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THERMAL PERFORMANCE OF DUAL-OPERATED SOLAR COOKING AND DRYING SYSTEM

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ABSTRACT
In this work, the thermal efficiency of a dual-operated solar cooking and drying system that may be utilized for domestic use was examined. An analysis of the system's thermal performance was conducted at Sokoto Energy Research Centre (SERC) using the Bureau of Indian Standards (BIS). Sampling cooking and drying tests were carried out, and the potential for extended cooking time for brine solution and animal fat was conducted. The results showed that the first figure of merit (F_1) value agrees with the standard value of 0.12 and the second figure of merit (F_2) value is in close correspondence with 0.25 (BIS Standard). The system was able to dehydrate 89 % of the moisture content of banana slices weighing 118 g which is of uniform thickness of 4 mm to achieve a stable weight of 12 g after 8 hours of drying. Animal fat showed more potential for extended cooking time than brine solution, as it took 5 hours to cool after heating for about 3 hours. Six pieces of eggs were boiled for 45 minutes in a temperature range of 29.7 °C and 88.2 °C. These findings indicate the potential of this dual-operated system for domestic applications.

Keywords: solar cooking, solar drying, first figure of merit, second figure of merit, thermal storage

INTRODUCTION
Policymakers, investors, financial institutions, and academics are all very interested in the global oil market because it has remained unstable and unpredictable (Rapu *et al*., 2015). Energy crisis conditions are a result of the unpredictability and volatility of the world's oil prices as well as their environmental challenges. This has compelled a fundamental change in perspective, moving away from complete dependence on fossil fuels and shifting towards the utilization of renewable energy sources. Africa is undoubtedly endowed with a significant number of renewable energy resources, the majority of which go unused. Based on a map illustrating the annual accumulation of solar irradiation on earth, the solar belt encompasses the entire continent of Africa. Notabely, at a location approximately 1000 km to the south of the Mediterranean, the regions of Africa including the Sahara, the Namib Desert, and the Arabian Peninsula experirnce some of the highest levels of irradiation on earth. In this area, the annual global irradiation is twice as much as that in the southern Germany.

Africa has yet to fully tap into its potential for utilizing renewable energy resources due to insufficiently designed, implemented, and invested renewable energy policies (Karekezi *et al*., 2003). Undoubtedly, renewable energy presents itself as a feasible remedy for Nigeria's energy dilemmas. Its sustainability and renewability are accompanied by the advantage of being deployed in smaller-scale installations, rendering it a suitable choice for rural communities to manage and own. This aspect bears substantial potential in fostering economic progress within the nation (Rapu *et al.*, 2015). South Africa leads the way in Africa with the greatest installed solar energy capacity, outpacing its closest competitors Algeria, Ghana, and Moroco, all of which have an installed capacity ranging from 200 to 300 megawatts.

The northern and middle belt parts of Nigeria, which are located in the equatorial region and receive a lot of solar radiation, appear to be sitting on a vast energy reservoir that is rapidly becoming economically viable (Agbo and Oparaku, 2006; Newsom and SDN, 2012). However, due to insufficient availability of comprehensive data on Nigeria's solar energy technology, capacity, and projects, it becomes challenging to evaluate the extent of the country's solar integration (Bamisile *et al*., 2017). The coastline region receives an average daily solar radiation of about 5.25kW/m^2/day, whereas the far northern boundary receives approximately 7.0kW/m^2/day. The annual average daily sunlight duration is 6.25 hours, varing from about 3.5 hours along the coast to 9.0 hours at the far northern boundary (Osueke and Ezugwu, 2011). Based on the global horizontal map of Nigeria, the northern regions including Sokoto, Zamfara, Kano, Jigawa, Yobe, and Maiduguri receive an average annual planetary horizontal irradiation of approximately 2200 kWh/m^2. On the other hand, the coastal states such as Rivers, Cross River, and Bayelsa State receive slightly over 1000 kWh/m^2 on average annually (Solar Resource Map, 2017). This indisputably indicates that Nigeria is situated in a region with abundant potential for solar energy (Sambo, 2009). It suggests a relatively equitable distribution of solar energy across Nigeria.

The earth moves around the sun, causing seasonal and nocturnal variations, as well as fluctuations due to cloud cover, making the sun the world's main source of energy. Solar energy is inexhaustible, eco-friendly, and capable of being transformed into diverse forms of alternative energy (Kelechi *et al.*, 2014). Converting it to thermal energy in order to cook or dry farm produce is done with a solar cooking or drying system. In order to ensure a consistent and dependable energy supply, solar systems necessitate the utilization of energy storage systems (Kronhardt *et al.*, 2014). Due to the intermittent nature of solar radiation, the storage of solar thermal energy (TES) plays a crucial role in the effective utilization of solar energy. This technology is extensively applied in concentrared solar thermal power plants to generate electricity, as well as in solar water heating systems, solar space heating for buildings, and drying processes (Tesfay and Venkatesan, 2013). Solar thermal technology stands out as one of the most adaptable and effective forms of renewable energy (Asif and Muneer, 2013). Consequently, solar cooking and thermal storage systems encompass a range of technical considerations, emcompassing aspects such as material choice, insulation, methodologies, and thermal transportation.

MATERIALS AND METHODS

The methods used for the conduct of the study are described as follows:

Determination of Stagnation Temperature for Solar Cooking Application (1st Figure of Merit F_1)

The solar cooker was positioned to face the direction of the sun. The cooker's orientation was such that the lid reflector (mirror) was occasionally adjusted to reflect the sun's rays directly into the cooking chamber. Thermocouple wires were connected to a data logger thermometer and placed on the cooker's absorber plate and the solar collector (glazing material) to measure their temperatures. The cooker was then securely shut. The ambient temperature around the cooker was monitored using a digital thermohygrometer, and the solar insolation of the sun's rays was measured using a pyranometer. Measurements were taken every ten minutes until the temperature reached stagnation. This was repeated for two days.

Plate 1: Stagnation Temperature under Cooking Condition

Determination of Stagnation temperature for solar drying applications

The experimental setup was the same as described in paragraph 2.1, except that the two venting ports (inlet and outlet) are kept open. The variation in solar radiation, ambient temperature, solar collector temperature and temperature of the absorber plate were measured at intervals of ten minutes. The experiment was carried out until stagnation was reached. This was repeated for two days.

Plate 2: Stagnation Temperature Test under Drying Condition with vents open

Determination of Water Boiling Test (2nd Figure of Merit F_2)

The experimental setup for this determination is the same as described in paragraph 2.1, however, 0.51 kg of water was loaded into the cooker. Water temperature inside the pot, ambient temperature, solar collector temperature and solar radiation were recorded at intervals of ten minutes. The experiment was carried out until water temperature reached 100°C. This was repeated for two days.

Plate 3: Experimental Set-up of Water Boiling Test

Determination of Figures of Merit

The first figure of merit (F_1) is the ratio of optical efficiency to heat loss factor while the second figure of merit (F_2) is heat transfer capacity of the cooker interior. (F_1) was determined by monitoring the time and temperature of the solar box cooker under no load condition while F_2 was determined under full load condition. Hence according to Mullick et al. (1987), F_1 and F_2 can be determined using equation 1 and 2, respectively.

$$F_1 = \frac{F'\eta_o}{F'U_L} = \frac{T_{ps} - T_{as}}{H} \quad (1)$$

$$F_2 = \frac{F_1 (MC)w}{A_t} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{Tw_1 - T_a}{H}\right)}{1 - \frac{1}{F_1}\left(\frac{Tw_2 - T_a}{H}\right)} \right] \quad (2)$$

Where

F_1 = stagnation temperature (first figure of merit)

$F'\eta_o$ = system optical efficiency

$F'U_L$ = overall heat loss coefficient.

T_{ps} = stagnation plate (tray) temperature (°C),

T_{as} = average ambient temperature (°C)

MC_w, = product of the mass of water and its specific heat capacity,

A_t = the aperture area of the box-type solar cooker per the time interval during which water temperature rises from T_{W1} to T_{W2}.

F' represents the heat exchange efficiency factor.

T_w = water temperature

H = solar radiation level (W/m^2)

T_a = ambient temperature.

Sample Cooking and Drying Application Evaluation Tests

Cooking Test

An aluminum cooking pot of 200 mm diameter × 100 mm height was used to evaluate the cooking performance of the cooker. Six pieces of eggs were boiled in 0.51 kg of water, taking note of the temperature range and time it took the eggs to be cooked. However, the system was heated up to the minimum cooking temperature rage (72 °C – 82 °C) before loading the cooking materials into the system. The eggs were considered to have been cooked when the temperature of the water reached 82 °C. Additionally, the amount of time it took to cook the eggs was recorded. Water temperature inside the pot and absorber plate temperature was taken with the aid of thermocouple wires and digital data logger thermometer.

Drying Test

Solar drying performance test was evaluated by drying banana slices weighing 118 g. The banana was peeled and sliced into a uniform thickness of size 4 to 5 mm, it was then placed on the drying rack layer in the dryer. Following loading at 10:00 am, drying began right away and continued until the banana slices reached its minimum moisture content. A digital scale was used to monitor the sample's weight loss at hourly intervals throughout the drying process. To allow the solar collector to efficiently absorb the most solar radiation throughout the drying process, the reflector's location was modified in relation to the solar angle. Moisture content from the specimen was determined based on the wet basis analysis by using equation 3. Also, the time it took the banana slices to stabilize in weight were recorded as well as weight of the sample, and solar radiation at an interval of one hour.

$$\%MCwb = \frac{Mass\ of\ the\ Product - Mass\ of\ the\ Fully\ Dried\ Product}{Initial\ Mass\ of\ the\ Wet\ Product} \times 100 \quad (3)$$

Plate 4: Before Drying

Plate 5: After drying

Assessment of Brine Solution and Animal Fat as Storage Material

The experimental setup used for this determination was the same as described in the stagnation test (F_1). The potential of each thermal storage material in the system was determined by monitoring the length of time the system took to cool after heating to stagnation. This was carried out by putting the dual solar cooking and drying system to a close by covering it with its cover to block the penetration of solar radiation. During this procedure, temperature variations of the absorber plate were recorded over thirty minutes using thermocouple wires and a digital data logger. This was repeated for two days.

RESULTS AND DISCUSSION

Stagnation Temperature for Solar Cooking Application (1st Figure of Merit F₁)

The first figure of merit (F_1) was attained through the air stagnation temperature test of the passive solar cooking system. The test was conducted under variable solar radiation measured in W/m^2. The results of the (stagnation) tests are shown in Figures 3.1 and 3.2, shows the variations of the system temperatures until the stagnation conditions are achieved. The tests were conducted with and without a storage tank. Both tests have attained stagnation temperatures of 120.9 ºC and 130.8 ºC for the collector plate for a period of 2 hours 10 minutes and 2 hours 40 minutes respectively. The first test was conducted without the storage tank, and the test results showed stagnation temperature was attained in 2 hours 10 minutes at an ambient temperature of 22.9 ºC, 120.9 ºC of absorber plate temperature at corresponding solar radiation of 812 W/m^2. See Figure 3.1

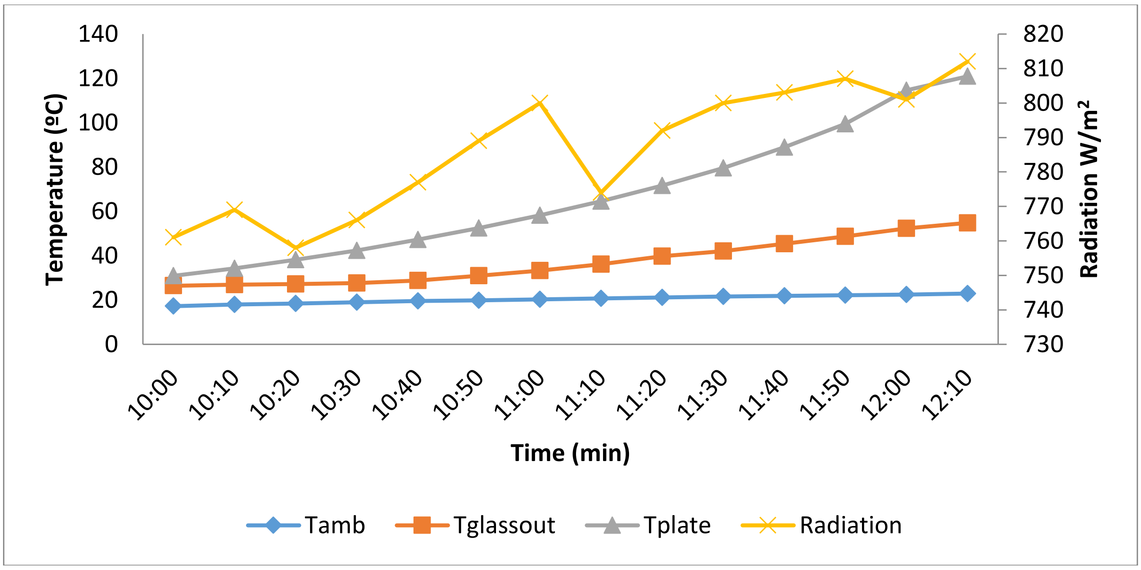

Figure 1: F_1 Stagnation Test Conducted Without Storage Tank

The second test was conducted with unloaded thermal storage tank, where the stagnation was achieved in 2 hours 40 minutes at an ambient temperature of 25.6 ºC, 130.8 ºC of absorber plate temperature at corresponding solar radiation of 868 W/m^2 (see Figure 3.2). A slight time increase of 30 minutes was recorded for the system to attain stagnation as the above test, without the tank. The time increase was due to sensible heat stored in the system within the introduced (empty) thermal heat storage tank. The thermal storage tank was introduced in the system to enable performance evaluation of the heat storage materials that could be used to store excess solar radiation to extend cooking and drying operation beyond the sunny periods.

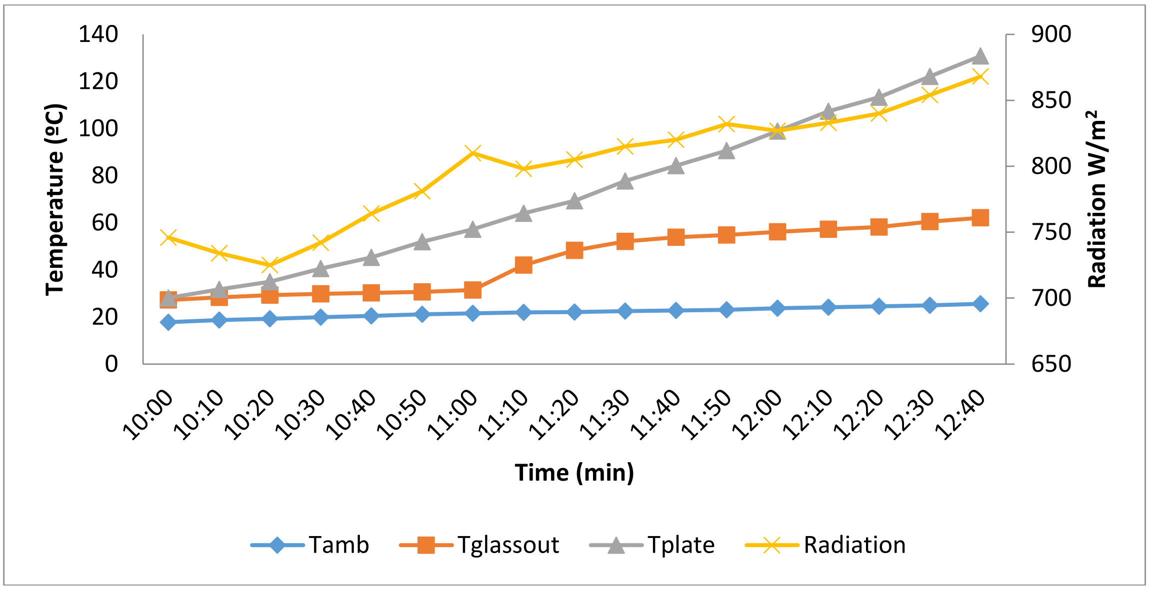

Figure 2: F_1 Stagnation Test Conducted With Storage Tank

A minimum temperature of 82ºC is needed for the system to function for cooking purposes. In the F_1 stagnation test evaluation criterion, a minimum of 0.12 is needed for the cooking system to meet the cooking temperature. A high value of F_1 indicates that the system has high optical efficiency and a low heat loss factor (Aremu, 2013). Therefore the first figure of merit (F_1) was calculated as follows;

$$F1 = \frac{\Delta T}{H} = \frac{T_{ps} - T_{as}}{H} = \frac{120.9\ ºC - 22.9\ ºC}{812} = 0.120$$

Where Tp is the plate temperature (ºC), Ta is the ambient temperature (ºC), and H is the solar radiation (W/m^2). Therefore, using the F_1 equation, the system has passed the F_1 evaluation criterion.

Stagnation Temperature Test for Drying

Solar drying stagnation test was conducted with an unloaded thermal storage tank and venting ports kept opened. Stagnation was achieved over 4 hours at an ambient temperature of 30.1 ºC, maximum absorber plate temperature of 125.2 ºC, solar collector temperature of 73.1 ºC, under a variable solar radiation level of 821 W/m^2. (Figure 3.3)

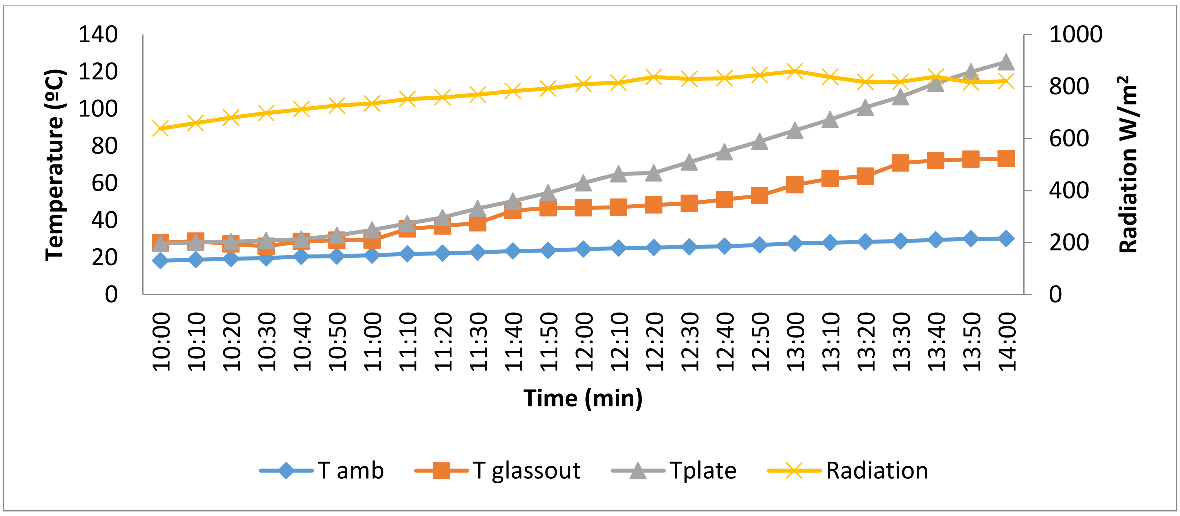

Figure 3: Stagnation Temperature for Solar Drying Application

Water Boiling Test (2nd Figure of Merit F_2)
The water boiling test was conducted under variable solar radiation level with aluminium pot as a cooking utensil. From an initial ambient temperature of 22 ºC, a 0.51 kilograms weight of water took 2 hours 30 minutes to reach a boiling point in the dual-operated solar cooker on the first day and took exactly 2 hours to reach boiling point on the second day. 131.7 ºC and 98.7 ºC were temperatures recorded for absorber plate collector and inner pot (water) respectively. In the F_2 stagnation test evaluation criterion, a minimum of 0.24 was needed for the cooking system to meet the cooking temperature (Mullik et al, 1987). However, second figure of merit F_2 was calculated to be 0.235. This value compared favorably with the ASAE value 0.25 (ASAE, 2002), a high value of F_2 indicates that the system has high heat exchange efficiency. (Figure 3.4)

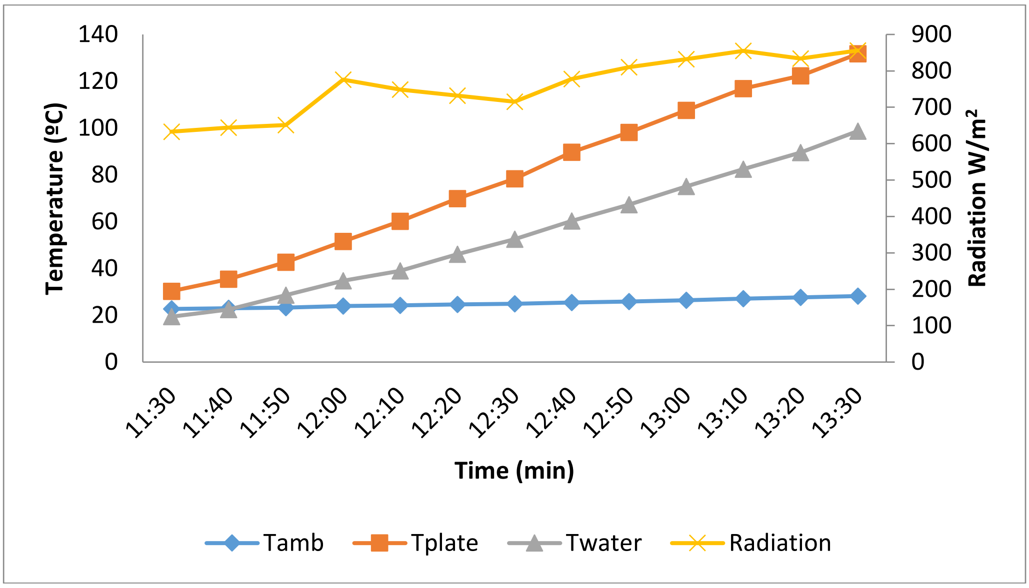

Figure 4: Temperature Variations during Water Boiling (F_2) Test

The value of the figures of merit agrees with the standard values of $F_1 \geq 0.12$ and $F_2 \geq 0.25$ (BIS Standard 1993)
Aremu (2013) carried out a similar study, and determined the figures of merits of five different solar cookers over three years. The F_1 values of the five solar cookers that were put to test ranged from 0.11 to 0.15 for first year, from 0.092 to 0.124 for second year, and from 0.087 to 0.103 for third year. In the first, second and third year, the values of F_2 varied from 0.33 to 0.44, 0.22 to 0.66, and 0.020 to 0.025, respectively.

Sample Cooking and Drying Application Evaluation Tests
Cooking Test
The solar cooking performance test was conducted using the same aluminium pot. Six pieces of eggs weighing 0.36 kg were boiled in 0.51 kg of water which was cooked under a variable solar radiation as above. The egg was cooked in a temperature range from 29.7 ºC to 88.2 ºC in 45 min with a maximum absorber plate temperature of 103 ºC as shown in Figure 3.5

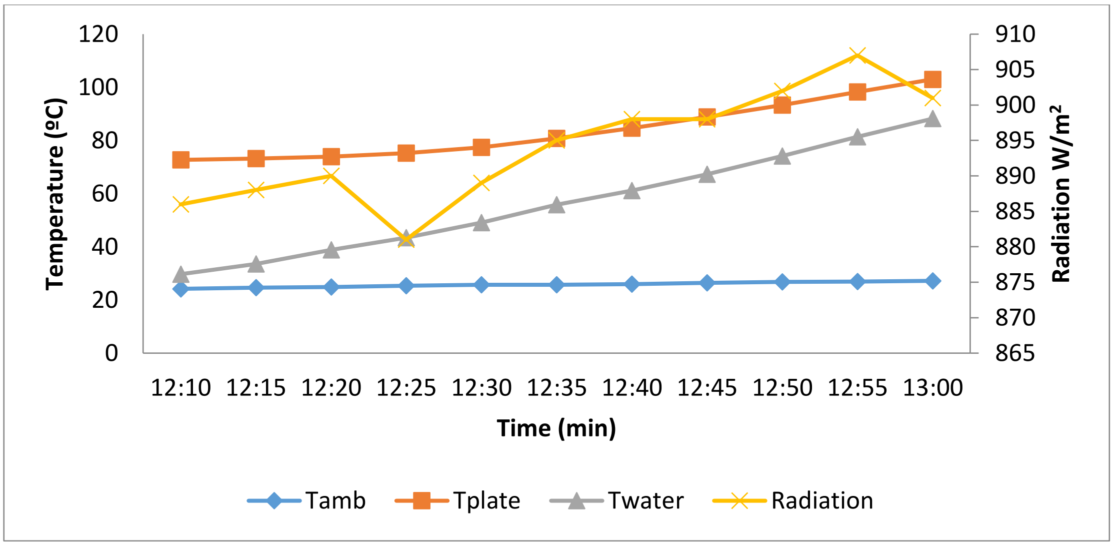

Figure 5: Egg Boiling Performance Test

A similar cooking test was carried out by (Garba, 2009). Parboiled basmati rice was cooked in 0.70 kg of water and cooking was achieved in three hours within a temperature range of 82 ºC to 95 ºC with a maximum cooking pot temperature of 95 ºC.

Drying Test

Banana slices of about 4 – 5 mm in thickness, weighing 118 g dried using the dual-operated solar cooking and drying system. The initial moisture content on a wet basis was found to be 100% before drying. And after drying, it was found that the dual-operated solar cooking and drying system was able to dehydrate 89 % of moisture content, achieving a stable weight of 12 g after 8 hours of drying. See Figure 3.6

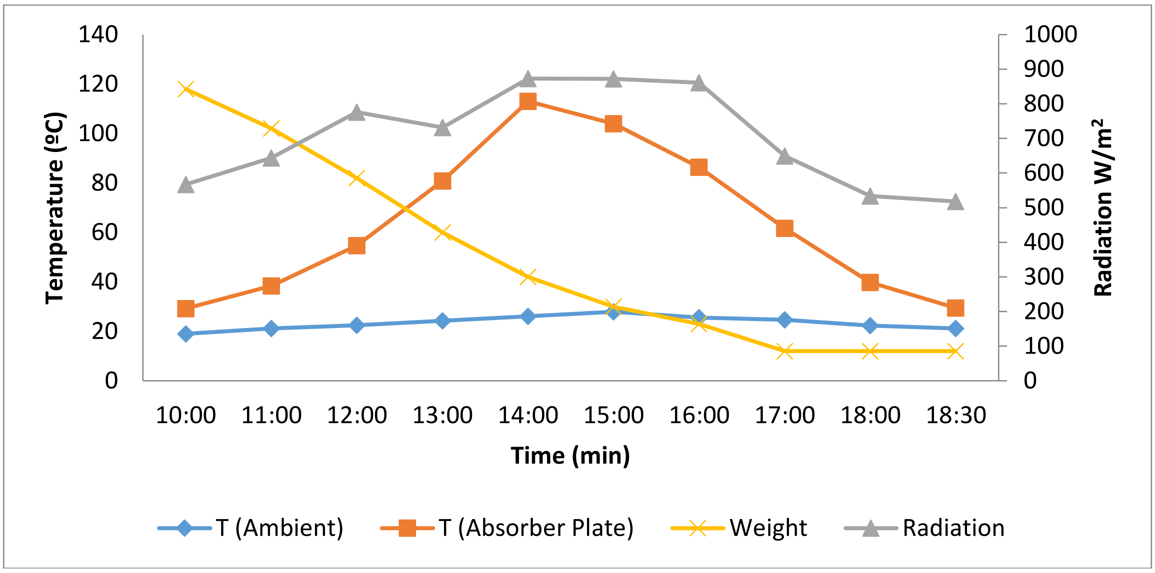

Figure 6: Drying Curve of Banana Slices

This result comes in consistence with a similar drying test which was conducted by (Fernandes et al, 2022) using sliced foods which include; apples, mushrooms, zucchini, lemon peel, sweet potatoes, and bananas. These sliced foods were dried to a moisture level of less than 10 % in less than 6 hours, necessitating only one drying day. However, due to the tough serous peel that covers fruits such as tomatoes and blueberries, drying tomato quarters took at least two days, and drying full blueberries can take several days to dehydrate below 10 % of moisture content.

Determining the Potential of Brine Solution and Animal Fat as Storage Material

The results of the thermal energy retention test for the dual-operated solar cooking and drying system using Brine Solution and Animal Fat as heat storage materials, which can be used for both cooking and drying applications are presented in figures 3.7 and 3.8

Thermal energy stored in the system under cooking application was conducted on two dimensions, charging and discharging periods. This enabled the assessment of the thermal energy storage potential by monitoring the length of time the system took to cool to 30 ºC after heating to stagnation of 126.1 ºC and 128.3 ºC for Brine Solution and Animal Fat respectively.

Brine Solution as a Potential Thermal Storage Material

The stagnation test shows that the system has taken 4 hours to heat to a stagnation of 126.1 ºC at an ambient temperature of 31.8 ºC and solar radiation of 807 W/m^2 and 4 hours 30 minutes to cool down to 26.9 ºC. The stored thermal energy in the storage tank could enable a continued late evening cooking or a continued drying application using the thermal energy stored from the 4 liters of Brine Solution in the system.

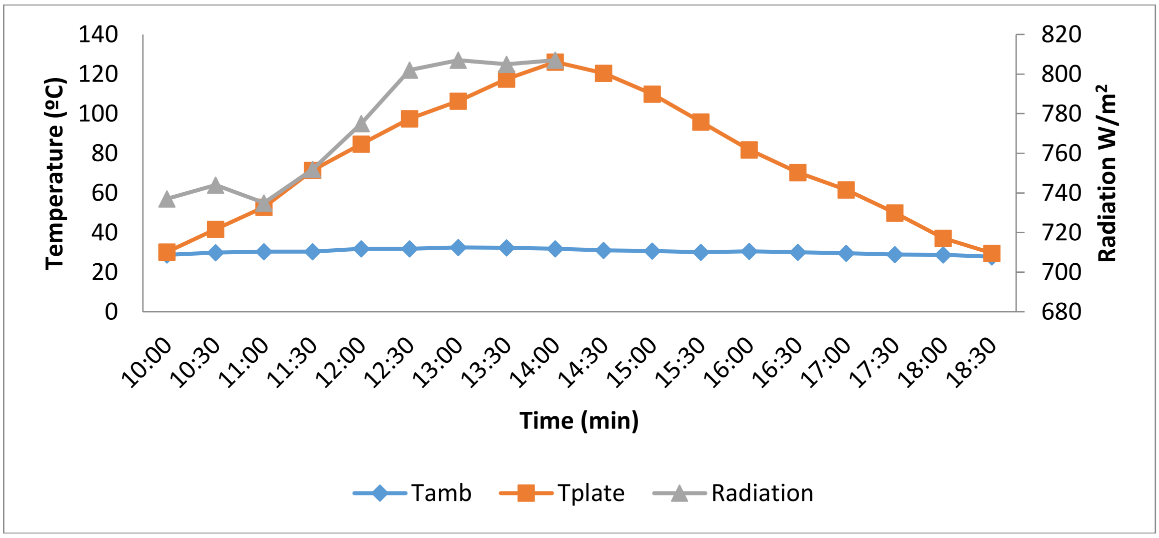

Figure 7: Temperature Variation of Solar Cooker in Cooking Mode Using Brine Solution as a Storage Medium with the System Closed

Animal Fat as Potential Thermal Storage Material

Four liters of animal fat was used as heat storage medium, and it was evaluated under solar cooking conditions. The result shows that the plate temperature has reached 128.3 ºC at an ambient temperature of 31.2 ºC with corresponding solar radiation of 824 W/m^2 within 3 hours. It further shows that it took the system 5 hours to cool down to 28.8 ºC. The stored thermal energy in the storage tank could enable a continued late-evening cooking or drying application.

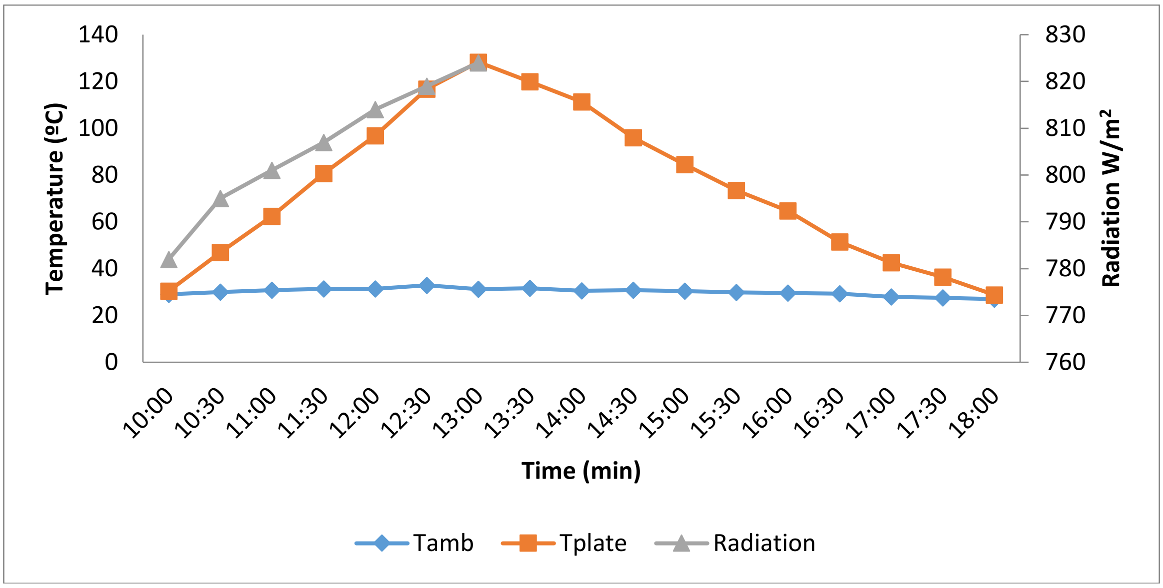

Figure 8: Temperature Variation of Solar Cooker in Cooking Mode Using Animal Fat as a Storage Medium with the System Closed

This indicates that the system could meet the dual requirements of meat/fish smoking, solar drying and cooking applications, as the required temperature for cooking most food products is between 72 ºC and 82 ºC (Garba 2009). Garba (2009) carried out a similar study determining the potential of four liters of used engine oil and two other organic storage materials. Table 3.1 shows the summary of the result.

Table 1: Solar Cooking Performance Analysis Using 4 Liters of Used Engine Oil, and 2 Other Organic Storage Materials

Material Quantity	Cooking Period	Cooling Period	Max. Plate Temp.	Storage Material
2 liters	2 hrs 30 min	5 hrs 25 min	82 ºC	Organic Material
4 liters	1 hrs 30 min	4 hrs 27 min	82 ºC	Encapsulated Material
4 liters	1 hrs 30 min	4 hrs 25 min	83 ºC	Engine Oil

CONCLUSION

The first figure of merit (F_1) for the dual-operated solar cooker fell within the recommended range of 0.12-0.16 m^2 ºC/W, indicating its functionality. The second figure of merit (F_2) was calculated to be 0.235, which aligns closely with the suggested range for a functional cooker. A solar cooking test successfully boiled six eggs in 45 minutes, with a temperature range of 29.7 ºC to 88.2 ºC. Drying tests demonstrated that banana slices can be dehydrated within a day, although the achieved temperature exceeded the recommended drying temperature. The use of brine solution and animal fat as storage materials showed promising results for extended cooking and drying periods, with brine solution enabling up to 4 hours and 30 minutes of cooking or drying, and animal fat allowing for 5 hours of operation. These findings indicate the potential of this solar cooking and drying system for domestic applications.

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NOMENCLATURE

F_1 = stagnation temperature (first figure of merit)
$F'\eta_o$ = system optical efficiency
$F'U_L$ = overall heat loss coefficient.
T_{ps} = stagnation plate (tray) temperature (ºC),
T_{as} = average ambient temperature (ºC)
MC_w, = product of the mass of water and its specific heat capacity,
A_t = the aperture area of the box-type solar cooker per the time interval during which water temperature rises from T_{W1} to T_{W2}.
F' represents the heat exchange efficiency factor.
T_w = water temperature
H = solar radiation level (W/m^2)
T_a = ambient temperature.

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