha and the outgoing air at a temperature Te has a relative humidity He. This is because Te > Ta and the dryer contain no item, Ha > He. Thus, there is tendency for the outgoing hot air to pick more moisture within the dryer as a result of difference in humidity. Therefore, insulation received is principally used in increasing the affinity of the air in the dryer to pick moisture.

### 2.5. Orientation of the solar collector

The solar collector is tilted and oriented in such a way that it receives maximum solar radiation. The best stationary orientation is due south in the northern hemisphere and due north in the southern hemisphere, the tilted angle is $20^{o}$.

### 2.6. Dryer design features

The dryer has a tilted transparent top. The angle of the slope of the dryer cover is $20^{o}$ for the latitude location of Bauchi metrological data [10]. The dryer with air inlet and outlet holes at the front and back respectively. The outlet vent is at higher level. The vents have sliding covers which control air inflow and outflow. The movement of air through the vents, when the dryer is placed in the path of air flow, brings about a thermosyphon effects which creates an updraft of solar heated air laden with moisture out of the drying chamber. The source of air is natural flow.

### 2.7. Design consideration of the dryer

A solar dryer was design based on the procedure described by [11] for drying procedure of date and drying rough rice. (Natural convection a mixed-mode type). The size of the dryer was determined based on preliminary investigation on the tomatoes products and the size of the tray. [12] gave a model equation of calculating the Area of a solar collector as;

$$A_c = \frac{Q}{F_R t[IT_r - U_l(T_c - T_a)]} \quad \text{... (1)}$$

Where:

Ac = solar collector Area, = collector useful heat energy gain required to dry a given quantity of tomatoes product,

T = drying time,
FR = collector heat removal factor,
I = total solar radiation incident on the dryer,
Tr = polythene transmissivity,
$U_l$ = overall heat transfer coefficient,
Tc = drying air temperature and
Ta = ambient temperature.

The dryer performance depends largely on its ability to generate sufficient useful thermal energy gain. [12], gave the prediction equation as expressed.

$$Q = \{C_P W_P(T_c - T_a) + L_V(M_{C_f}\frac{(W_P - M_{Ci}W_P)}{1 - M_{cf}})\} \quad \text{... (2)}$$

Where;

$C_P$ = Specific heat of tomato before drying,
$W_P$ = Weight of tomato before drying,
$L_V$ = Heat of vaporization of moisture at the drying air temperature,
$M_{ci}$ = Initial moisture content of tomato in wet basis,
$M_{Cf}$ = final moisture content tomato in wet basis

The following points were considered in the design of the natural convection solar dryer system:

- The amount of moisture to be removed from a given quantity of fresh tomatoes.
- The quantity of air needed to affect the drying.
- The daily solar radiation to determine energy received by the dryer per day.
- Wind speed for the calculation of air vent dimensions.
- The daily sunshine hours for the selection of the total drying time.

### 2.8. Design Calculations

In carrying out any design, calculations on the size of the dryer, and the design conditions applicable to Bauchi is required. The conditions and assumptions summarized in Table 1 were used for the design of an intermittent solar dryer. From the conditions, assumptions and relationships, values of the design parameters were calculated.

**Table 1** Design conditions and assumptions

| S/N | ITEM | DESIGN VALUES |
|---|---|---|
| 1 | Location | Bauchi ($Latitude 10^{o}$22'N) |
| 2 | Material | Tomatoes (Roma variety) |
| 3 | Loading rate (kg/day) | 5 |
| 4 | Initial moisture contents, Mi:(%) w.b | 95.7 |
| 5 | Final moisture contents, MF (%) w.b | 4.5 |
| 6 | Ambient air Temperature, Tam (°C) | 27 |
| 7 | Ambient relative humidity, RHam | 0.78 |
| 8 | Maximum allowable temp. tmax | 70 |
| 9 | Drying time (sunshine hours), td (hrs) | 12 |
| 10 | Wind speed, Ws (M/S) | 4.4 |
| 11 | Number of trays | 1 |
| 12 | Air density p(kg/m3) | 1.2252 |
| 13 | Base insulator thickness of the collector (cm) | 7.00 |
| 14 | Latent heat of evaporation of water (J/kg) | 2256 |
| 15 | Average daily irradiation on Collector (w/m$^2$) | 245.94 |

### 2.9. Dyer capacity

$Vc = L_c \times B_c \times D_c$ ... (3)

Where:

Lc = length
Bc = breath of the tray
Dc = depth of the tray
Vc = 1.15 x 0.45 x 0.08 = 0.0414 $m^3$

### 2.10. Angle of Tilt (β) of the solar collector

The angle of tilt of the solar collector as suggested by [13].

$$\beta = 10^0 + lat.\theta \quad ... (4)$$

Let $\theta$ be the latitude of the solar collector location where the dryer is to be designed. The latitude of Bauchi where the dryer is to be designed is $10^0 22'$N.

Hence the suitable value of $\beta$ use for the collector:

$$\beta = 10^{\circ} + 10.37^{\circ} = 20.4^{\circ}$$

### 2.11. Amount of the moisture to be removed in (kg) Mg

$$MR0 = M\left(\frac{Q1-Q2}{1-Q2}\right) \quad ... (5)$$

Where:

M = Dryer capacity per batch
Q1= Initial Moisture content of the tomatoes
Q2 = Final moisture content of the tomatoes

$$MR = \mathbf{5}\left(\frac{\mathbf{0.957-0.045}}{\mathbf{1-0.045}}\right)$$

$$= 5(0.9549)$$

$$= 4.7745 \text{ kg}$$

### 2.12. Quantity of Air requires effecting the drying in (kg) $Q_a$

$$Q_a = \frac{MR}{Hr2-Hr1} \quad ... (6)$$

Where:

MR **=** Amount of moisture to be removed (kg)
$Hr_1$ **=** Initial humidity ratio in kg/kg air
$Hr_2$ **=** Final humidity ratio in kg/kg air

$$\boldsymbol{Q_a} = \frac{\mathbf{4.7745}}{\mathbf{0.028-0.01}}$$

$$= 265.25 \text{ kg}$$

### 2.13. Volume of air to affect the drying in $m^3$ ($V_a$)

This can be expressed as [13]

$$V_a = \frac{Q_a}{r_a} \quad ... (7)$$

Where:

$Q_a$ = density of air requires affecting drying
$r_a$ = density of air in kg/m$m^3$ which is determined to be 1.115 kg/$m^3$ based on properties of common fluids presented by:

$$V_a = \frac{265{,}25}{1.115}$$

$$= 237.8924\, m^3$$

### 2.14. Average drying rate $D_r$ (kg/s)

$$D_r = \frac{M_R}{T_d} \quad \dots (8)$$

Where:

$M_R$ = amount of moisture to be removed
$T_d$ = drying time

$$D_r = \frac{4.7745}{12 \times 60 \times 60} = \frac{4.7745}{432000}$$

$$= 0.000110520833 \text{ kg/s}$$

### 2.15. Volumetric air flow rate $V_a$ ($m^3$/s)

$$\boldsymbol{V_a} = \frac{\boldsymbol{M_a}}{\boldsymbol{S_a}} \quad \dots (9)$$

Where:

$M_a$ = Mass flow rate
$S_a$ = density of air
$V_a$ = $\frac{0.168}{1.115}$

**=  0.1507 $m^3/s$**

### 2.16. Air vent area $A_v$ ($m^2$)

$$A_v = \frac{V_a}{W_s} \quad \dots (10)$$

Where:

$V_a$ = volumetric air flow rate ($m^3$/s)
$W_s$ = wind speed (m/s), 4.3 m/s [13]
$A_v$ = $\frac{0.1507}{4.4}$

= 0.0342 $m^2$

Length of the area vent $L_v$ (m) is equal to the length of the dryer = 1.15 m

### 2.17. Width of the air vent $B_v$ (m)

$$\boldsymbol{B_r} = \frac{\boldsymbol{A_v}}{\boldsymbol{L_v}} \quad \dots (11)$$

$$\boldsymbol{B_r} = \frac{\mathbf{0.0342}}{\mathbf{1.15}}$$

$$= 0.0297 \text{ m}$$

Insulation of the collector surface Area

The insulation value for Bauchi was obtained from [14]. i.e. the average daily radiation "**H**" on the horizontal surface area as:

H = 245.94 W/$m^2$ .

And the average effective ratio of solar energy on titled surface to that on the horizontal surface:

R = 1.0035

Thus, isolation on the collector surface was obtained as:

$$I_c = HR \quad \text{... (12)}$$

$$I_c = 245.94 \times 1.0035$$

$$I_c = 246.8008 \text{ W}/m^2$$

### 2.18. Energy required to dry Tomatoes

$$E = m \times s \times D_t \times M_1 L_v \text{ [15]} \quad \text{... (13)}$$

Where:

$m$ = mass of tomatoes with water (fresh)
$s$ = Specific heat of the material (J/kg°$C$)
$D_t$ = Temperature difference (°$C$)
$M_1$ = Mass of Tomatoes without water, (kg).
$L_v$ = Latent heat of vaporization

Latent Heat of vaporization of water = 2256 kJ/kg [16], mean daily global radiation

R = 13553 W/$m^2$ [17] specific heat of tomato (red) = 3.98 kJ/kg/k [17]

$$E = \text{m} \times s \times D_t \times M_1 L_v$$

$$E = 5 \times 3.98 \times 103 \times (65 - 30) + 0.\ 2916 \times 103$$

$$= 835800 + 291.6$$

$$= 836091.6\ J$$

$$= 836.0916\ kJ$$

### *2.19.* The useful energy needed per day $Q_u$

$$Q_u = \frac{E}{days..of..drying} \quad \text{... (14)}$$

$$Q_u = \frac{836.0916\ kJkJ}{2\ days}$$

$$= 418.0458 \text{ kJ/day}$$

Useful energy per sec

$$= \frac{418.0458\ k}{12 \times 3600}$$

$$= \quad 0.00967986\ kJ/sec$$

Collector Area (m2)

$$A_c \quad = \frac{Q_u}{R^1\ \%_c} \qquad \text{... (15)}$$

Where:

$\%_c$ = Efficiency of the collector

Range of collector efficiency is within 50-70% [18]

$$A_c = \frac{0.00967698 \times 10^3}{245.94 \times 0.7} = \frac{9.676986}{172.158}$$

$$A_c \quad = \quad 0.056209912\ m^2$$

### 2.20. Amount of Bio-mass required to evaporate water from the tomatoes

Charcoal has a heating value near 7500 Kcal/kg. [19] 1 g of charcoal will have an energy value of 7500 Kcal/1000 g = 31.5 kJ/g. Therefore, the amount of charcoal required to evaporate 5.7298 kg of water will be:

$$n \quad = \quad \frac{energy\ required}{charcoal\ heating\ value} \qquad \text{... (16)}$$

$$n \quad = \quad \frac{836.0916\ kJkJ}{31.5\ kJ/g}$$

$$n \quad = \quad 26.54\ g$$

## 3. Results

Two series of test were conducted, and the data obtained during the test was used for evaluating the developed Tomato solar dryer.

### 3.1. No Load Test of the dryer

Table 2 shows the empty chamber and open-air temperature during the drying which was used to compare the temperature inside the dryer with the atmospheric temperature.

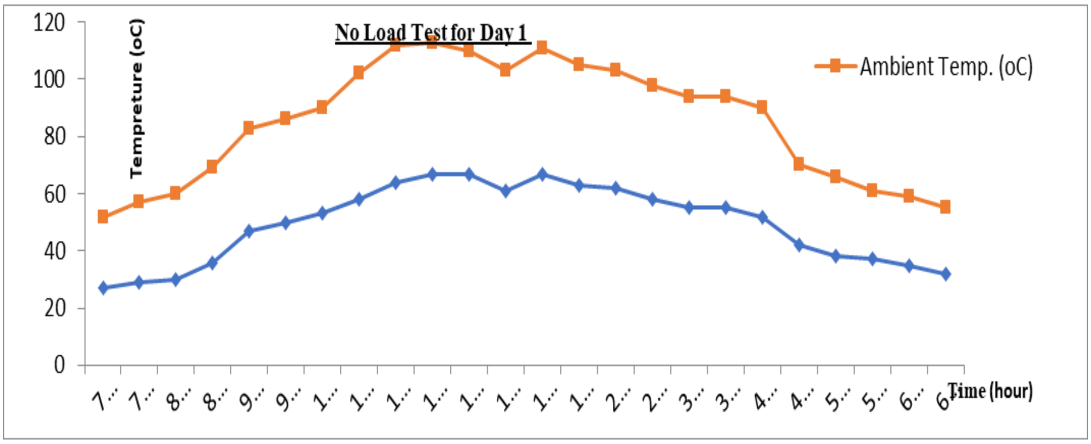


**Figure 5** Graph showing Ambient and Dryer Temperature variation of No-Load test for Day 1

**Table 2** No load test of dryer and open air temperature

| *S/N* | *TIME* | ***DRYER TEMPRETURE*** (°C***)*** | | ***AMBIENT TEMPRETURE (***°C) | |
|---|---|---|---|---|---|
| | | **Wet bulb** | **Dry bulb** | **Wet bulb** | **Dry bulb** |
| *1* | 07:00 | 21 | 27 | 12 | 25 |
| *2* | 07:30 | 23 | 29 | 13 | 28 |
| *3* | 08:00 | 26 | 30 | 15 | 30 |
| *4* | 08:30 | 30 | 36 | 17 | 33 |
| *5* | 09:00 | 37 | 47 | 19 | 36 |
| *6* | 09:30 | 45 | 50 | 17 | 36 |
| *7* | 10:00 | 48 | 53 | 19 | 37 |
| *8* | 10:30 | 55 | 58 | 20 | 44 |
| *9* | 11:00 | 54 | 64 | 21 | 48 |
| *10* | 11:30 | 55 | 67 | 19 | 46 |
| *11* | 12:00 | 57 | 67 | 19 | 43 |
| *12* | 12:30 | 55 | 61 | 19 | 42 |
| *13* | 01:00 | 52 | 67 | 19 | 44 |
| *14* | 01:30 | 50 | 63 | 18 | 42 |
| *15* | 02:00 | 53 | 62 | 18 | 41 |
| *16* | 02:30 | 52 | 58 | 18 | 40 |
| *17* | 03:00 | 50 | 55 | 18 | 39 |
| *18* | 03:30 | 50 | 55 | 18 | 39 |
| *19* | 04:00 | 46 | 52 | 18 | 38 |
| *20* | 04:30 | 30 | 42 | 17 | 28 |
| *21* | 05:00 | 29 | 38 | 17 | 28 |
| *22* | 05:30 | 25 | 37 | 17 | 24 |
| *23* | 06:00 | 24 | 35 | 17 | 24 |
| *24* | 06:30 | 23 | 32 | 17 | 23 |

### 3.2. Load test

Table 3 shows the load test of the weight sample of tomatoes 5.0 kg and the moisture loses in the improved tomatoes solar dryers and the open sun drying method, thus the moisture removed at each time interval was compared as well as the drying rate.

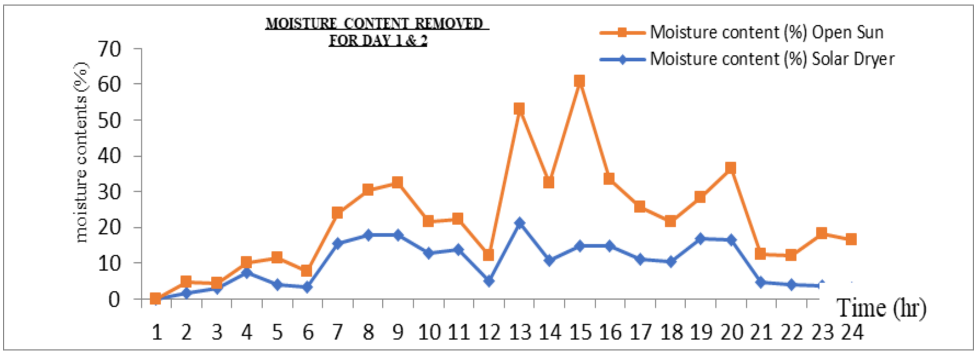


**Figure 6** A graph showing moisture content removed at various time intervals for day 1 & 2

**Table 3** Load test of weight and moisture content

| Day | Time (hr) | Weight of sample (g) | | Moisture content (%) | |
|---|---|---|---|---|---|
| | | Solar Dryer | Open Sun | Solar Dryer | Open Sun |
| Day 1 | 07:00 | 2741.4 | 2258.6 | 0.0 | 0.0 |
| | 08:00 | 2691.0 | 2190 | 1.8 | 3.0 |
| | 09:00 | 2607.9 | 2164.9 | 3.1 | 1.2 |
| | 10:00 | 2418.0 | 2105.1 | 7.3 | 2.8 |
| | 11:00 | 2316.5 | 1951.5 | 4.2 | 7.3 |
| | 12:00 | 2239.4 | 1868.2 | 3.3 | 4.3 |
| | 01:00 | 1890.8 | 1711.2 | 15.6 | 8.4 |
| | 02:00 | 1553.1 | 1498.8 | 17.9 | 12.4 |
| | 03:00 | 1276.4 | 1282.0 | 17.8 | 14.5 |
| | 04:00 | 1111.3 | 1169.2 | 12.9 | 8.8 |
| | 05:00 | 957.4 | 1070.2 | 13.8 | 8.5 |
| | 06:00 | 910.4 | 993.3 | 4.9 | 7.2 |
| Day 2 | 07:00 | 715.9 | 678.3 | 21.4 | 31.7 |
| | 08:00 | 637.7 | 494.3 | 10.9 | 21.7 |
| | 09:00 | 543.5 | 266.2 | 14.8 | 46.1 |
| | 10:00 | 402.4 | 217.0 | 14.9 | 18.5 |
| | 11:00 | 411.2 | 185.6 | 11.1 | 14.5 |
| | 12:00 | 367.9 | 165.0 | 10.5 | 11.1 |
| | 01:00 | 306.2 | 145.7 | 16.8 | 11.7 |
| | 02:00 | 255.8 | 116.7 | 16.5 | 19.9 |
| | 03:00 | 244.1 | 107.4 | 4.6 | 7.9 |
| | 04:00 | 234.2 | 98.7 | 4.1 | 8.1 |
| | 05:00 | 225.5 | 84.5 | 3.7 | 14.38 |
| | 06:00 | 218.7 | 72.9 | 3.0 | 13.7 |

**Table 4** Hygrometer readings for both wet bulb and dry bulb temperatures

This table shows the hygrometer readings for both wet bulb and dry bulb temperatures inside the dryer and the ambient during the two days of drying

| ***Day 1*** | | | | |
|---|---|---|---|---|
| ***Time (hr)*** | **Dryer Hygrometer 1** | | **Ambient Hygrometer 2** | |
| | **Wet bulb (°C)** | **Dry bulb (°C)** | **Wet bulb (°C)** | **Dry bulb (°C)** |
| *07:00am* | 23 | 28 | 16 | 23 |
| *08:00* | 28 | 37 | 16 | 29 |
| *09:00* | 36 | 48 | 18 | 33 |
| *10:00* | 48 | 56 | 23 | 37 |
| *11:00* | 56 | 67 | 22 | 48 |
| *12:00* | 58 | 69 | 21 | 43 |
| *01:00* | 57 | 65 | 21 | 44 |
| *02:00* | 54 | 60 | 23 | 44 |
| *03:00* | 48 | 57 | 21 | 39 |
| *04:00* | 44 | 49 | 21 | 37 |
| *05:00* | 32 | 41 | 20 | 28 |
| *06:00pm* | 24 | 34 | 20 | 26 |
| ***Day 2*** | | | | |
| ***Time (hours)*** | **Dryer Hygrometer 1** | | **Ambient Hygrometer 2** | |
| | **Wet bulb (°C)** | **Dry bulb (°C)** | **Wet bulb (°C)** | **Dry bulb (°C)** |
| *07:00am* | 20 | 27 | 18 | 24 |
| *08:00* | 27 | 36 | 19 | 32 |
| *09:00* | 35 | 39 | 32 | 37 |
| *10:00* | 44 | 49 | 24 | 39 |
| *11:00* | 46 | 54 | 22 | 39 |
| *12:00* | 45 | 58 | 22 | 40 |
| *01:00* | 53 | 62 | 23 | 40 |
| *02:00* | 47 | 50 | 21 | 38 |
| *03:00* | 44 | 48 | 21 | 38 |
| *04:00* | 42 | 47 | 91 | 37 |
| *05:00* | 31 | 43 | 20 | 35 |
| *06:00pm* | 25 | 38 | 20 | 22 |

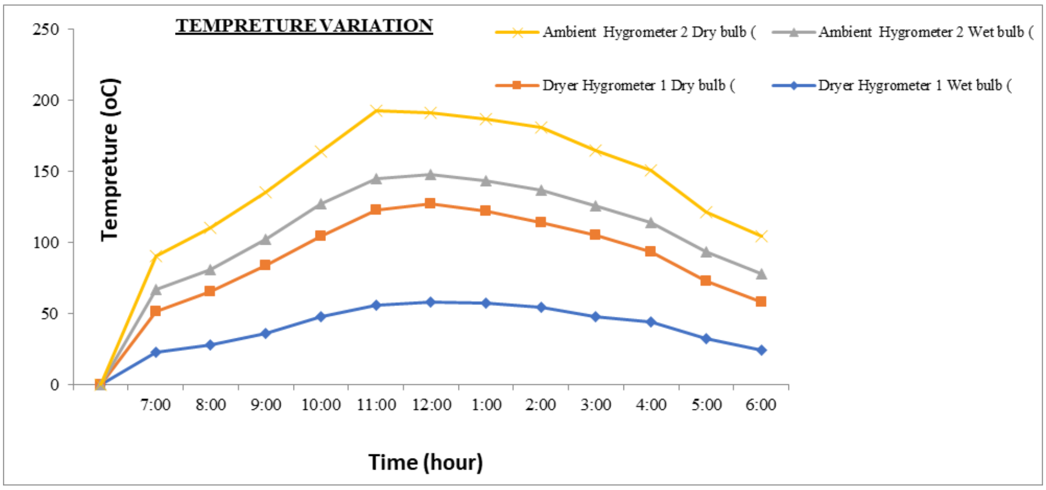


**Figure 7** Graph showing wet bulb and dry bulb temperature variation for day 1

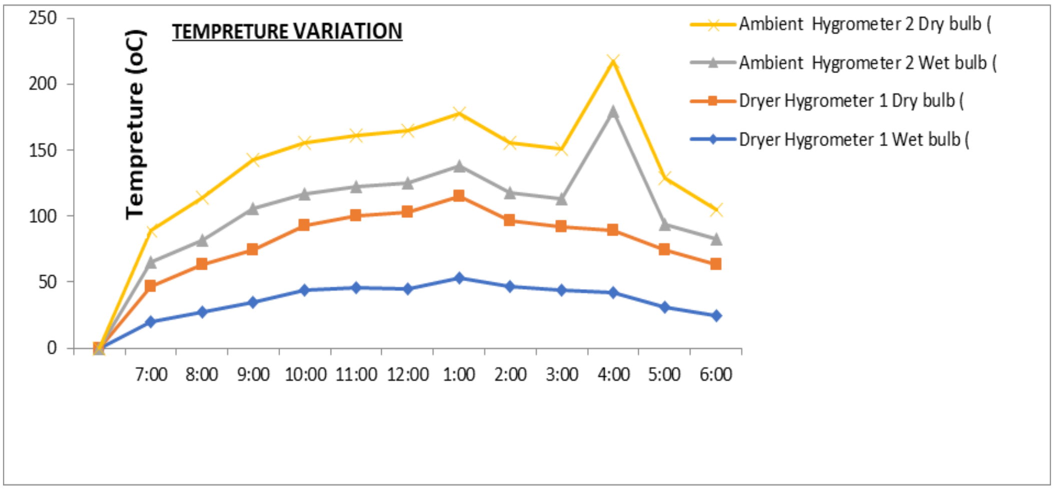


**Figure 8** Graph showing wet bulb and dry bulb temperature variation for day 2

### 3.3. Dryer Performance and Evaluation

The performance test of the developed solar dryer was carried out first when drying chamber as empty to study the maximum obtainable temperature per day for a day. Secondly a known mass of tomato slices of 2.7414 kg with initial moisture content of 95.7% were spread on the dryer tray and 2.2586 kg on the control open air. Temperature of the sample was taken for moisture content determination every hour for 12 hours per day for 2 days.

### 3.4. Moisture Removed

$$M_R = M_i - M_f$$

Where:

$M_L$ = moisture Loss
$M_i$ = initial weight of the load
$M_f$ = final weight of the load
$M_R$ = 2.7414 − 0.2187
$M_R$ = 2.5227 kg

### 3.5. Average drying rate $R_d$

$$R_d = \frac{M_R}{T_d}$$

$$R_d = \frac{2.5227}{12X2} = \frac{2.5227}{24}$$

$$R_d = 0.1051125 \text{ kg/hr}$$

### 3.6. Dryer Efficiency ($\eta$)

$$\eta = \frac{ML}{I_c At}\%$$

Where:

$\eta$ = dryer efficiency
M= weight of water evaporated from the load (kg)
L = latent heat of evaporation of water (J/kg)
$I_C$ = average daily radiation on collector (w/$m^2$)
A = area of the collector ($m^2$)
t = drying time (s)

### *3.7.* For the Dryer

$$\eta = \frac{2.5227\times2256\times1000}{245.94\times0.525\times24\times3600} = \frac{5691211.2}{11155838.4}\times 100\%$$

$$\eta = 51\%$$

### 3.8. For the Open Sun drying

$$\eta = \frac{2.1857\times2256\times1000}{245.94\times0.525\times24\times3600}\times100\% = \frac{4930939.2}{111155838.4}\times 100\%$$

$$\eta = 44\%$$

**Table 5** Tomatoes drying data

| S/N | Tomatoes drying data | Data |
|---|---|---|
| *1* | Name of the product | Tomato |
| *2* | Type of the product (variety) | Roma |
| *3* | Date of drying | 22$^{nd}$ March 2020 - 23$^{rd}$ March 2020 |
| *4* | Starting time | 7:00 am |
| *5* | Ending time | 6:00 pm |
| *6* | Initial weight total | 5.000 kg |
| *7* | Tested weight of fresh tomatoes with the Dryer | 2.7414 kg |
| *8* | Tested weight of fresh tomatoes with the open sun drying | 2.258.6 kg |

## 4. Discussion

The results of the test carried out with the developed solar dryer and the open-sun dry were given in Table 2 for No load test Temperatures of both ambient and the dryer while Table 3 shows the results of Load test of weight samples of the tomatoes and the moisture content removed at various time interval. The developed solar dryer was used to determine rate at which tomatoes of 95.7 % moisture content will be dried to a safe moisture content of 4.5 % and it is of course tested and found to dry tomatoes of weight 2.7414 kg to a safe moisture level of 0.2187 kg within 24 hours (2 days) with drying rate of 0.1051125 kg/hr. While the load (tomatoes) dried in open sun dry was tested and found to dry tomatoes weight of 2.2586 kg to safe moisture level of 0.0729 kg within 24 hours (2 days), the difference in moisture removed between loads (tomatoes) dried in the developed solar dryer and the open sun dry method was found to be 0.1458 kg, the Efficiency of the developed dryer was calculated and found to be 51% while that of open sun dry method 44 %.

The result of the performance evaluation shows that under all-weather condition, the solar dryer performs better than the natural sun-drying method from the calculated efficiencies of both the two methods. Figure. 5 shows the obtained temperature of ambient and dryer profile for empty chamber similar to those obtained by [20]; [21] and [22] with high average temperature of about 48 °C. Table 2 shows that a maximum temperature of about 67 °C is obtainable compared to open air tray of 55 °C and the temperature varied with the time of the day. The temperature obtained in this work was higher than the temperature range of 30-45 °C for drying foods and fruits obtained by [23] and in agreement with [20].

## 5. Conclusion

Performance evaluation of a developed tomato solar dryer was carried out under Bauchi climatic conditions. The results showed that the solar dryer dries faster than the natural open sun drying method with drying chamber temperature of up to 67 °C. The tomatoes were dried from initial moisture content of 95.7 % in two days of drying process to a long-term storage moisture content of 3.5 % while it took about four and half days for the open-air sun drying sample to attain a moisture content of 13.7 % from the same initial moisture content of 95.7 %. The dryer has a capacity of about 5.000 kg, the highest attainable temperature of 67 °C. This shows that solar energy can be harnessed and used to dry tomatoes especially during crop harvest season as well as at a time of poor weather condition. The drying efficiency was found to be 38 %. Tomatoes dried under the solar dryer are of higher quality and over 50 % time saving than open air sun drying.

## Compliance with ethical standards

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### *Disclosure of conflict of interest*

The Authors declare that there is no conflict of interest in the publication of this paper.

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