FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 7 No. 6, December, 2023, pp 171 - 179
DOI: https://doi.org/10.33003/fjs-2023-0706-2113

CONSTRUCTION AND PERFORMANCE EVALUATION OF AN INTEGRATED SOLAR COOKING AND DRYING SYSTEM

[*1]Inuwa Jibrin, [2]Garba, M. M., [3]Argungu, G. M., [1]Mohammed, M. L. and [1]Usman Anas

[1]Department of Energy and Applied Chemistry, Faculty of Chemical and Life Sciences, Usmanu Danfodiyo University, Sokoto
[2]Sokoto Energy Research Center, Usmanu Danfodiyo University, Sokoto
[3]Department of Physics, Usmanu Danfodiyo University, Sokoto

*Corresponding authors' email: jbkwankwaso@gmail.com

ABSTRACT

An integrated solar cooking and solar drying system was developed using locally available materials. The system performs both functions of cooking and drying simultaneously. Performance evaluation of the system was carried out using tomatoes for drying; while rice, beans and eggs were used to carryout cooking experiment. For the purpose of performance evaluation, total global radiation, ambient temperature, humidity, water temperature were monitored, taken and recorded. Results obtained from the system and that of the non-integrated systems were compared using excel as a statistical tool for analysis to ascertain the performance of the integrated system. The average temperatures recorded in the integrated system during drying were 45.3℃, 46.0℃ and 45.9℃, while that of the non-integrated system were 40.2℃, 39.9℃ and 39.7 ℃. The average temperatures recorded during cooking of egg, beans and rice using the integrated system were 83.1℃, 83.4℃ and 78.2℃, while that of the non-integrated system were 68.8℃, 86.3℃ and 65.0℃. This indicates higher heat generation and faster drying and cooking rates in the integrated system than the non-integrated system. The system has a total cost estimate of N30,600 with an added advantage of cooking and drying simultaneously. It is portable and can help in improving the ambient air quality. Furthermore, the integrated system will occupy less space and gives higher efficiency compared to the conventional single use systems.

Keywords: Integrated solar cooking, solar drying system, non-integrated system, stagnation test, full load test

INTRODUCTION

Energy is one of the major parameters for measuring growth and development of any country, as the standard of living depends upon per capital energy consumption. Most energy on the earth is received from the sun (solar energy), it is the world's most abundant source of energy known and used by mankind. Solar energy or solar radiation arises from the conversion of mass of energy in the sun through the nuclear fusion of hydrogen atom to form helium, and as a renewable energy resource whose reserve and rate of supply is such that, for all practical purposes, remains inexhaustible with time (Danshehu, 1997). The availability of this energy is never questionable as in every second the earth received a quantity of energy amounting to 1.73 x 10^{17} Joule, therefore solar energy can supply more than 10,000 times than the current world energy demand projections (Danshehu, 2012).

Massive and excess use of energy has raised people's concern on the limited energy resources, deterioration of the global climate as well as the disappearance of ozone layer (Shuaibu *et al.*, 2019). In many parts of the world, there is a growing awareness that renewable energy has an important role to play in extending technology to Agricultural sector in developing countries to increase farmers' productivity. In the developing countries, more than 80% of the populace lives in the rural areas where up to 90% of the energy being consumed comes from non-commercial sources of conventional energy of which fuel wood is the major energy source. The increasing cost and non-availability of conventional energy sources in the rural areas necessitate exploration of other sources of energy and fortunately the rural areas are blessed with abundant solar energy.

Solar thermal technology is a technology that is rapidly gaining acceptance as an energy saving measure in household and agricultural applications. The technology is more preferred to other alternative sources of energy such as wind, because of its abundance, in exhaustible nature and non-polluting (Bukola *et al*., 2008).

According to Jayaraman and Gupta (2020) fruits and vegetables losses in developing countries are estimated to be between 30 and 40% due to inadequate storage of these perishables food items. Solar dryers are specialized devices that control the drying process through a deliberate use of solar energy to heat air or the products so as to achieve dehydration/drying and protect agricultural produce from damage by insect pest, dust and rain.

Cooking is a reoccurring energy intensive operation use to prepare food for human survival. The average daily wood consumption in the developing world is 1.3–kg per person, thus, a family of 5 requires 6.5 kilograms (Garba *et al*., 2008). Supplementing conventional energy sources with solar energy in producing hot water, cooking and drying will not only make it cheaper source but also more reliable. For instance, when an urgent demand of boiling a small amount of water arises for drinking or sanitizing equipment or for cooking, making fire from wood or stove is often cumbersome. In this situation, solar energy becomes easier, cheaper and more accessible. Hence, the use of solar cookers is one way of reducing the demand for firewood, coupled with improving the efficiencies of wood-based cooking devices and other biomass-based fuels (Schwarzer *et al*., 2008).

In this work, an integrated solar cooking and drying system with a dual function of cooking and drying was constructed. The system has a conventional box type solar cooker placed on top of a moveable and four chambers cabinet dryer. The cooker consists of a glazing with reasonable depth to accommodate a range of cooking pots. The cabinet dryer was fabricated to have a solar collector tilted at an appropriate angle which absorbs the incoming solar radiation, converts it to heat, transfers the heat to a fluid (e.g. air) flowing through the collector. Two ducts ventilation openings (air inlet and air outlet) were provided at opposite faces to enable cross ventilation.

The system was designed to cook different household commodities and to dry various agricultural produce. A thermal storage facility with locally sourced heat storing materials for storing excess solar energy was incorporated to extend the system's operational period beyond sunshine hours.

MATERIALS AND METHODS:

Materials:

The materials and instruments used in constructing and assessing the performance of the integrated system include: plywood, flanks, metal sheets, mirror and glass, angle iron, wire mesh, nails and screws, handle and hinges, paints and glue, foams, weighing balance, data logger, thermometer, hygrometer, anemometer and pyranometer.

Methods

System construction and integration

The integrated system with a total length of 1.15 m and 0.50 m wide has 2 major components, i.e. the drying and cooking components.

The drying component or chamber with a dimension of 0.50 m by 0.85 m by 0.90 m was constructed using laminated plywood of 1-inch thickness. The chamber has 4 in-built sliding trays of 0.50 m by 0.45 m and drying racks which serve as a space where the actual dehydration occurs. A solar collector measuring 0.90 m by 0.60m by 0.55 m was also constructed using wooden flank for casing, Galvanize Iron sheet metal as absorber, single glass cover and 2 inch foam for insulation. The collector was placed in a south-facing position and tilted upward from horizontal at an angle of tilt (15^0 inclination angle of the location). It is expected to transform the radiant sunlight energy in to heat energy.

The cooking component was made up of a box solar cooker measuring 0.50 m by 0.44 m by 0.26 m as its length, breath and height respectively which was mounted on the drying chamber. An inlet was created to link the cooking and drying components of the integrated system for proper integration. The schematic diagram of the integrated system is shown in Figure 1.

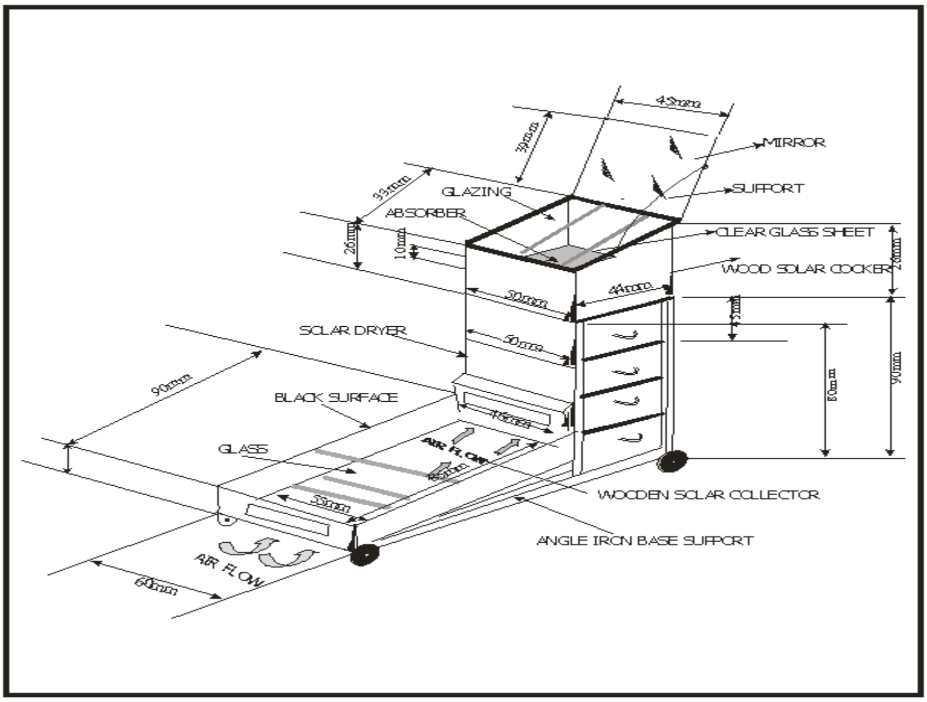


Figure 1: Schematic Diagram of the Integrated Solar Cooking and Drying System Showing Three (3) Dimensional Views

Performance Evaluation Test

Stagnation temperature test for solar cooker

The system 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 thermometer, and the solar radiation of the sun's rays was measured using a pyranometer. Measurements were taken every 30 minutes until the temperature reached stagnation. This was repeated for three days. After the measurements, Equation 1 was used to calculate the stagnation temperature test.

$$F_1 = \frac{\eta_o}{U_L} = \frac{Tps - Tas}{Hs} \text{----} \quad (1)$$

Stagnation temperature test for solar dryer

The experimental setup been integrated was the same as described in Figure 1. The variation in solar radiation, inlet and outlet temperatures, relative humidity, chamber temperature and ambient temperature were measured at intervals of 30 minutes. The experiment was carried out until stagnation was reached. This was repeated for three days.

Full load test (F2) for solar cooker

The experimental setup for this determination is the same as described in Figure 1, except that quantities of samples (rice, beans, and eggs) were loaded into the cookers separately. Water temperature inside the pots, ambient temperature, solar collector temperatures, solar radiation, and relative humidity were recorded at intervals of thirty minutes. The experiment was carried out until the samples were cooked. This was repeated for three days each, using the integrated and the conventional non-integrated systems.

Full load test (F2) for solar dryer

Solar drying performance test was evaluated by drying sample of tomatoes inside drying tracks of the drying chambers. A digital scale was used to measure the samples' weight every day. Solar radiation, relative humidity, ambient temperature, inlet

and outlet temperatures and chambers temperatures were measured for three days using both systems.

RESULTS AND DISCUSSION

The results obtained from the existing non-integrated system and that of the integrated system are as follows.

Results of stagnation temperature test

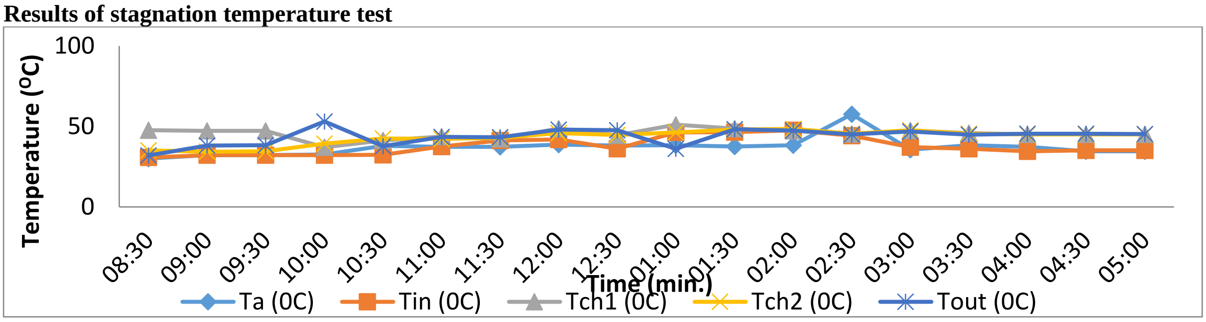


Figure 2: Solar Drying Stagnation Test for day 1, using Integrated System

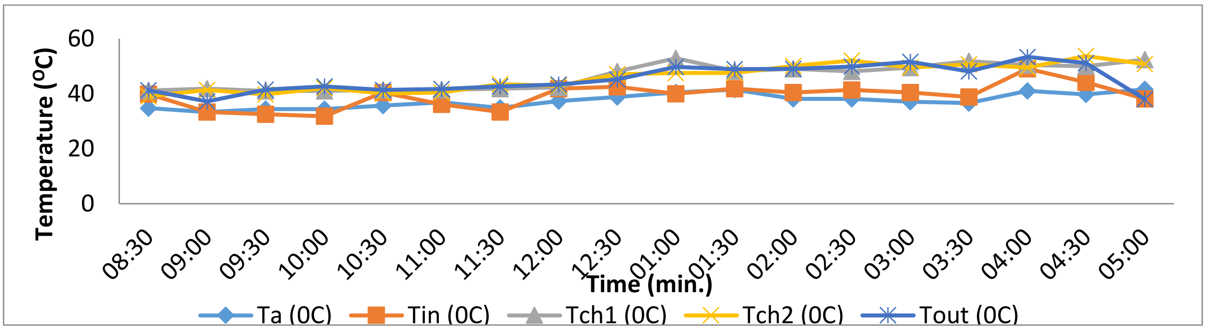


Figure 3: Solar Drying Stagnation Test for day 2, using Integrated System

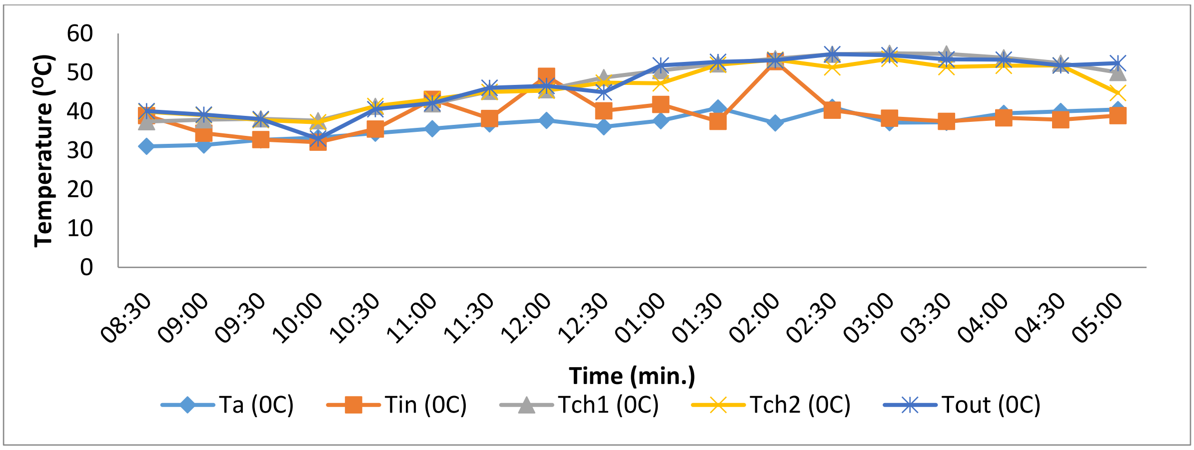


Figure 4: Solar Drying Stagnation Test for day 3, using Integrated System

Figures 2-4 represents the solar drying stagnation test for day1-day3 of the integrated system. On day 1, the maximum temperature achieved in chamber 1 was 51.1^{O}C after 4.5 hours of heating at an ambient temperature of 38.4^{O}C, while maximum temperature of 48.5^{O}C was achieved in chamber 2 at the same ambient temperature as shown in Figure 2.

On day 2, the maximum temperature in chamber 1 achieved was 52.9^{O}C after 4.5 hours of heating at an ambient temperature of 40.4^{O}C, while maximum temperature of 53.7^{O}C was achieved in chamber 2 at ambient temperature of 39.79^{O}C as shown in Figure 3.

On day 3, the maximum temperature in chamber 1 achieved was 54.9^{O}C after 6.5 hours of heating at an ambient temperature of 37.16^{O}C, while maximum temperature of 53.5^{O}C was achieved in chamber 2 at the same ambient temperature as shown in Figure 4.

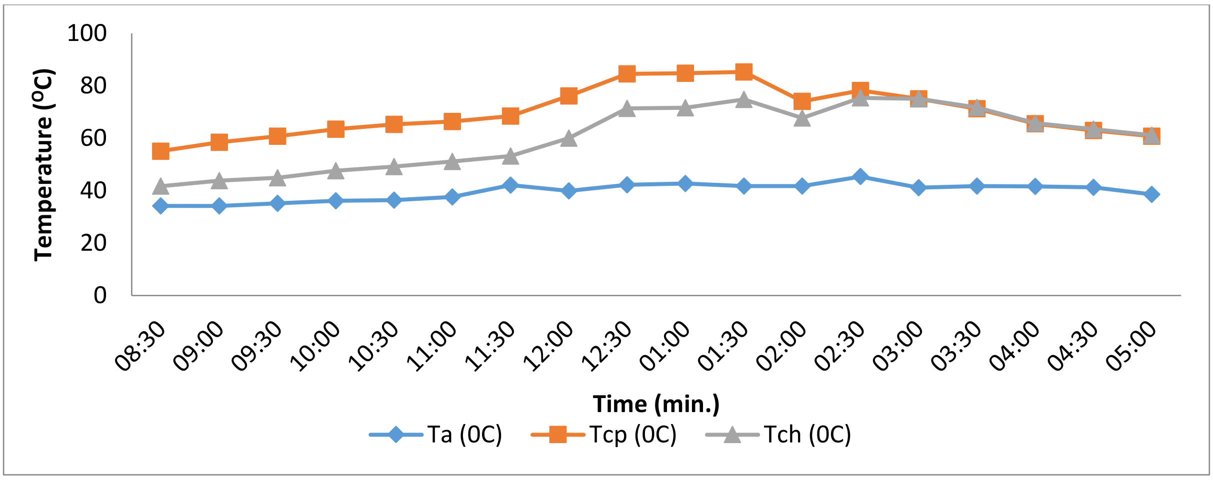


Figure 5: Solar Cooking Stagnation Temperature Test for day 1, using the Integrated System

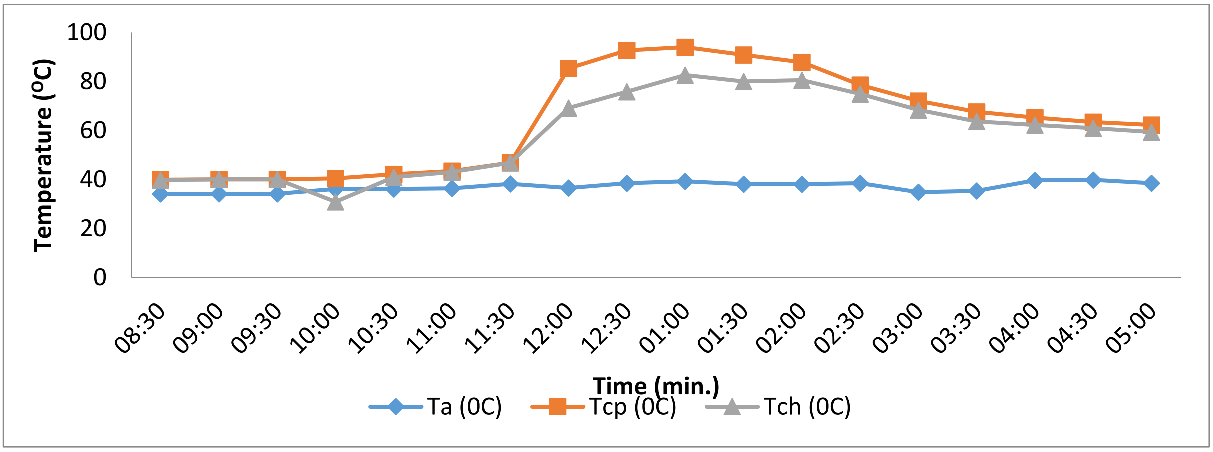


Figure 6: Solar Cooking Stagnation Temperature Test for day 2, using the Integrated System

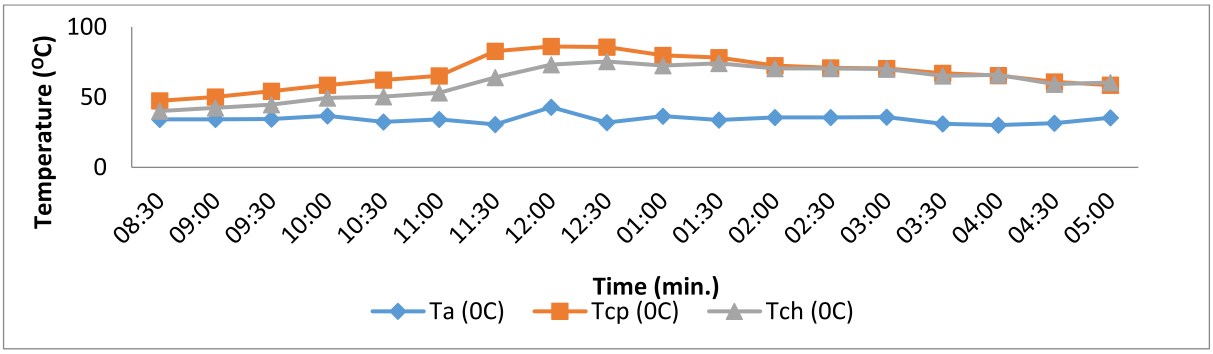


Figure 7: Solar Cooking Stagnation Temperature Test for day 3, using the Integrated System

Figures 5-7 represents the solar cooking temperature stagnation tests of the integrated system. The results of the cooking test conducted over 3 days are as follows:

On day 1, the maximum plate temperature achieved was 85.3^{O}C after 5 hours of heating at a solar radiation level of 872 and an ambient temperature of 41.71^{O}C. The chamber temperature has a maximum temperature of 75.4^{O}C as shown in Figure 5.

On day 2, the maximum plate temperature achieved was 94.0^{O}C after 4 hours: 30minutes of heating at a solar radiation level of 948 and an ambient temperature of 39.24^{O}C. The chamber temperature has a maximum temperature of 82.6^{O}C as shown in Figure 6.

On day 3, the cooker was able to achieve a maximum plate temperature of 86.1^{O}C after 3hours and 30munites of heating at solar radiation level of 980. The chamber temperature has a maximum temperature of 75.4^{O}C as shown in Figure 7.

Overall, the results indicate that, the solar cooker was able to achieve the highest temperature of 94.0^{O}C in day 2.

Result of water boiling stagnation temperature test

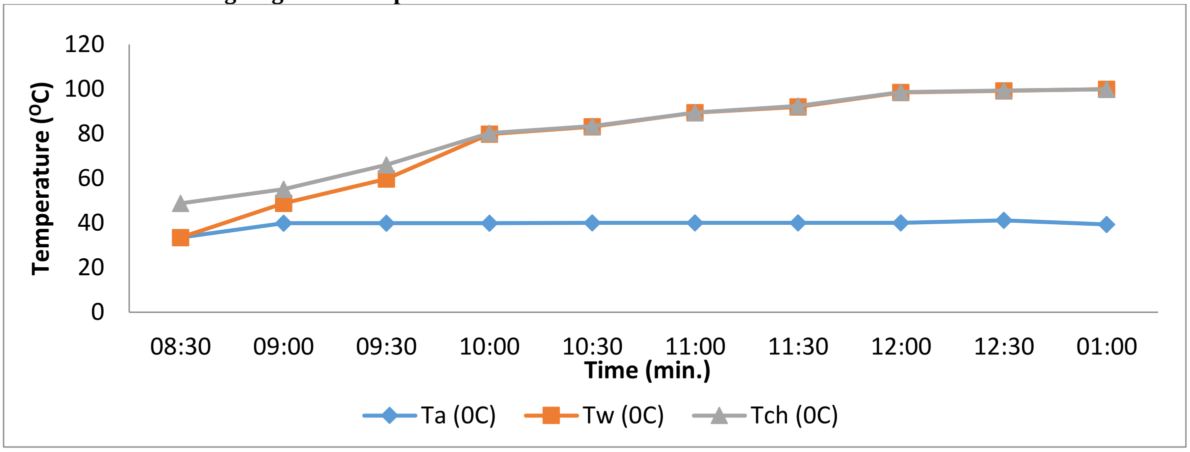


Figure 8: Water Boiling Stagnation Test for day 1, using Integrated System

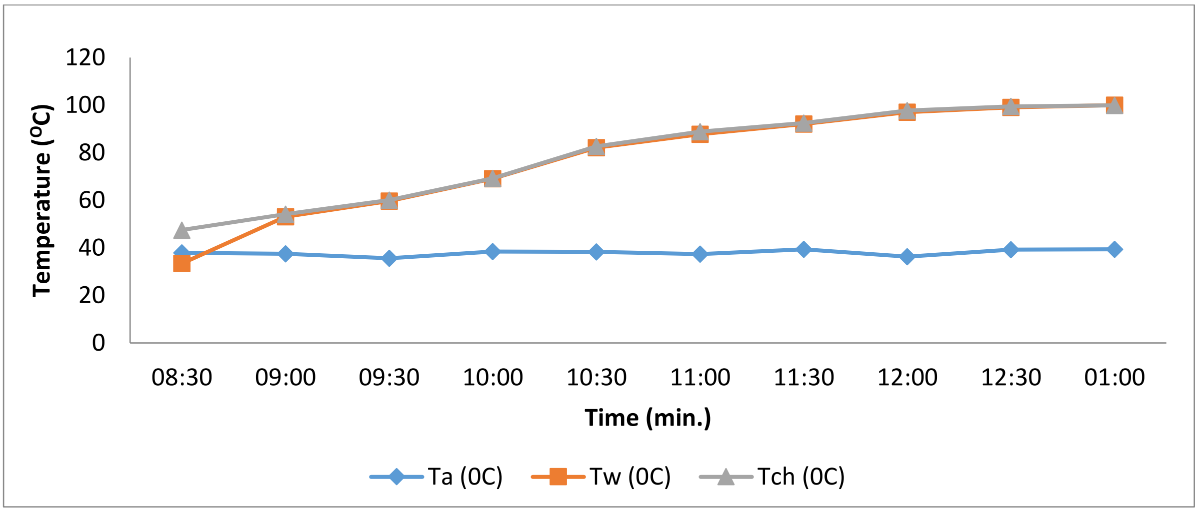


Figure 9: Water Boiling Stagnation Test for day 2, using the Integrated System

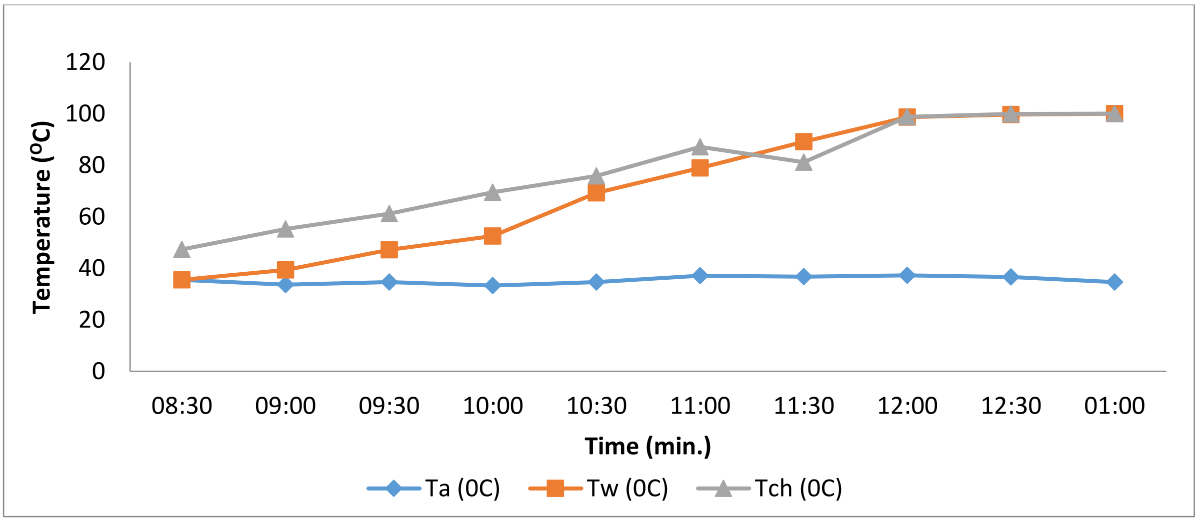
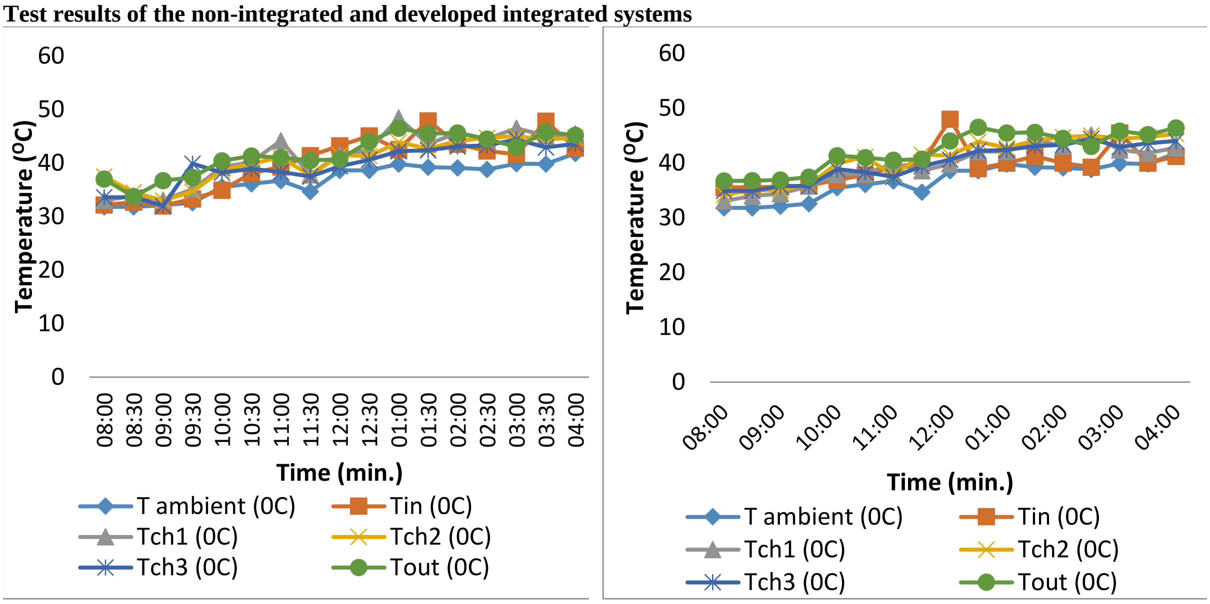


Figure 10: Water Boiling Stagnation Temperature Test for day 3, using the Integrated System

Figures 8-10 represents the water boiling stagnation test for day1-day3 of the integrated system. It was observed from the Figures that, the boiling temperatures during stagnation test were achieved already at about 12 noon for each of the three days tested with 98.5^{O}C, 97.1^{O}C and 98.6^{O}C as the boiling temperatures respectively as shown in Figure 8, 9 and 10.

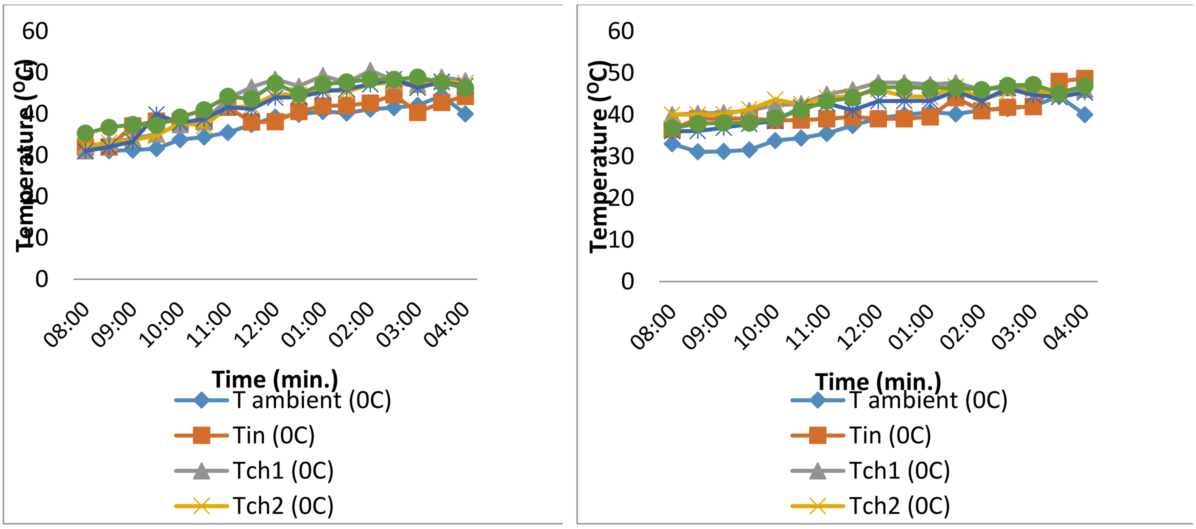
Test results of the non-integrated and developed integrated systems



(a) (b)

Figure 11: Day 1: Drying Test on Tomatoes using (a) Non-Integrated (b) Integrated system

Figure 11 indicates Drying Test on Tomatoes using Non-Integrated and Integrated systems in day 1. For the non-integrated system, the first, second and third chambers each reached maximum temperatures of 48.4^{O}C, 45.0^{O}C, and 44.4^{O}C respectively and at corresponding time of 1pm and 3pm for both second and third chambers as shown in Figure 11a. However, in the integrated system, the first, second and third chambers each reached maximum temperatures of 45.1^{O}C, 45.0^{O}C, and 44.4^{O}C respectively at 2:30pm for each chambers as shown in Figure 11b



(b) (b)

Figure 12: Day 2: Drying Test on Tomatoes using (a) Non-Integrated (b) Integrated system

Figure 12 indicates Drying Test on Tomatoes using Non-Integrated and Integrated systems in day 2. For the non-integrated system, the first, second and third chambers each reached maximum temperatures of 50.5^{O}C, 47.9^{O}C, and 48.4^{O}C respectively and at corresponding time of 2 pm, 3:30 pm and 2:30 pm respectively as shown in Figure 12a. On the other hand, the first, second and third chambers each in the integrated system reached maximum temperatures of 47.7^{O}C, 46.8^{O}C, and 45.6^{O}C respectively and at 1:30 pm for each chambers as shown in Figure 12b

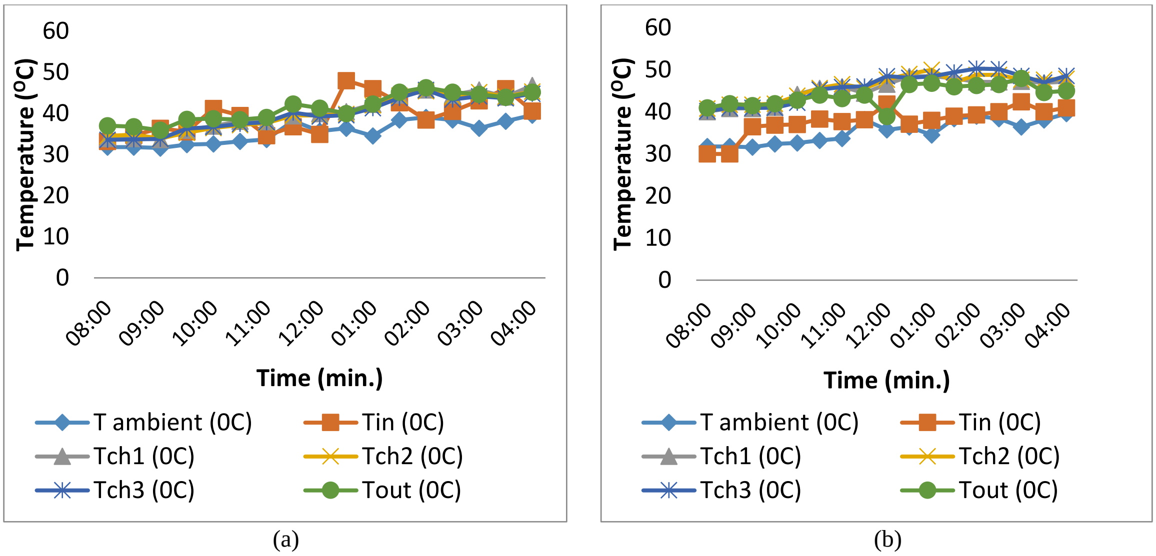


Figure 13: Day 3: Drying Test on Tomatoes using (a) Non-Integrated (b) Integrated system

Figure 13 indicates Drying Test on Tomatoes using Non-Integrated and Integrated systems in day 3. For the non-integrated system, the first, second and third chambers each reached maximum temperatures of 46.8^{O}C, 45.4^{O}C, and 45.7^{O}C respectively and at 4pm first chamber and 2pm for second and third chambers as shown in figure 13a.Where as in the integrated system, the first, second and third chambers each reached maximum temperatures of 48.5^{O}C, 50.0^{O}C, and 50.3^{O}C respectively, at 1:00pm for the first and second chambers while 2:00pm for the third chamber as shown in Figure 13b.

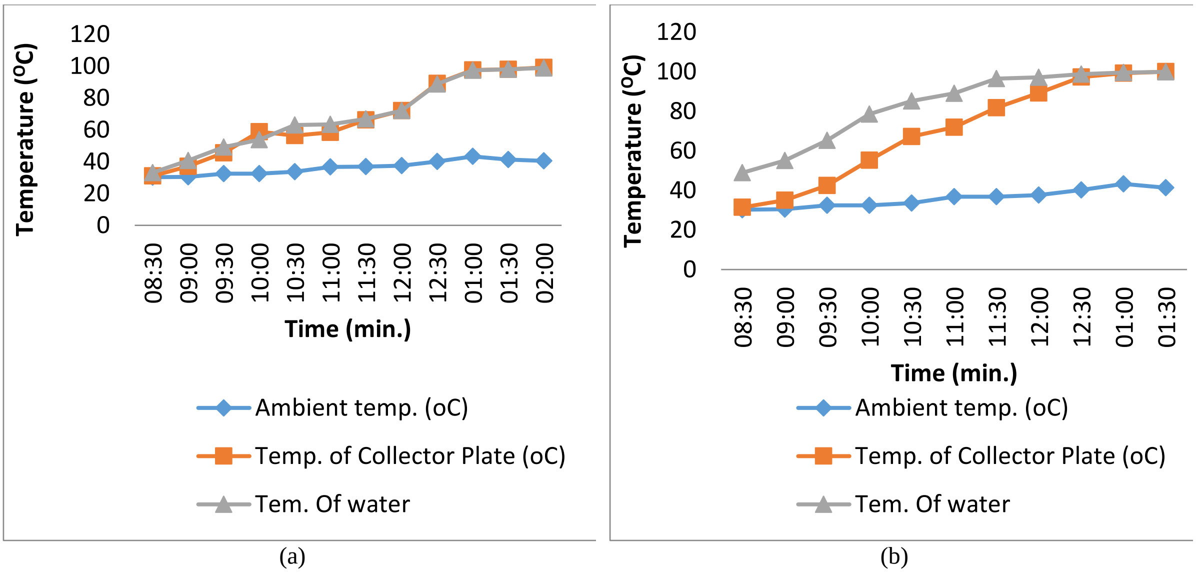
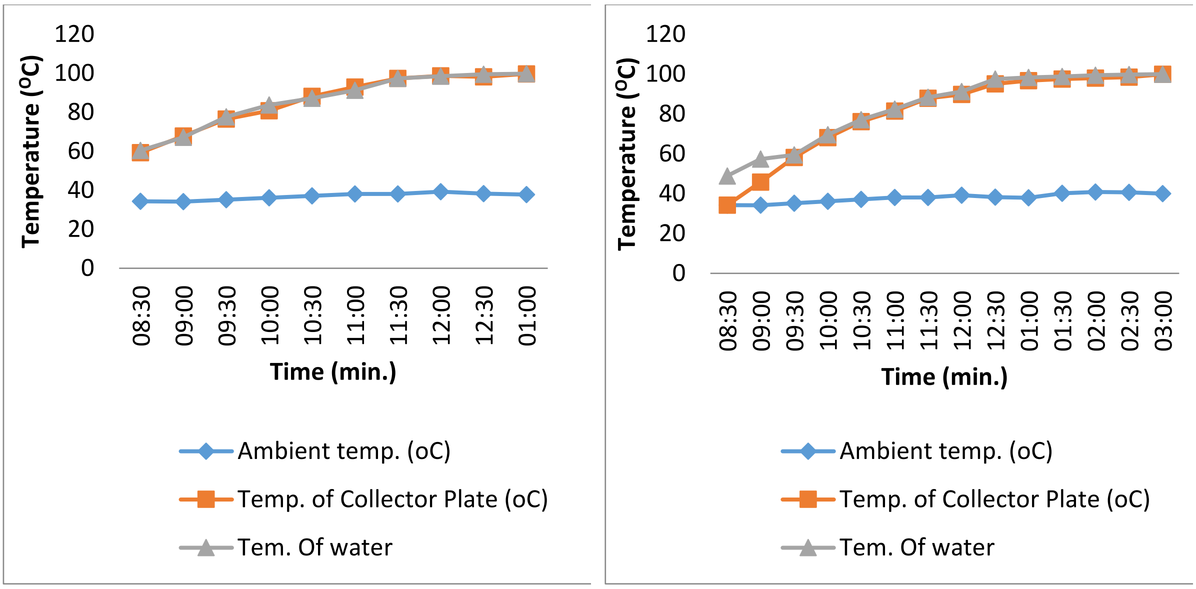


Figure 14: Day 1: solar cooking test (Egg) using (a) Non-Integrated (b) Integrated system

Figure 14 represents solar cooking test (egg) using Non-Integrated and Integrated systems. For the Non-Integrated system, the ambient temperature starts at 30.24^{O}C at sunrise and reaches its highest value at 1pm with the value of 43.29^{O}C. The collector plate temperature was high most of the time, ranging between 31.0^{O}C to 99.2^{O}C. The maximum water temperature on the day was 98.9^{O}C at 2pm as shown in Figure 14a.

For the Integrated system, under the same ambient temperature, the collector plate temperature reaches its maximum value of 100^{O}C at 1:30pm at the same time, the maximum water temperature was recorded as 99.9^{O}C as shown in Figure 14b.

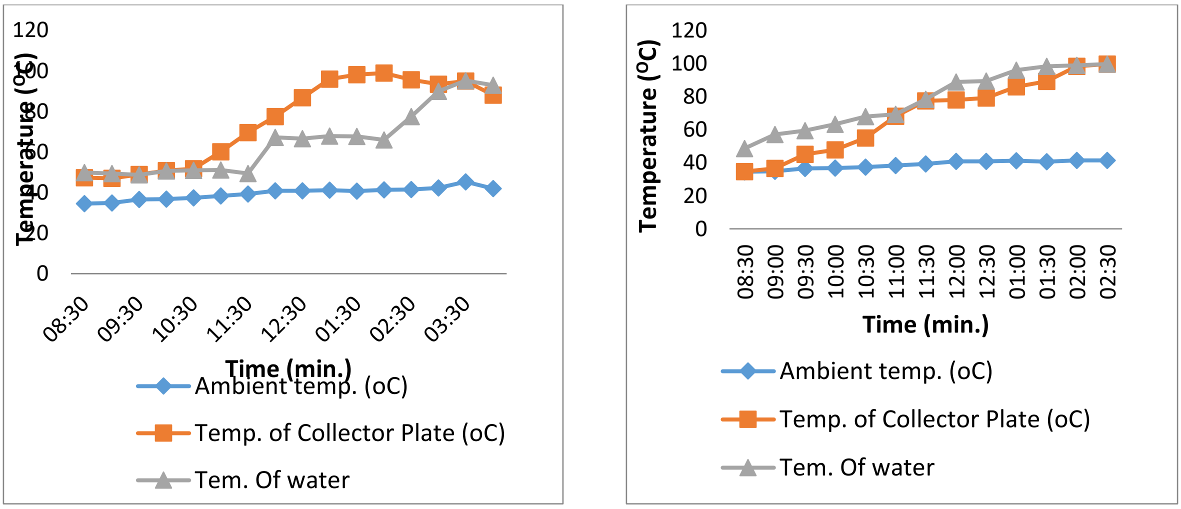


(a) (b)

Figure 15: Day 2: solar cooking test (beans) using (a) Non-Integrated (b) Integrated system

Figure 15 represents solar cooking test (beans) using Non-Integrated and Integrated systems. For the Non-Integrated system, the ambient temperature starts at 34.28^{O}C at sunrise and reaches its highest value of 39.28^{O}C at noon. The collector plate temperature was high most of the time, ranging between 59.3^{O}C to 99.7^{O}C. The maximum water temperature on the day was 99.8^{O}C at 1pm as shown in figure 15a.

For the Integrated system, under the same atmospheric condition, the collector plate temperature reaches its maximum value of 99.9^{O}C at 3pm at the same time, the maximum water temperature was recorded as 100^{O}C as shown in Figure 15b.



(a) (b)

Figure 16: Day 3: solar cooking test (rice) using (a) Non-Integrated (b) Integrated system

Figure 16 represents solar cooking test (rice) using Non-Integrated and Integrated systems. For the Non-Integrated system, the ambient temperature starts at 34.55^{O}C at sunrise and reaches its highest value of 45.30^{O}C at 3:30pm. The collector plate temperature was high most of the time, ranging between 47.0^{O}C to 98.9^{O}C. The maximum water temperature on the day was 95.2^{O}C at 3:30pm as shown in figure 16a.

For the Integrated system, under the same atmospheric condition, the collector plate temperature reaches its maximum value of 99.8^{O}C at 2:30pm at the same time, the maximum water temperature was recorded as 99.8^{O}C as shown in figure 16b.

CONCLUSION

It was observed from the experimental studies conducted from May, 2019 to May, 2020 on the integrated and non-integrated solar systems, that between the hours of 11.30 am to 2.00 pm, the solar intensities were high as recorded, ranging from about 430W/m^2 to 1000W/m^2 in almost all the days of the experiment, which represents a suitable range for solar cooking in the Usmanu Danfodiyo University, Sokoto (UDUS) meteorological area.

The integrated solar cooking and solar drying system was constructed using low-cost and locally available materials such as plywood, flanks, metal sheet, foam, mirror and glass, the system constructed generate high heat and effective while cooking and drying.

Parameters such as temperature, humidity, moisture content of the food to be dried, solar radiation, wind speed etc. were monitored, measured and recorded at intervals. The readings obtained were used for comparison using excel as a statistical tool for analysis.

It can be concluded that, the use of solar cookers and solar dryers is dependent on weather condition, as the performance of both integrated and non-integrated systems was found to be low during morning and evening hours when the sun angles were low.

ABBREVIATIONS/NOMENCLATURE

A	Aperture Area
AL	Arduino Logger/Automated Logger
Ad	Area of the dryer
ASEA	American Society of Agricultural Engineers
Cw	Specific heat capacity of water (J/kg°C)
ECSCR	European Committee on Solar Cooking Research
F1	Figure of Merit
G	Global Radiation (W/m^2)
GI	Galvanize Iron
Hs	Solar Radiation
H	Average Solar Radiation (W/m^2)
IS	Integrated System
I	Solar Radiation
lv	Latent heat of Vapourization
Mw	Mass of Water (kg)
NIS	Non-Integrated System
RH	Relative Humidity
T	Time Difference
Tps	Plate Temperature
Tas	Average Ambient Temperature
Ta	Ambient Temperature (°C)
TC	Collector Temperature
Tw	Water Temperature (°C)
Tin	Inlate Temperature
Tout	Outlet Temperature
Tch	Chamber Temperature
Tcp	Plate Collector Temperature

ACKNOWLEDGEMENT

The main author extends his gratitude and appreciation to his major and co-supervisors for all their guidance, support and contributions during the research project.

REFERENCES

Bukola, O., Bolaji, A., and Ayola, P. O. (2008): Performance Evaluation of a mixed mode solar dryer; Department of Mechanical Engineering. University of Agriculture Abeokuta, Ogun state, Nigeria.

Danshehu, B. G. (2012): Development and Performance Evaluation of a PV Powered Indirect Solar Dryer, Sokoto Energy Research Centre, and Department of Physics, Usmanu Danfodiyo University, Sokoto

Danshehu, B.G. (1997) Design and Development of an 85 litres Solar Assisted Hot Water System, M. Eng (Energy studies). Thesis Bayero University, Kano – Nigeria

Garba, M. M., Omer, S. A., Elzaidabi, A. A., and Riffat, S. B. (2008). An Improved Solar Cooker for Application in Developing Countries. Technical Performance and cost Considerations. *Proceedings of the International Sustainable Energy Technologies Conference, South-Korea* 1, 730 – 737

Jayaraman, K. S., and Gupta, D. D. (2020). Drying of fruits and vegetables. *In Handbook of industrial drying* (pp. 643-690). CRC Press.

Schwarzer, K., Vieira, S., and Maria, E. (2008). Characterization and Design Methods of Solar Cookers. *Solar Energy* 82 157 – 163.

Shuaibu, M. I., Musa, M., Nawawi, Y. H., Uba, A., Mohammad, A., and Adamu, S. S. (2019). ‘’ Design, Construction and Performance Comparison of Indoor and Outdoor Configuration of a Solar Powered Evaporative Air Cooler’’ Conbatoir Institute of Information Technology (CiiT) *International Journal of Programmable Device Circuits and Systems*, 11(6), 1-2.