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Design fabrication and characterization of a solar food dryer for Palapye, Botswana

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Abstract
Dehydration is a way to preserve food that may spoil. Drying removes water and thus prevents fermentation or the growth of molds. It also slows the chemical changes that take place naturally in foods as when fruit ripens. People in Botswana and the rest of the world have been drying food for thousands of years by placing the food on mats in the sun. This simple method, however, allows the food to be affected or ruined by dust, airborne molds and fungi, insects, rodents, and other animals. Furthermore, open air drying is often not possible in humid conditions. Solar food dryers represent a major improvement upon this ancient method of dehydrating foods.
This study profiles the design, fabrication and performance evaluation of an indirect cabinet solar dryer. The dryer consists of a separate solar collector that heats up ambient air entering the collector and creates a convectional current that drives warm air into a coupled drying chamber. Food samples comprising tomatoes and apples were used for the performance evaluation of the dryer. The comparison experiment sought to differentiate the performance of the dryer from the largely uncontrolled natural drying i.e., direct sun drying. The results from the experiment showed that the temperature inside the drying chamber was consistently higher than the ambient air temperature. The drying rate of the dryer and percentage moisture loss content were 0.18 kg/hr and 91 % respectively. For natural drying the drying rate and percentage moisture loss were found to be 0.14 kg/hr and 71 % respectively. The dryer revealed its ability to dry products without them losing most of their original color as compared to direct sun drying as well as protecting products from birds, insects, strong winds and being soiled. Some of the open-air dry samples were eaten up by birds.

Keywords: Solar dryer, design, fabrication, drying chamber, food dryer

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Introduction

Drying food removes the moisture from the food that may otherwise cause spoilage of the food product. The growth of fungi and molds can also be prevented by drying as this organisms flourish in environments where there is more moisture. Drying also derails the chemical process that lead to the over ripening of fruits and thus increasing the shelf life of the fruits after they are harvested.[1]Over the years individuals and farmers have employed the traditional method of drying surplus grains which is now known as direct open air-sun drying. Although this method as way cheaper and simple it is not very efficient and one cannot rely on it, as it comes with disadvantages and limitations. The shortcomings of this method are that the products being dried are exposed to both wild and domestic animals that may eat the products being dried during the drying period. Insects and pests can also destroy the food being dried as the food is just in an open area and not enclosed. Dust and strong winds also affect the product being dried as strong winds can take the products being dried from the place where they are being dried to different locations. Unexpected rainfall can also derail the drying process as it can lead to reabsorption of moisture by the products. It is also time consuming as it needs close monitoring which most people living in the 21^{st} century do not have. Solar food dryers were an improvement that was done to this already existing method of drying. The only problem with solar food dryers is that they require a very low amount to fabricate as compared to the direct open air sun drying which does not require any expense. The cost is worth it though as solar dryers dry food products at a much higher rate than open air drying, solar dryers also produce food that are more appealing to the human eye and they provide an enclosure for the food being dried thus protecting the food from external damage . Additionally solar dryers produce food with a higher nutritional value and better tasting food s compared to open air. Because this food dryers use solar energy they contribute significantly in the conservation of non-renewable energy resources. Because the drying takes a shorter time there is very little room for spoilage. [2] The storage required after drying is cheaper than refrigeration. Storage requires protection from the growth of molds and fungi. Additionally, Botswana lies in a region that receives high solar irradiance, enough to provide adequate energy for solar drying [3]. Solar energy is cleaner, cheaper and more environmentally friendly compared to use of gas, oil and in some cases firewood. A well-designed solar food dryer could convince local farmers to embrace this largely proven but shunned technology. The aim of this project is to design, fabricate and characterize a solar food dryer to be used in Botswana. We hope that the test results will be positive and form a basis for which solar dryer technology will be promoted.
The specific objectives of this paper were to:

- design a natural convection solar food dryer
- fabricate the designed solar food dryer
- test and compare the solar food dryer with traditional open air sun drying

Dryer design:

Design considerations

The following points were taken into consideration for the design of the dryer.

1. Solar dryer to be used on a small scale (prototype)

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2. Ability to exclude dust and foreign particles from product
3. Natural convection solar dryer
4. Ability to reduce moisture

Description:

A shelf type dryer with a separate solar collector and a drying chamber is the dryer that is going to be designed. The dryer will consist of three main components being:

- The solar energy collector
- Drying chamber
- Drying trays

The solar collector consists of the cover plate and the absorber plate that are discussed below.

Cover plate

This will be a 4mm thick glass that will collect the incident solar rays. Glass allows close to 90% of visible light to pass through which will ensure that the absorber plate absorbs maximum radiation that hits the collector. The glass also traps the heat inside the collector region and thus reducing heat loss to the ambient as glass is a very good insulator.

Absorber plate

It is an aluminum sheet of 1mm thickness painted black to absorb the incident solar radiation transmitted by the cover plate thereby heating the air between it and the cover. The aluminum sheet will be used because it is a very good absorber and emitter of heat. The distance between the absorber plate and the cover plate is 40 mm for proper heating of incoming air. [20]

Drying chamber

The drying chamber will be made using plywood which will be painted and vanished in order to avoid termite attack and damage from rain. The inside of the drying chamber will be insulated by aluminum foil to minimize heat loss by radiation. The drying chamber will house the drying trays which will be made from chicken wire mesh which is porous to allow heat from the absorber plate to pass through the food products being dried easily. Two drying trays made from wire mesh with wood frame will be housed in the drying chamber. The drying chamber will have a chimney with an internal diameter of 90 mm that will aid in the removal of air from the drying chamber. The chimney will be made from aluminum sheet with a height of 200 mm.

Design features of the solar dryer

The solar dryer is composed of two sections, the drying chamber which is the first section has the shape of a home cabinet and the flat collector which is the second section, is tilted to the North, the angle of the slope is 22.55˚ as stated that the best orientation for a solar collector in the southern hemisphere is due north and the best tilt angle is equal to its latitude [21] where the latitude of Palapye is 22.55˚. The solar collector has two openings, the inlet vent at the front and outlet vent at the back. The outlet vent is located at a high level while the inlet at a lower level

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just at the opening of the solar collector. The flow of air is natural flow since hot air is less dense than cold air, so cold air will enter the solar collector through the air inlet and get heated then flows into the drying chamber. Figure 1 below shows schematic sketch of the dryer.

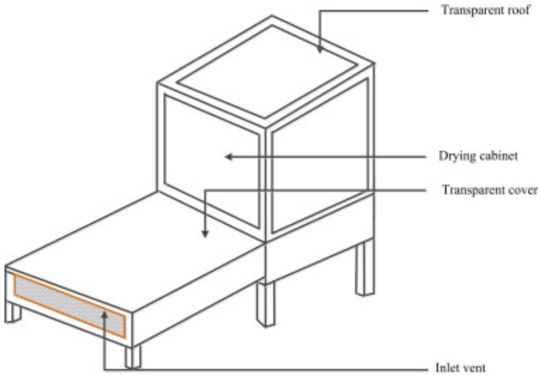

Figure 1: sketch of proposed solar dryer [22]

Design calculation and analysis:

1. **Energy balance on the absorber**

[17] States that energy absorber balance on a solar collector is found by equating the total heat gained to the total heat lost by absorber in the solar collector hence,

$$IA_C = Q_u + Q_{Cond} + Q_{conv} + Q_R + Q_P \quad (1)$$

Where: I = rate of total radiation incident on the absorber's surface (Wm^{-2});
A_C= collector area (m^2)
Q_U = rate of useful energy collected by the air (W);
Q_{cond} = rate of conduction losses from the absorber (W);
Q_{conv} = rate of convective losses from the absorber (W);
Q_R= rate of long wave re-radiation from the absorber (W);
Q_{p}= rate of reflection losses from the absorber (W).

Q_R, Q_{cond} and Q_{conv} are always combined into (Q_{L}), thus

$$Q_{\text{L}} = Q_{Cond} + Q_{conv} + Q_R \quad (2)$$

$$IA_C = \tau I_T A_C \quad (3)$$

Where: τ is the transmittance of the top glazing
I_T = total solar radiation incident on the top surface.

The expression for the reflected energy from the absorber is given by:

$$Q_{\text{p}} = \rho\tau\, I_T A_C \quad (4)$$

Where ρ is the reflection coefficient of the absorber
If we substitute equations (2), (3) and (4) into equation (1). We get

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$$\tau\, I_T A_C = Q_\mathrm{u} + Q_\mathrm{L} + \rho\tau\, I_T A_C \tag{5}$$

Or we can write it as:

$$Q_\mathrm{u} = \tau\, I_T A_C\,(1 - p) - Q_\mathrm{L} \tag{6}$$

We know that for an absorber (1 – ρ) = α

Where α is solar absorptance.

Therefore

$$Q_\mathrm{u} = (\tau\alpha)\, I_T A_C - Q_\mathrm{L} \tag{7}$$

2. Tilt and orientation of solar collector

Angle of orientation (β) = latitude of Palapye = 22.55° and orientation is due north.

3. Determining Collector Area and air vent dimensions.

The air vent was calculated by dividing the volumetric airflow rate by wind speed:

$$A_V = \frac{V_a}{V_w} \tag{8}$$

Where

V_a=Volumetric airflow rate

A_V = the area of the air vent, m^2,

V_w = wind speed, m/s.

The value used for the wind speed was 0.2 kilometers per hour as this was the average value of the wind speed forecasted for the month of May 2022 which was the duration of the drying period. This information was obtained from [23]

The expression for the width of the air vent is:

$$B_V = \frac{A_V}{L_V} \tag{9}$$

Where B_V is the width of air vent, m.

L_V = The length of air vent, m

Collector area

The collector area was determined by the dimensions of the glass cover that were found available at the local supplier and this was 1000 mm x 800 mm.

4. **Collector efficiency**:

[17]States that the collector efficiency is calculated using the formula:

$$\eta = \frac{\rho C_p V \Delta T}{A_C} \tag{10}$$

Where (ρ) is the density of air (kg/m^3),

(I_C) = the insolation on the collector,

(Δ) = the temperature elevation,

(C_p) = the specific heat capacity of air at constant pressure (J/kg K),

(V) = the volumetric flow rate (m^3),

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(A_C) = the effective area of the collector facing the sun (m^3).

5. **Dryer rate**: This is given as:

$$\eta d = \frac{ML}{\Delta t} \quad (11)$$

(ML) = change in mass of the crop,
(Δt) = the time of drying.

6. **Moisture Content (M_C):** The moisture content is given as:

$$M_C = \frac{M_i - M_f}{M_i} \quad (12)$$

M_i = mass of sample before drying and
M_f = mass of sample after drying.

7. **Moisture loss** M_L:

$$M_L = (M_i - M_f) \quad (13)$$

M_i = the mass of the sample before drying
M_f = the mass of the sample after drying.

8. **The heat gained by the air**Q_G:

$$Q_G = M_a C_{pa}(T_c - T_a) \quad (14)$$

Where:
M_a = Mass of air leaving the dryer per unit time (kgs^{-1})
C_{pa} = specific heat capacity of air$(KJKg^{-1}K^{-1})$

9. **Percentage moisture loss**:

$$\%M_c = \frac{ML}{M_i} \times 100 \quad (15)$$

Where:

$\%M_c$ = percentage moisture loss
ML= change in mass of dried product
M_i= initial mass of dried product
Reference is made to [24]

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Fabrication

Fabrication of the solar dryer was outsourced from a local manufacture. Figures 3-6 show the....

Figure 3: drying tray

Figure 4: solar collector

Figure 5: drying chamber

Figure 6: solar dryer

Experimental set-up and procedure:

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Two specimens were chosen at random for the experiment. The chosen specimen were apples and tomatoes. The two products were washed with distilled water and wiped using paper towel. The tomatoes were cut into 10 slices of 3mm thickness as this is the recommended thickness by [19]. The apples were also cut into 10 slices of 3mm thickness. The two specimen were then labelled and weighed, the initial mass was recorded. The weighing of the specimen was done using an electronic digital balance with an accuracy of 0.01g. The tomatoes and the apples were separated into two groups with 5 slices each. 5 slices from both the specimen were collected and put into the drying chamber of the solar dryer. The remaining slices of the apples and tomatoes were laid flat on a card box for direct solar drying. When drying commenced the hourly changes of mass of the products were recorded until there was no change in mass and the duration for drying noted. The data from the variation of mass was used to plot the graph of mass loss against time .A temperature data logger with two temperature probes was used to measure the hourly variation of temperature inside the drying chamber and outside the drying chamber. The hourly variation of temperature was recorded and used to plot a graph titled hourly variation of temperature inside and outside the dryer. The color of the specimens before drying and after drying was observed and noted. A total of 4 parallel experiments were undertaken and the average from the experiments used for result and analysis.

Results discussion:

- **Temperature comparison:**

The graph below show that the ambient temperature (in blue) will always be lower than the temperature inside the drying chamber (red). That is to say at any given point in time the temperature that is drying the products inside the solar dryer will be greater than the temperature drying products outside the drying chamber, i.e. direct solar drying temperature. [24] States that drying rate of the products is directly proportional to the temperature drying the products. This graph goes to show that solar dryer drying uses a higher temperature and is therefore likely to be more effective and efficient than direct sun drying.

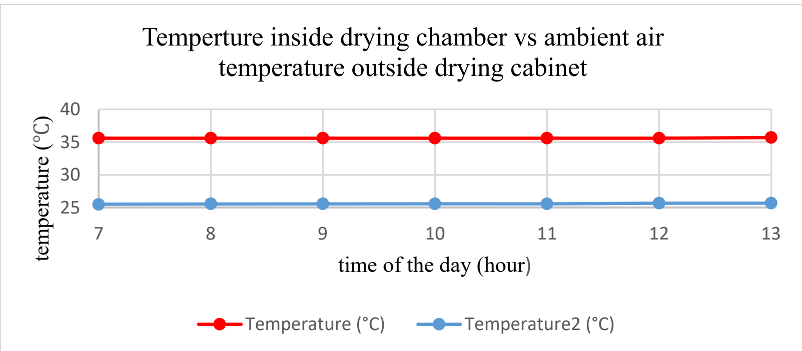

Figure 7: Graph of temperature comparison

- **Mass loss in the solar dryer and outside solar dryer:**

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The graph below show variation in mass loss of the samples in the dryer and in the direct sun. The graph shows that more mass was lost in the dryer than in the direct sun at any given time. This shows that the solar dryer is more effective than direct sun drying in terms of mass loss per given time. The graph shows that after 48 hours there was no change in mass in the product in the dryer while there was still change in mass in the product in the direct sun, this tells that the drying time of the solar dryer is shorter than the drying time in the direct sun.

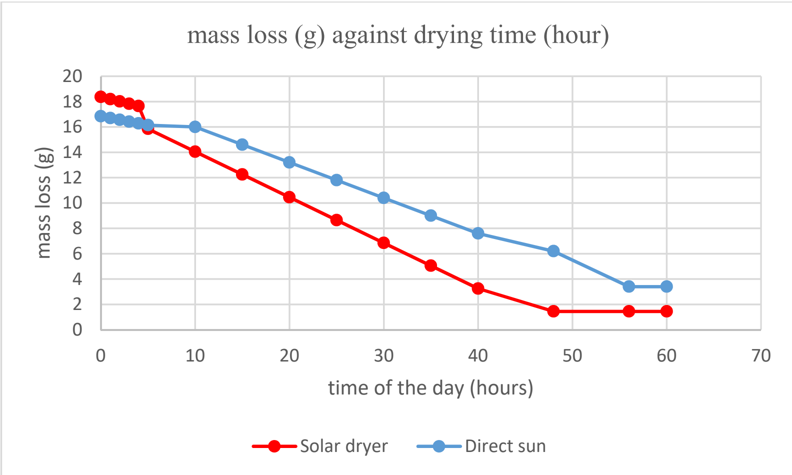

Figure 8: a typical variation of mass loss in the dryer and direct sun with respect to time

- **Drying rate and percentage moisture loss:**

Since there are 5 specimens, the average change in mass was calculated and used to determine the drying rate of both methods.

$$\eta d = \frac{ML}{\Delta t}$$

Where; ML = change in mass of dried product

Δt = time taken to dry crop

- **Drying rate for solar dyer**

$$\eta d = \frac{8.73\ g}{48 hours}$$

$$\eta d = 0.18\ gh^{-1}$$

$$\eta d = 0.18\ \times 10^{-3} kgh^{-1}$$

- **Drying rate for direct sun drying**

$$\eta d = \frac{7.94\ g}{56\ hours}$$

$$\eta d = 0.14\ gh^{-1}$$

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$$\eta d = 0.14 \times 10^{-3} kgh^{-1}$$

The above results show that the drying rate of the solar dryer is higher than the drying rate of the direct sun drying method.
The percentage moisture loss for both methods was also calculated using the average data from the samples used in the experiment. The formula below was used

$$\%M_c = \frac{ML}{M_i} \times 100$$

Where: $\%M_c$ = percentage moisture loss
ML= change in mass of dried product
M_i= initial mass of dried product

- **Percentage moisture loss for solar dryer**

$$\%M_c = \frac{8.73g}{9.61} \times 100$$
$$M_c = 91\%$$

- **Percentage moisture loss for direct sun**

$$\%M_c = \frac{7.94\ g}{10.64} \times 100$$
$$M_c = 76\ \%$$

Color comparison of solar dryer dried product and direct sun dried:

- **Color comparison in apples**

One of the most easily spotted and distinguishing features that attracts the customers is the color or the overall physical appearance of the product or fruit they are purchasing. Figure 9 shows the color comparison of fresh, solar dryer dried and direct sun dried apple specimen from right to left respectively.

Figure 9: fresh, solar dryer dried and direct sun dried apple

The color difference from Figure 9 shows clearly that products dried by the solar dryer retain their color and they are more appealing to the human eye than products that are dried directly by

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the sun. This is because products dried by the traditional open air drying are exposed directly to the sun ultraviolet rays. Direct solar drying leads to the sudden rise of the internal temperature of the fruit leading to damage to the tissues inside the product being dried, in our case apples hence the color of the direct sun dried apples was darker than the solar dryer dried apples which were not exposed to direct solar rays.

- **Color comparison in tomatoes.**

Figure 6 shows that the tomatoes in the solar dryer retained their most important feature, lycopene which is responsible for the darkening of the tomato i.e., the red pigmentation. The other tomato on the left from direct solar air drying shows low levels of lycopene and an overall dull appearance.

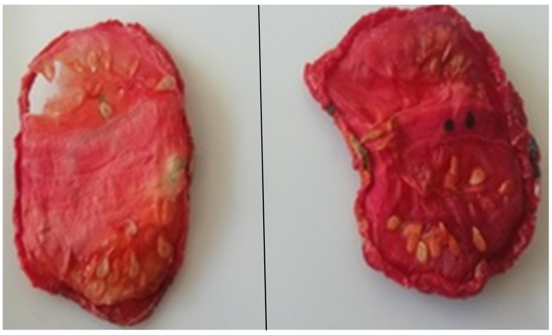

Figure 10: sun dried on the left and solar dryer dried on the right

Attack by animals:

The figure below shows some of the damages that were done by animals during and after drying. The picture on the bottom far right in Figure 11 shows apple specimens that were attacked by birds during drying. This on its own shows just how direct sun drying is not as conservative and reliable compared to solar dryer drying were the products being dried are enclosed in a drying chamber.

Figure 11: From the left, specimen before drying, after drying and apples after drying.

Figure 11 also goes to show how all the specimens that were being directly dried on the third trial of the experiment were all eaten by birds and insects. This shows that solar dryers are

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needed to protect the products being dried from predators as all products being dried by the solar dryer were not attacked by any predator or animals.

Conclusion:

The project was a success and all the objectives of the project were accomplished. The hypothesis of the whole project was proved to be right by the results obtained from the experiment.

The results obtained from the experiment are:

It is easy to monitor the drying of the solar dryer compared to natural drying.

Solar dryer drying protects the products from animals and wind.

The drying rate of the solar dryer was found to be $0.18 \times 10^{-3} kgh^{-1}$ while the drying rate of direct sun was$0.14 \times 10^{-3} kgh^{-1}$.

Overall the mass loss was faster in the solar dryer than for direct sun drying. Percentage moisture loss was 91% in a period of 48hrs for tomatoes and apples in the solar dryer and 76% for direct sun drying for a period of 56 hours for the same fruits.

The loading capacity of the dryer was 500 g per tray making a total of 1kg since it had 2 trays.

The temperature in the dryer was found to be high as compared to direct sun drying.

Recommendation:

The department of physics should have more equipment's so that the students can be able to measure different parameters that are needed for evaluation of the results and collecting some results. Equipment like the food spectrometer, a contrast color analyzer (TPGI) etc.

More can be done to compare the two methods like people testing the dried samples.

Another area of improvement is the possibility of having energy storage capability of the solar dryer to improve its performance.

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