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Design and Fabrication of an Agricultural Solar Dryer: Drying of Chili Pepper

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This research is based on the design and fabrication of an agricultural produce solar dryer for the drying of chili pepper. The solar dryer consists of a solar absorption chamber and a drying chamber. The solar absorption chamber has an opening for the inlet of air, a dark-walled enclosure, and a dark corrugated metal sheet. The drying chamber has tray racks on which two trays are placed, a door for easy access to the trays, their placement, and removal, a transparent glass roof, and a circulation fan. An STC3028 humidity and temperature controller is connected to the drying chamber to measure its humidity and temperature. Connected to the controller is a fan that spins to control the humidity when it exceeds the set point (RH of 50%). The system runs on solar power

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and its operation is initiated and halted by an electric switch. Two experiments were carried out with the same mass samples to analyze the performance of the solar dryer as compared to open sun drying. The drying rate, drying time, and efficiency of drying in the solar dryer and the open sun were compared and the results showed a higher drying rate of 11.73g/h on average and a shorter drying time of 27 hours for drying in the solar dryer for each experiment. Drying the chili pepper in the sun took 36 hours for each experiment and it happened at a rate of 8.83g/h and 8.78g/h, respectively. The average efficiency of the dryer is 32.34%.

Keywords: Solar dryer; drying rate; drying time; open sun drying; chili pepper; drying chamber.

1. INTRODUCTION

The earth makes a full revolution around the sun every year and uses its solar energy to support life. Solar energy has numerous benefits in sustaining life and is a renewable energy source. It is estimated that 71% of solar energy is absorbed by the earth's system [1]. Thus, solar energy is inexpensive and available for its use. Farming is the fundamental means of nourishing the people living in a locality, supplying raw materials for food processing and medicinal industries, and revenue generation for the farmers. Most of the crops grown by these farmers are staples and require to be available for consumption and use daily. Examples of such are tubers, cereals, vegetables, leaves, spices, and fruits and they subsequently have to be dried to preserve them for a long time with good quality. Drying flora produce is a part of the post-harvesting activities of farming. It helps to eliminate the moisture contents from crops thus preventing spoilage, re-germination of seeds, and preserving them for a long time as well as retaining the essential nutrients in them [2]. Microbes such as bacteria, yeasts, and molds thrive under moist conditions and drying is one of the methods of preventing their growth.

The commonly used method for drying is direct sun drying where crops are spread on the ground or concrete floor to dry within a couple of days. It remains the cheapest method for drying since no finance is involved and is hence adopted by most indigenous farmers. The limitations associated with this drying method include exposure of crops to high temperatures, dirt, dust, insect and rodent infestations, and pollution [3]. Other limitations are chemical alteration and decolorizing of crops and which are harmful to human consumption. To eliminate these limitations, the use of a solar dryer is efficient and safe.

Agricultural produce dried in the open is exposed to dust, insects, rodents, and sudden rainfall. This leads to food wastage, an increase in post-harvest losses, and a loss of income for indigenous farmers. When crops decay, they produce methane which contributes to climate change. Although open sun drying is easy to employ and involves no money, the majority of crops dried using that method normally take a long time to dry especially, during rainfall and as a result of overlying layers of the agricultural produce to be dried. This leads to spoilage of the crops, reducing the total income of farmers and increasing the price of their purchases. Most crops get spoilt before they get to the market due to insufficient drying, adverse weather conditions, and so on. Dirt, dust, insect, and rodent infestation, contaminate the crops making the end-users susceptible to diseases and this can lead to death or long-lasting or chronic sicknesses. Considering all factors, this is a problem worth studying and curbing and the intervention of solar dryers does so. This project seeks to design and fabricate a solar dryer that not only dries agricultural produce faster but does so efficiently with no environmental disturbances such as rodent and insect infestation, no loss of the quantity of produce dried, dirt, and sudden rainfall. Solar dryers offer advantages of better-quality produce, shorter periods of drying, reduced loss of raw materials and larger scale of production [4].

2. MATERIALS

The solar dryer was constructed using readily available materials. The list below shows the materials and apparatus used for the project.1" square pipes, ½" Alucobond sheet, Plain Glass, Hinges, weighing scale, STC 3028 (Humidity and temperature controller),80W Inverter, Solar charge controller, Backup 9AH 12V battery, Corrugated metal sheet, Metal mesh, wood, mosquito net, zip tags, S witch, wires,20W Solar Panel, Rivet gun and pins, Glue gun and glue sticks, Black Paint, zip tag, Castor wheels.

2.1 Materials Selection for Body of Solar Dryer

For the construction of the solar dryer body, several materials were considered but the ideal material needed was an insulating material that will be able to retain heat in the drying chamber without getting too hot. The material should be resistant to harsh conditions such as high temperatures, and rain and should be highly durable. The various considerations were wood, steel metal plate, and Alucobond. Below are the advantages and disadvantages of the materials leading to the selection of Alucobond.

2.2 Wood: Advantages and Disadvantages

Wood is a hygroscopic material that is obtained from the trunk and branches of trees, which are renewable sources. It is a good insulator, with low thermal conductivity of 0.12-0.04 W/mK [5]. It is more sustainable than other materials such as concrete and steel. Even though wood is one of the cheapest materials for construction and makes construction simpler and faster, it has some disadvantages. Wood rots when it is exposed to moisture forming molds and mildew. It has a short life span and can easily catch fire [6].

2.3 Steel Metal: Advantages and Disadvantages

Steel metal is an alloy of iron and carbon. The percentage of carbon content in the alloy alters the arrangement of the atoms giving it different characteristics. Generally, steel is a highly ductile, hard, tough, and malleable material [7]. In as much as steel is a good conductor of heat, resistant to wear and tear, and is less susceptible to corroding, it may absorb and conduct more heat making the drying chamber overly hot (above 50℃) and this will expose the product to excessive heat, altering its chemical composition and resulting in “case hardening”. “Case hardening” occurs when the pericarp of a vegetable or fruit cooks and hardens while trapping moisture on the inside [8].

2.4 Alucobond: Advantages and Disadvantages

Alucobond is a composite panel made up of two aluminum cover sheets and a mineral-filled core that is non-combustible and is used in stands for long-term construction quality. It stands out in the market for its superior product features such as flatness, formability, durability, and ease of manufacture, and it comes in a wide range of fashionable colors and finishes. Alucobond has lightweight, weatherproof, and can be easily folded. It is a good insulating material and is suitable for the body of the solar dryer [9].

2.5 Concept Designs

Before settling on the particular design for the solar dryer, three designs were reviewed and they are as follows;

2.5.1 Direct solar dryer design

The direct solar dryer consists of an enclosure with a transparent roof (glass or plastic) and has vents for the intake of air and the exhaust of air. Even though the crops are dried in a hygienic environment and the cost of construction is low, it has the same drying rate as drying in the sun. This makes it less efficient and sustainable. Fig. 1 shows the structure of a direct solar dryer [10].

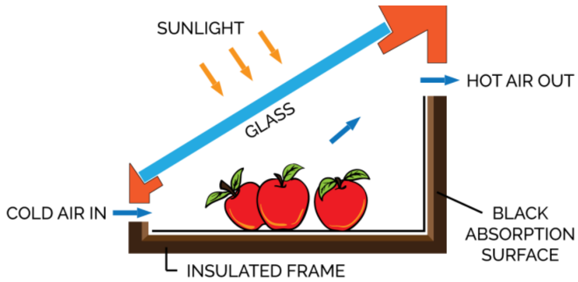

Fig. 1. Structure of a direct solar dryer

2.5.2 Indirect solar dryer design

The indirect solar dryer, unlike the direct solar dryer, has a solar absorption chamber for the heating of the incoming atmospheric air before it passes over the fruits to be dried in the drying chamber. The drying rate is faster as compared to the direct solar dryer and has a higher cost for initial construction. Fig. 2 shows the structure of an indirect solar dryer [11].

2.5.3 Mixed-mode solar dryer design

Fig. 3 shows the structure of the mixed-mode solar dryer. It has the highest drying rate as compared to the other types of solar dryers. It was chosen for its high efficiency and ability to dry produce at a faster rate, shortening the drying time [12].

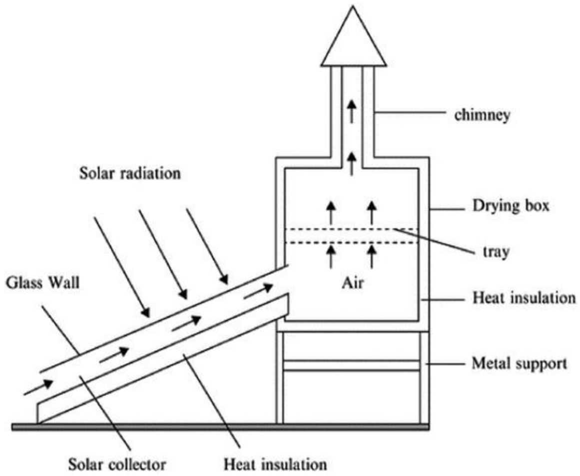

Fig. 2. Structure of an indirect solar dryer

2.5.4 Overview of system

This project is considered a mixed-mode agricultural produce solar dryer that is tested for the drying of chili pepper due to its high-performance rate. The drying rate in mixed-mode solar dryers is faster as compared to other dryer configurations although the operating conditions such as temperature and humidity must be continuously monitored. It consists of a solar radiation absorption chamber and a drying chamber.

The solar radiation absorption chamber contains a solar-absorbing-black-coated corrugated metal plate enclosed in a chamber, made of Alucobond with a glass cover. The corrugated metal plate with an area of $0.\mathrm{cm}^2$, enables maximum absorption of solar radiation [13]. The glass cover allows for the penetration of solar radiation to heat the incoming air, downstream, as it flows over the hot plate. The inner walls of the solar radiation absorption chamber are coated black to absorb more heat. The Alucobond acts as an insulator as it has a low thermal conductivity of 0.44 or 0.49 as compared to steel [4]. The chamber is inclined at an angle of 22.5° [14]. The dimension is 65 by 45 by 20 cm. The inlet is a vent covered with metal mesh and mosquito net to prevent insects, dust, and unwanted material from entering the system. The 1” square pipes were cut into sizes and welded to form the frame. The frame was then sprayed black and the Alucobond was riveted to the frame to form the chamber.

The drying chamber is the area for drying the agricultural produce (in this case, chili pepper). It consists of tray rails, and two fans; one for air circulation and the other for humidity and temperature control. There is a humidity and temperature controller that is used to assess the readings of temperature and humidity in the chamber. The tray rails are made of 1” sheet metal angle welded to the inside of the frame at equal distances (10cm) apart. They are made of a wooden frame with a metal mesh lining and an overlying mosquito net to prevent the falling of the chili pepper. A door is carved on one side of the drying chamber to allow the placing and removal of the trays. The drying chamber has a glass roof that adds more heat to increase the internal temperature.

The overall dimension of the drying chamber is 50 x 45 x 71 cm, with the glass angled at 22.5°. It is also sprayed black on the inside to trap more heat. The system runs on solar power, hence there is a backup battery to enable the system to work during rainfall or cloudy days. Because the STC3028 (7.62 x 7.62 x 2.7cm) is an AC humidity and temperature controller, an inverter was connected to the output of the 20W solar panel to convert the DC voltage to AC to be used by it. The STC3028 was placed at the front of the drying chamber to display the readings. The solar panel is mounted on extensions at the top side of the drying chamber so that it does not block the sun rays from reaching the drying chamber. The backup battery, inverter, and battery controller are mounted at the base of the drying chamber. The fans are of the same size (12 by 12 by 2.5cm), with a voltage of 12V, speed of 3500 rpm, and power of 3W. Fig. 4a) and b) show the frame and the finished constructed solar dryer.

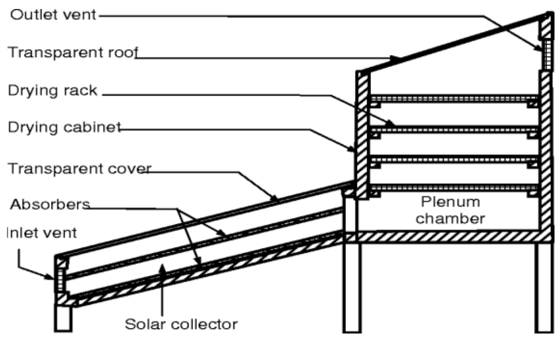

Fig. 3. Structure of a mixed mode solar dryer

2.5.5 Cost analysis

The Table 1 shows the material name, description, quantity, unit cost, and total cost for their purchase and miscellaneous costs on the project. Some of the materials were ordered online, others were purchased at the China Mall, Spintex Road, and others in the nearby market. The overall cost of fabricating the solar dryer is shown in Table 1 and Table 2 respectively. The total cost of the project was GHC 1580.

Fig. 4a. The frame of the solar dryer

Fig. 4b. Constructed solar dryer

Table 1. Cost analysis

Material	Description	Quantity	Amount (GHC)
Solar Panel	20W 12V Solar Panel	1	120
STC3028	AC110-220V 10A STC-3028 Dual LED Temperature Humidity Control Thermostat and Probe	1	160
DC Fan	12V System Unit Fan	2	15
Switch	Two Terminal Switch	1	5
Wires	Low Voltage Cable	15yards	27
Rivet Gun	10”/250mm Hand Riveter	1	40
Rivet Pins Packet	Rivet I4x18mm	2	9
Castor Wheels	2x2 Castor Wheels	4	19
Painting Brush	2” & 1.5” Painting Brush	2	7
Alucobond	3mm 5.9kg/m^2 Alucobond Sheet	1 sheet	220
Battery	9Ah 12V Battery	1	110
Solar Charge Controller	30A Solar Charge Controller 12V/ 24V Solar Panel Charge Controller	1	90
Power Inverter	DC to AC 12V 220V 80W Inverter	1	180
Metal Mesh	8x8 Metal Mesh	1yard	20
Corrugated Metal Sheet	Coated Galvanized Aluminum Sheet for Roofing		20
Glass	6mm Thick Glass Sheet	1	160
Plywood	1x1 Plywood	1	16
		Total	1218

Table 2. Miscellaneous Costs

Item		Cost
Chili Pepper	4kg	120
Labor Cost	N/A	170
Transportation	N/A	72
	Total	362

2.5.6 Solid works

It is used to design and build mechanical, electrical, and software elements [15]. SOLIDWORKS was utilized for the modeling of the components of the solar dryer system for its three-dimensional graphical description.

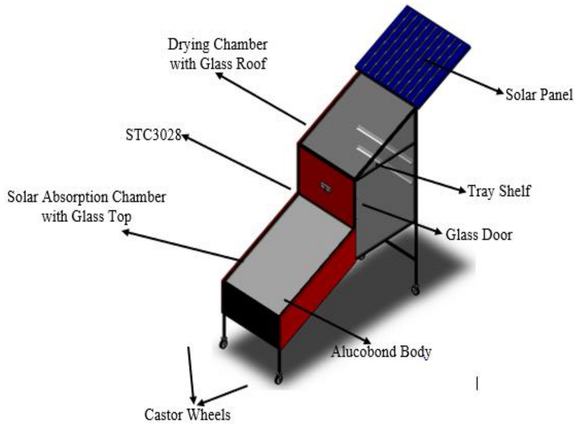

Fig. 5. Solid work models of the solar dryer

2.5.7 Chili pepper preparation

1.5kg of fresh chili pepper were purchased at the Madina, Zongo Junction market. The pedicel (stalk) was removed from the fruit and washed to remove dirt. 3 cups of distilled water were heated to boil and the washed pepper was cooked for 10 minutes. The boiled chili was sieved and kept in the tray to allow for cooling as shown in Figures 6a and b below. The next morning, 424g of the pepper was spread on the trays and placed in the solar dryer at 7:30 am. At the same time, two similar samples were dried in the open to undergoing natural drying. Readings (humidity and temperature) were taken at 8:00 am and hourly till 5: 00 pm. The mass of the samples before and after drying between the nine hours of drying was recorded. The experiment lasted four days, which is equivalent to 36 drying hours. Two tests were carried out in May, from the 10^{th} to the 22^{nd}.

2.5.8 Solar dryer and open-air testing

Four samples of the chili pepper of the same masses; 424g were weighed and kept in the two trays for the solar dryer and the open. Because of the difference in sizes of the chili pepper, the samples had different numbers of peppers. This is also to help measure the effectiveness of drying in the solar dryer and drying in the open, as some of the pepper could be lost as a result of strong winds and being fed on by rodents (such as lizards). Another consideration was how the number affects the final weight of the dried produce. The atmospheric humidity and temperature were recorded from the weather.com website [16]. Table 3 below shows the number of peppers in each sample. The arrangement of the chili pepper for drying is shown in Figs. 7a and b.

Fig. 6a. Washed fresh chili pepper

Fig. 6b. Cooling of boiled chili pepper

Table 3. Number of pepper per 424g of sample

Sample	Number of Pepper
Tray 1	151
Tray 2	150
Open Drying 1	145
Open Drying 2	140

a

b

Figs. 7. a: Solar dryer; b: Open-air drying

3. RESULTS AND DISCUSSION

3.1 Temperature and Humidity in the Drying Chamber During Testing

The temperature and humidity variation with time in the drying chamber over the first 9 hours, through to the 27th hour of drying in the solar dryer is shown in Figs. 8 and 9. The produce in the solar dryer became brittle by the 27th hour while the one in the open was brittle by the 36th hour. That reduced the drying time by 9 hours as compared to drying in the open.

Fig. 8 shows how the temperature in the drying chamber increased from 8:00 am and reached its maximum at noon where the atmospheric temperature is the highest as a result of the vertical (90°) slant of the sun rays. Getting towards the evening, the temperature decreases as the sun goes down.

The maximum temperature in the drying chamber was found to be 46.7℃ with an ambient temperature of 31℃. On average, the maximum temperature in the drying chamber was 47.37℃ with an average ambient temperature of 30.5℃. This gave a temperature difference of 15.7℃ more than the ambient temperature during the day. During the evening, the temperature in the dryer was an average of 26.72℃. The humidity had an inverse proportionality to temperature, so as the temperature increased, the relative humidity decreased as shown in Fig. 9. Figs. 10 and 11 below show the temperature and relative humidity against time for drying in the open.

3.2 Experimentation

The chili pepper samples were tested both in the solar dryer and also in the open. The samples were left to dry for 9 hours per day from 8: 00 am to 17:00 when the sun is mostly shining. In the evening, the chili pepper dried in the solar dryer is left in it for the next morning while the samples dried outside are left in trays in the workshop.

3.2.1 Experiment 1

3.2.1.1 Solar dryer

The chili pepper was dried in the solar dryer from the 10th of May to the 12th of May, 2022. In the test, 424g of boiled chili pepper were dried and by the 27th hour, the mass reduced to an average of 84g. The number of chili pepper per sample is shown in Table 4 as that affects the final mass of the dried produce.

Table 4. Number of pepper per 424g of sample for solar dryer

Sample	Number of Pepper
Tray 1	141
Tray 2	140

The mass reduction per 9 hours in the solar dryer over the 27 hours of testing is shown in Fig. 11 below;

It can be seen that the mass of the sample in tray 1 reduced faster as compared to the sample in tray 2 as tray 1 is closer to the top surface so it receives more heat than tray 2.

3.2.1.2 Open drying

The test was carried out at the same time as that in the solar dryer from the 10th to the 14th of May, 2022. Two samples of 424g of boiled chili pepper were spread on a concrete floor at 8:00 am and left till 5:00 pm. At the end of the 36th hour, the masses had reduced to an average of 85g. The mass reduction per 9 hours in the open is shown in Fig. 12. The results show that the produce in the solar dryer dried 9 hours faster than the produce dried in the open.

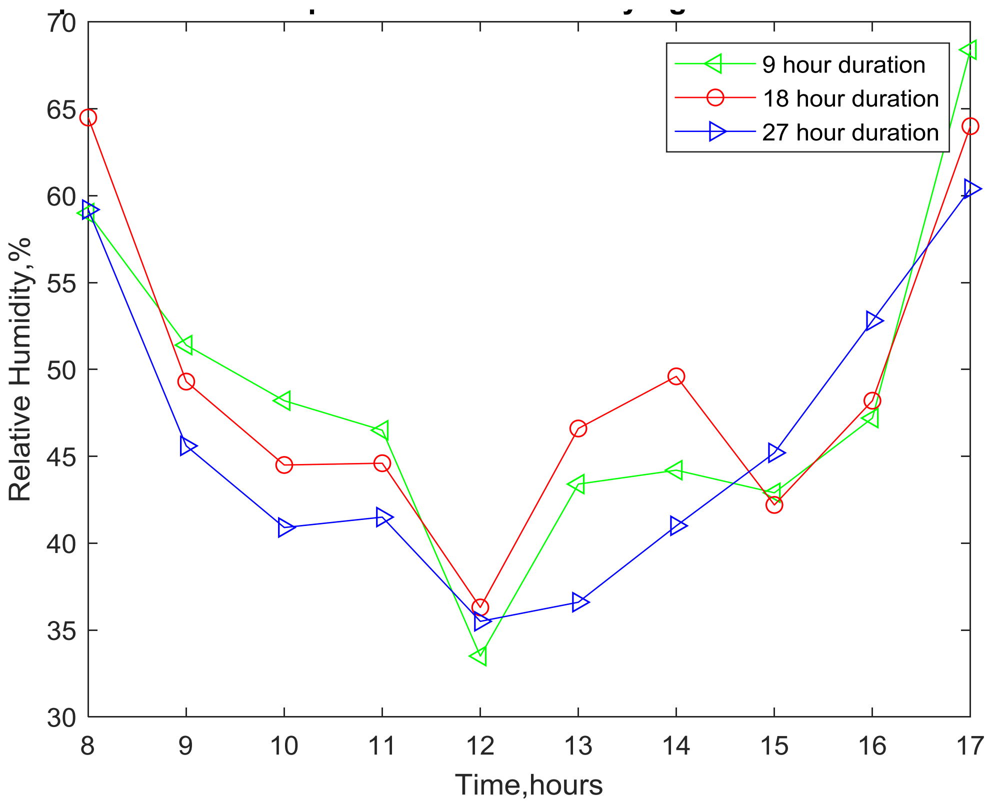

Fig. 8. Relative humidity against time graph in solar dryer during experiment 1

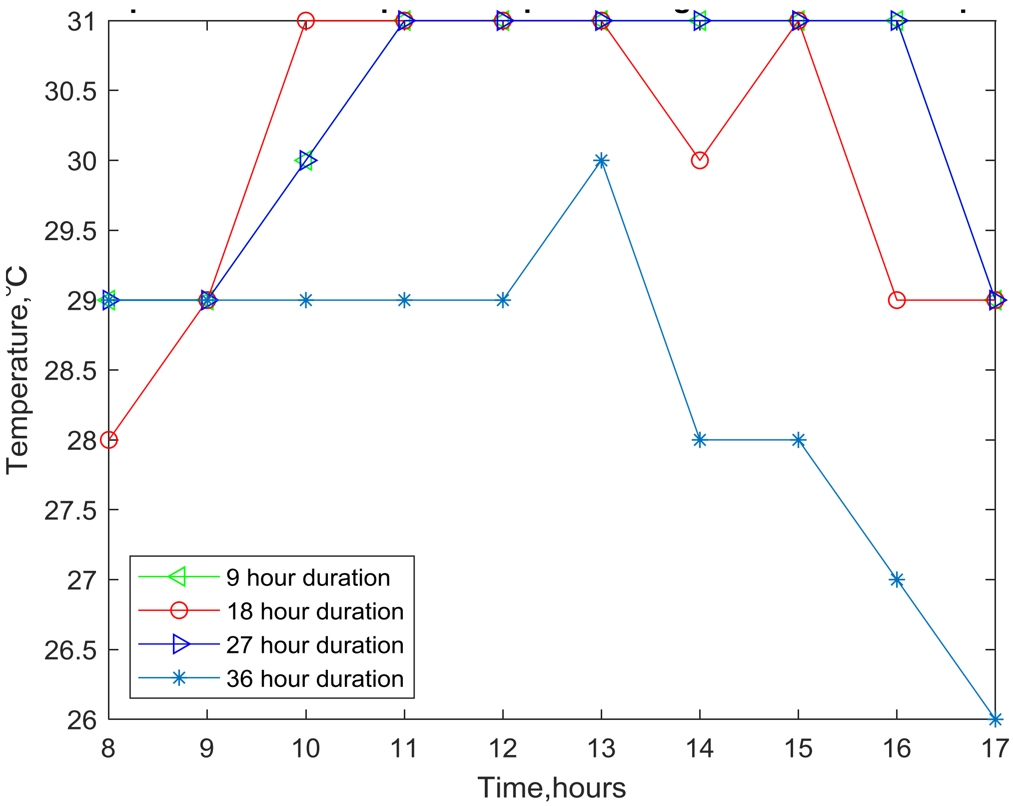

Fig. 9. Temperature against time graph in the open during experiment 1

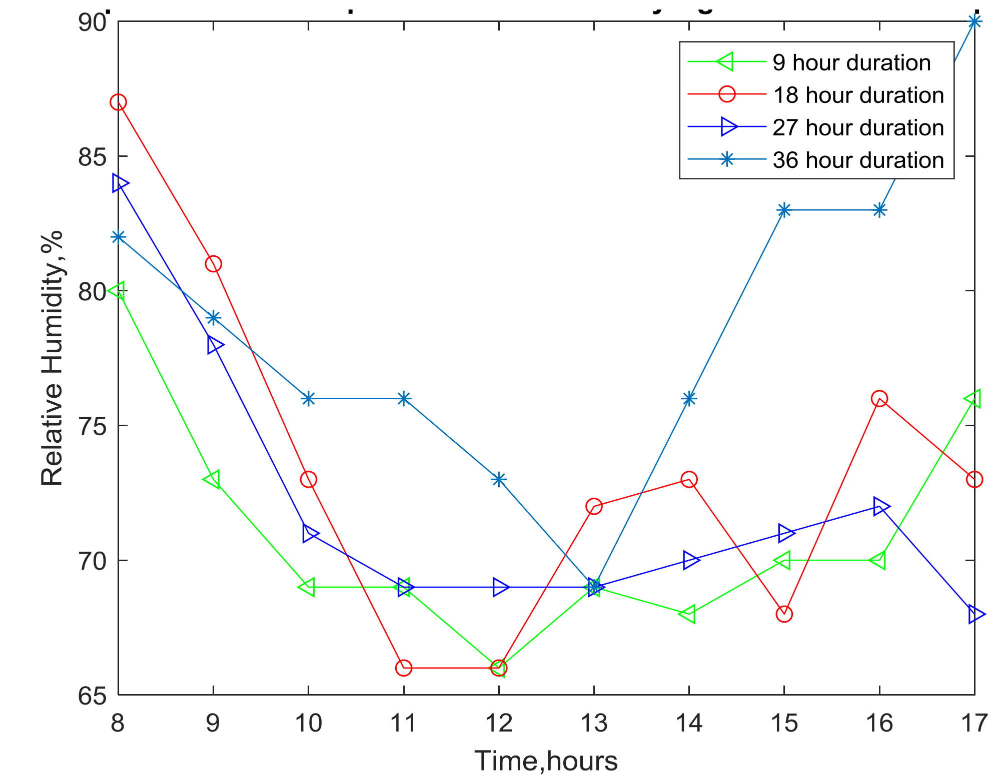

Fig. 10. Relative humidity against time graph in open during experiment 1

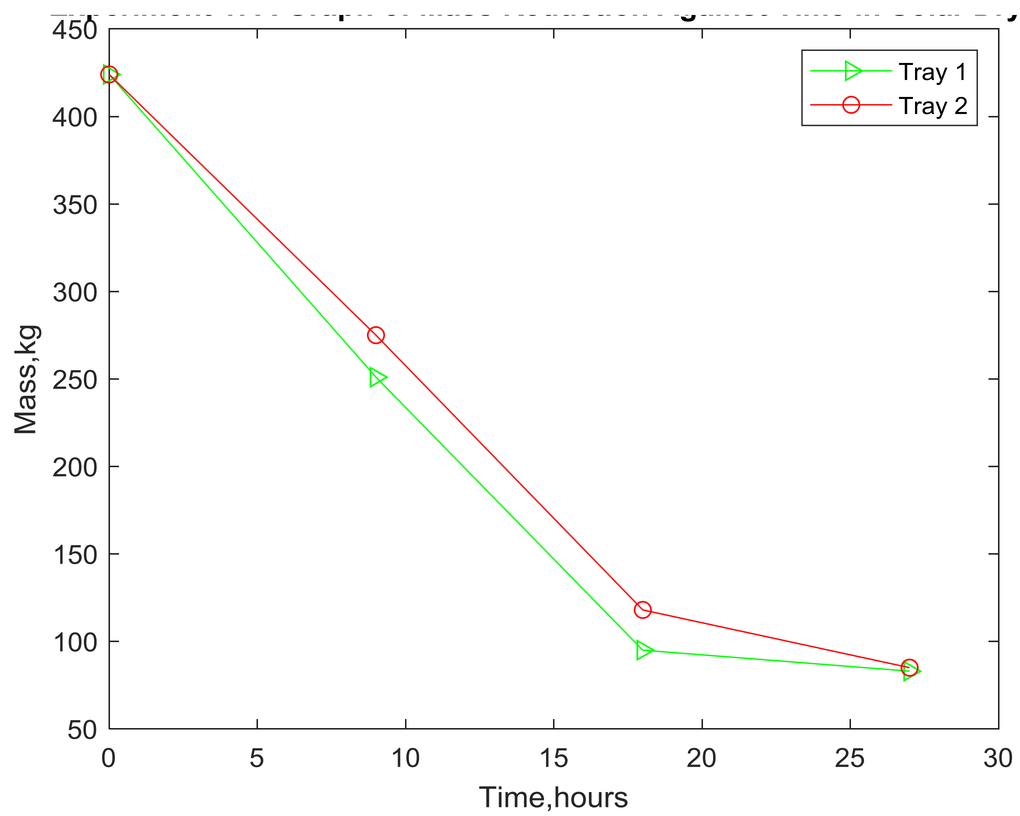

Fig. 11. Mass reduction against time graph in solar dryer during experiment 1

3.2.2 Experiment 2

3.2.2.1 Solar dryer

The chili pepper was dried in the solar dryer from the 19th of May to the 21st of May, 2022. In the test, 424g of boiled chili pepper were dried and by the 27th hour, the mass reduced to an average of 98g. The mass reduction per 9 hours in the solar dryer over the 27 hours of testing is shown in Fig. 13.

It can be seen that the mass of the sample in tray 1 reduced faster as compared to the sample in tray 2 as tray 1 is closer to the top surface so it receives more heat than tray 2.

3.2.2.2 Open Drying

The test was carried out at the same time as that in the solar dryer from the 19th to the 22nd of May, 2022. Two samples of 424g of boiled chili pepper were spread on a concrete floor at 8:00 am and left till 5:00 pm. At the end of the 36th hour, the masses had reduced to an average of 93.5g. The mass reduction per 9 hours in the open is shown in Table 5.

Table 5. Number of pepper per sample in the open

Sample	Number of Pepper
Open Drying 1	140
Open Drying 2	142

The reduction in the number of peppers contributed to the reduction in the mass of the sample. The chili pepper samples in the solar dryer were dried in the 27th hour but the ones in the open were still moist and had reduced in number. The produce dried in the open dried by the end of the 36th hour.

Fig. 14 shows the dry state of the chili pepper in the solar dryer at the 27th hour and the red color of the peppers was preserved after drying. Fig 15a and b shows how difficult it was to break open the chili pepper that was dried in the open by the 27th hour. Table 6 shows the parameters used for the performance evaluation of the agricultural produce solar dryer. The solar insolation per day in Ghan is between $4\frac{\mathrm{Wh}}{\mathrm{m}^2}$,and $\mathrm{Wh/m}^2$, so the average was used in the evaluation of the performance of the solar dryer [17].

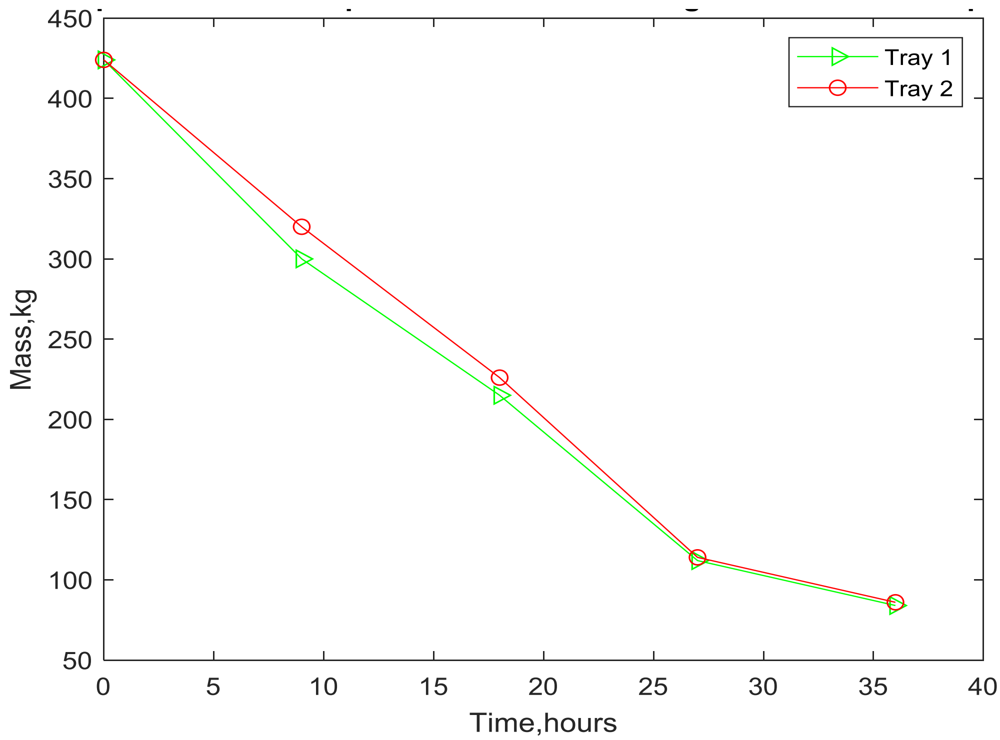

Fig. 12. Mass reduction against time graph in the open during experiment 1

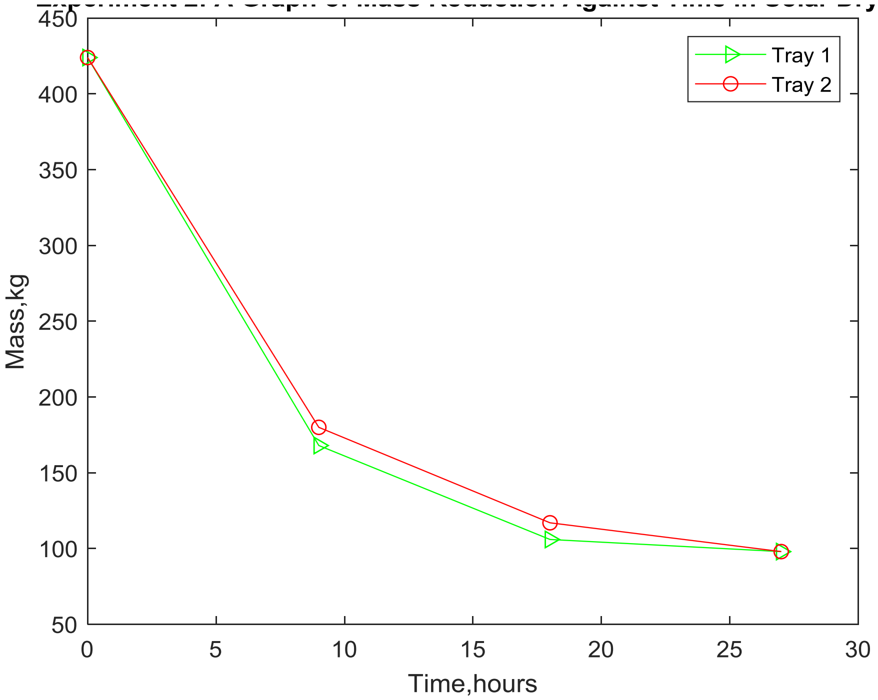

Fig. 13. Mass Reduction against time graph in the solar dryer during experiment 2

Fig. 14. Brittleness of chilli pepper in solar dryer by 27th hour

Table 6. Parameters used for performance evaluation

Parameter	Value (Experiment 1)
Solar Insolation I_T	500W/m^2
Latent Heat of Vaporization, L	2260 kJ/kg
Air Speed, v	3.33m/s
Drying Time, t_d	36h
Mass Flow Rate, m_a	0.3675 kg/s
Specific Heat of Air, C_s	1.005 kJ/kg/K

3.3 Collector Efficiency

The collector efficiency of the dryer was calculated using equation (1) [18]. During the experimentation period, the collector efficiency was computed for both experiments. For experiment 1, the collector efficiency per 9 hours was 26.62%, 30.16%, and 32.31% over the 27 hours of testing. The average collector efficiency was 30.37%. In experiment 2, 32.01%, 34.78%, and 38.16% were the efficiencies per 9 hours, over the 27 hours of testing. The average collector efficiency was 34.98% shown in Table 7. These average collector efficiencies were greater than those with mode natural convection dryer without storage made by Abubakar et al. [19] with an efficiency of 24.2% and force with auxiliary heating made by Fudholi et al [20] with an efficiency of 28% which makes this solar dryer design more efficient than others. These were lower than 39.6% in the forced convection dryer without dehumidification [21] and higher than 13.45% achieved in the solar tunnel drying of garlic [22].

$$\eta_c = \frac{Q_g}{I_T A_c} \quad (1)$$

I_T = Average solar insolation (W/m^2);
A_c = Area of the primary collector (m^2)

Table 7. Collector efficiency for experiments 1 and 2

	Experiment 1	Experiment 2
Number of Hours	**Collector Efficiency, %**	**Collector Efficiency, %**
9 hours	26.62	32.01
18 hours	30.16	34.78
27 hours	32.31	38.16
Average Efficiency	29.70	34.98

3.4 Drying Efficiency

The drying efficiency was calculated using equation (2) [18]. The computed drying efficiency of the solar dryer during experiments 1 and 2 and the results are as follows. For experiment 1, the drying efficiency of the solar dryer was 3.18% and that for experiment 2 was 3.15%.

$$\eta_d = \frac{m_w L}{I_T A_T t_d} \tag{2}$$

Where;

$m_w =$ Moisture removed (kg)
$L =$ Latent heat of vaporization of water (kJ/kg)
I_T = Average solar insolation (W/m^2)

3.5 Drying Rate

The drying rate was calculated using equation (3) [18]. The drying rate for both the solar dryer and open drying for both experiments 1 and 2 are 11.78g/h and 8.83g/h, 11.67g/h, and 8.78g/h respectively. Table 8 shows that the drying rate in the solar dryer was faster than that of the open drying constituting the difference in total hours of drying. Open drying displayed physical degradation and loss of color.

$$m_{dr} = \frac{m_w}{t_d} \tag{3}$$

$m_{dr} =$ average drying rate (kg/h)
$m_w = the$ mass of moisture removed by the dryer (kg)
$t_d =$ overall drying time (h)

Table 8. Drying Rate for Solar Drying and Open Drying

	Experiment 1	Experiment 2
Mode of Drying	**Drying Rate (g/h)**	**Drying Rate (g/h)**
Solar Dryer	11.78	11.67
Open Drying	8.83	8.78

a)

b)

Fig. 15 a) and b): Less brittle chili pepper dried in the open by the 27th hour

Fig. 16a. Washed fresh chili pepper

Fig. 16b. Cooling of boiled chili pepper

4. CONCLUSION

This project aimed at the design and fabrication of an agricultural solar dryer that not only reduces the drying time but does the drying in a hygienic and controlled environment. With various design considerations, the materials for fabrication and the type of dryer design (mixed mode solar dryer) were chosen. The performance of the solar dryer was evaluated and compared to that of drying in the open. Two experiments were conducted for the analysis and it was found that the average drying chamber temperature was 47.37℃ with an average ambient temperature of 30.5℃ which represents an increase in temperature that facilitates a faster drying rate. 424g of boiled chili pepper were dried in both the solar dryer and in the open for 9 hours per day. At the end of the 27^{th} hour, the sample in the solar dryer was dried and brittle while that in the open was still moist. The samples in the open dried in 36 hours meaning the solar dryer reduces the drying time by 9 hours. The sizes of the chili pepper affected the number of chili pepper fruits per sample, with the number of fruits in each experiment between 140 and 151 chili pepper.

The drying efficiency and drying rate were computed to evaluate the performance of the solar dryer as compared to open sun drying. The drying rate for both the solar dryer and open drying for both experiments 1 and 2 are 11.78g/h and 8.83g/h, 11.67g/h, and 8.78g/h respectively. This shows that there was a faster drying rate in the solar dryer as compared to open solar drying with a difference of 2.95g/h and 2.89g/h respectively for experiments and 2.

It can be concluded that the solar dryer can accommodate higher temperatures, hence holding higher heat to remove the moisture in fruits and crops. With the increase in temperature, the relative humidity decreases, and the continuous flow of air in and out of the system makes drying faster and more efficient. The product is not exposed to rodents, dust, and sudden rain and this prevents food spoilage and maintains the nutrient content and quality of the agricultural produce. The drying time is reduced drastically, making the sales and transportation of farm yield easier and more economical.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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