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Design, Fabrication and Thermal Performance Evaluation of a Parabolic Solar Cooker in Sokoto City, Nigeria

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ABSTRACT

This study investigated the design, fabrication and thermal performance of a parabolic solar cooker constructed using locally available materials for application in Sokoto city, Nigeria. The cooker incorporated a parabolic reflector and receiving vessel mounted on a supporting frame at a fixed southward tilt angle of 13°. The fabricated concentrator had an aperture diameter of 77 cm, an estimated focal length of 0.309 m and a geometric concentration ratio of 4.15. Thermal performance was assessed through a water-heating experiment involving 1.0 L of water as well as statistical correlation tests using Analysis of Variance (ANOVA). The water temperature increased from 29.3 °C to 81.4 °C over 150 minutes, corresponding to a calculated useful energy gain of approximately 2.18×10^5 J and average useful thermal power of 24.2 W. A thermal efficiency of approximately 22.7% was estimated using an assumed average solar irradiance of 229.17 W/m² because irradiance was not measured during the experiment. The correlation tests showed statistical significant evidence for a strong relationship amongst the dual-based thermal performance parameters considered at the considered confidence level. The findings demonstrate that the fabricated cooker was capable of heating water under the investigated outdoor conditions. However, the absence of measured solar irradiance, repeated experimental trials and uncertainty analysis limits the reliability of the estimated thermal efficiency. Further evaluation under measured solar conditions and standardised solar-cooker testing procedures is recommended to establish reproducible performance characteristics.

Keywords: Clean Energy, Solar Thermal System, Parabolic Cooker, Sustainability, Sokoto City

INTRODUCTION

Africa as a whole is blessed with huge renewable energy resource potentials although termed a continent of paradox due to the gap in utilization level as compared with the fossil fuels (Jumare et al., 2024; Jumare, 2019). In line with such, thermal aspects of the renewable energy is a key, of which the traditional cooking method utilizing biomass is considered inefficient, and causes excessive deforestation and uncontrolled smokes leading to respiratory diseases. These are threats to our environment especially in view of climate change struggles for sustainability of energy services. It is further mentioned that economic implication of such practices is strongly impacted negatively as a result of the rising cost of the solid fuels. However, it is obvious the gradual transition to the use of liquefied petroleum gas cooking via utilizing cylinders and gas burners occur, which people usually called the clean cooking approach focusing on air pollutants. However, this is a misnomer as greenhouse gases are evident to such system as a carbon positive approach, which has a global warming potential. Further transition to a real clean cooking approach has become a driver for the switch to solar cooking methods.

Solar energy, being the primary energy source and a clean energy with strong impacts on most if not all the other renewable energy sources has a significant role to play in the gradual energy transition with climate friendliness for different energy services (Muhammad et al., 2025). As far as the solar energy potential is concern, the global total solar irradiance reaching the top of the atmosphere has been estimated as 1361 W/m^2, being the extraterrestrial solar irradiance intensity, as contrary to the ground level (terrestrial) solar irradiance intensity applicable to the solar cookers and having a peak value of 1,000 W/m^2 (Laboratory for Atmospheric and Space Physics, n.d). Solar thermal concern being the focus of this project has got different technologies, of which narrowing down to solar cooking has been divided fundamentally into 3 types. There exist the box type solar cooker, the panel type solar cooker, and the parabolic type solar cooker (Otte, 2009). The box type seldom referred to as the solar oven, is in box shape with insulating materials and reflectors for the solar thermal energy harnessing and impacts. The panel cookers consist of a flat panel that reflects and direct solar irradiance to its central part for the heating purpose. The parabolic type solar cooker consists primarily of the solar concentrator, which is a parabolic dish, and a solar receiver which can be in any design. These in combine are called solar collecting system as they trap solar irradiance in view of usable heat generation at elevated temperature for the cooking purpose. The cooking process in such design has been reported to be fast at very high temperature just like fire, however, requires frequent adjustment in line with the tracking system employed (Solar Cookers International, 2004). Owing to the solar concentration arising with the parabolic type, it is considered more efficient based on the concentration ratio parameter involved in the system. This is even the reason why such systems in large sizing are considered for power generation due to the need for high temperature harnessing.

The mechanism is in such a way that the solar irradiance get transmitted to the parabolic dish, of which the reflected rays

converge at a focal point or a focus, which is where the solar receiver has to be placed based on its design and coating considerations. This ensures harnessing the maximum heat possible arising from the concentrations and temperature rise where the cooking occurs. It is mentioned further that the heat transfer and heat loss comes in all the three modes namely: radiation, conduction and convection during the whole cooking process in the system depending on different scenarios.

Numerous solar thermal studies relating to solar cooker have been conducted around the world. Sani et al. (2024) carried out the performance evaluation of a building integrated solar cooker, which combines both box and parabolic designs for improved efficiency in the Nigerian context. Statistical evaluations were incorporated for data tests. Mathematical modelling of a box type solar cooker while employing asymmetric compound parabolic concentrator was done in Algeria by Harmim et al. (2011). Different models were considered based on heat transfer principles of the system and thermal performance parameters were generated. Jibrin et al. (2023) developed an integrated solar cooking and drying system in the Nigerian context. The design was box type with a dryer mounted coupled with performance evaluation of the dual system as well as statistical analysis of the obtained thermal data. Design and construction of a solar box cooker system utilizing the climate data for Myanmar in view of testing and performance evaluation was conducted by Soe et al. (2019). Terres et al. (2014) carried out mathematical modeling in view of studying the box-type solar cooker with internal reflectors, utilizing the climate data of Mexico. This was a validation and a comparison approach using a numerical and programming package on the models analysis to an already established experimental data from a separate research work of the system. Lastly, Kumar et al. (2022) designed, construct and analyze the performance of a parabolic solar cooker, based on the climatic data of India.

This study aimed to design, fabricate and evaluate the thermal performance of a locally constructed parabolic solar cooker under outdoor conditions in Sokoto city, Nigeria.

The specific objectives are as follows:

i. To design the solar cooker using geometric and thermal principles with parametric evaluations
ii. To fabricate the solar cooker using affordable and accessible materials in line with the design parameters analyzed in the first objective.
iii. To evaluate the performance of the solar cooker via experimental water heating tests on different thermal performance parameters.
iv. To carry out statistical significance test on the thermal performance parameters

On a final note, the solution provided for the Sokoto city, being clean cooking approach at considerably low cost is emphasized as environmentally friendly due to zero greenhouse gases emission and zero pollutants associated with the system. Therefore, threats of environmental impact categories namely global warming potential and acidification potential doesn't exist at operational level, basing on direct emissions or pollution of the system. On the health and safety aspect linked to the system, owing to the fact that no pollutants or particulate matters occur, it therefore means that the challenge of any respiratory disease doesn't exist. Safety measures regarding the system operation however involves the use of protective and sterilized hand gloves to avoid food contaminations and direct contact of the heated receiving surface with the skin to avoid potential burn. Further safety measure is aligned with the hygiene of the receiving surface and the container to be used for the food sample to be cooked.

MATERIALS AND METHODS

Materials Selection

The fabrication materials were carefully selected while considering local availability, performance efficiency, costs implications, and durability. Based on such baselines, the materials considered with specifications to their targets in the solar thermal system have been presented in the table 1.

Table 1: Selected Materials and their Rationales

Component	Material	Rationale
Dish Body	Mild steel sheet	Strong, formable, and cost-effective
Receiver Container	Black-coated stainless steel pot	High thermal conductivity and absorptivity and safe for edible substances
Wrapping Sheets	Mylar film	For additional reflectivity and insulation to the dish body
Supporting Frame (Piping)	Mild Steel	Strong, durable and cost effective

The material bill of engineering for the parabolic solar cooker system has been presented in the table 2.

Table 2: Bill of Engineering for the Selected Materials

Item	Description	Quantity	Unit Cost (₦)	Total Cost (₦)
Mild Steel Sheet	1 mm thickness	1 sheet	30,000	30,000
Mylar Film	High reflectivity	1 roll	9,000	9,000
Stainless Steel Pot	22 cm diameter	1	8,000	8,000
Bolts and Nuts	M10	1 pieces	1,000	1,000
Welding Rod	3.2 mm	1 pack	15,000	15,000
Black Heat-Resistant Paint	400°C rated	1 litre	5,000	5,000
Miscellaneous	_	_	5000	5000
Adhesive	_	_	3,000	3,000
Labour	_	_	7000	7000
Grand Total			83,000	83,000

Basing on the table 2 for the bill of engineering based on the materials used, labor and the overall cost, it is important to specify that operation and maintenance cost is considered insignificant or far low. This is because only cleaning is required and maximum care during system transfer out and in doors. It is further stated that the life span and replacement

cost is excluded at the moment, as the study does not entail economic evaluation or cost benefit assessment.

Design Consideration, Fabrication and Testing Procedure

Regarding the design considerations in view of the fabrication stage, different data both measured ones and from literature as well as models have been utilized in view of generating both geometric and technical parameters necessary for impacts to the overall system performance. On the fabrication stage, the process began with the formation of the steel plate from the sheet on molding to take the shape of a parabola coupled with welding process and smoothening for an appropriate finishing in forming the dish body. It was linked by welding with a connecting steel pipe frame from its tip bottom to the focal point where the receiving pot was placed. The reflective surface of the dish body was wrapped with the aluminum foil for smooth generation of the reflected rays to the receiving pot. The receiving pot was stainless steel made, and coated in black at the back side for enhanced heat absorbance. The piping frame of the system was completed by adding with welding, supporting stands from the ground level based on appropriate and medium height for better handling of the system and testing. Roller supports were added from the base using bolts and nuts to enhance the mobility of the system at ease. The system mounting on the frame was at an angle of 13 degrees. This was in view of proper but fixed positioning of the system to the sunlight although, no tracking mechanism was incorporated in view of system readjustment as a limitation, considering the changing position of the sun with time and optical losses for the system. It must be mentioned that the concentrator diameter was taken at random but was made sure of being wider than the receiver in favor of the concentration ratio, which is a determinant for system thermal efficiency. On the testing procedure, 1.0 L of water was used in the fabricated system after sunrise, during the dry season of the year, around October, 2025, specifically from 12:00 PM to 2:30 PM with ambient and water temperature measurements at time intervals of 15 minutes using a calibrated thermocouple with optimal accuracy, coupled with other models utilization in predicting the other critical thermal performance parameters of the system. The different models with sources where necessary have been broken down as follows:

The focal length of the fabricated parabolic dish in view of proper positioning of the receiver was computed using the standard geometric relationship for a paraboloid as provided by WGBH Educational Foundation (2007):

$$F = \frac{D^2}{16d} \quad (1)$$

Where:

D = dish diameter = 0.77 m

d = dish depth = 0.12 m

The concentration ratio (CR) expresses how effectively the dish concentrates solar radiation onto the receiver. It is defined as obtained from Shaw (n.d) by:

$$CRg = \frac{A_{aperture}}{A_{receiver}} \quad (2)$$

Where: $A_{aperture}$ = Area of the Aperture based on its model.

The parabolic opening ($A_{aperture}$) $= \frac{\pi D^2}{4}$ (3)

$A_{receiver}$ = Area of the Receiving surface based on its shape, being frustum-like (Total Surface Area (TSA) of the receiving pot as obtained from Bhanzu (2026) is as follows:

$$TSA_{receiver} = \pi\left(\sqrt{(h^2 + (R-r)^2}\right)(R+r) + \pi R^2 + \pi r^2 \quad (4)$$

Where R = Outer Radius of the Frustum = 0.11m

r = Inner radius of the frustum = 0.075

h= Height of the frustum = 0.09m

Further to the Aperture, the whole solar collector i.e. the Parabolic Solar Collecting Dish Model Area used as obtained from Smart Conversion (2026) is as follows:

$$A_{Collector} = \frac{\pi D}{12d^2}\left(\left(\frac{D^2}{4} + 4d^2\right)^{\frac{3}{2}} - \frac{D^3}{8}\right) \quad (5)$$

The useful thermal energy gained by the water was computed using the standard heat-gain expression as follows:

$$Q = m \times cp \times (Tf - Ti) \quad (6)$$

Where: Q = Thermal energy gained on heating the water sample

m = Mass of the water sample considered

C_p = Specific heat capacity of the water sample

T_f = Final heating temperature at the given time interval

T_i = Initial temperature of the water sample prior to heating

The average power delivered to the water during a given time interval of the heating operation was evaluated using:

$$P = \frac{Q}{t}) \quad (7)$$

Where: P = Power corresponding to the heat delivered (W)

Q = Heat delivered / gained (J)

t = Time interval for the heat gained (Sec)

The thermal efficiency (ηth) of the parabolic system was computed using:

$$\eta_{th} = \frac{Q}{IAt} \times 100 \quad (8)$$

Where: I = Site solar irradiance = Solar Power Flux (W/m^2)

A= Aperture Area (m^2)

t = Time interval for the heat gain (sec)

Q = Heat gain at the time interval t (J)

Statistical Evaluations of Thermal Performance Parameters

To analyze the obtained design data of the parabolic solar cooker system, inferential statistics as a statistical significance test was conducted on some thermal performance parameters of the system. This was addressed using Anaysis of Variance (ANOVA) considering the following correlations:

i. Correlation between ambient temperature and water temperature
ii. Correlation between water temperature and heat gain
iii. Correlation between heat gain and the generated thermal power

In view of such correlations, the ANOVA models utilized are as follows:

$$SSB = \sum a_i(\bar{X}_i - \bar{\bar{X}})^2 \quad (9)$$

$$SSE = \Sigma\sum(X - \bar{X}_i)^2 \quad (10)$$

$$MSB = \frac{SSB}{b-1} \quad (11)$$

$$MSE = \frac{SSE}{N-b} \quad (12)$$

$$F = \frac{MSB}{MSE} \quad (13)$$

$$df_1 = v1 = b - 1 \quad (14)$$

$$df_2 = v2 = N - b \quad (15)$$

Where: SSB = Sum of Squares between Treatments; SSE = Error or Residual Sum of Squares; MSB = Mean Square between Treatments; MSE = Error or Residual Mean Square; X = Individual Observation; $\bar{\bar{X}}$ = Overall Sample Mean; a_i = number of observed data in a given group; $\bar{X}_i$ = Sample Mean for a given group; N = Total observed data for all groups; b = Number of Treatments or Groups. $df_1 = v1$ = Degrees of Freedom between Treatments; $df_2 = v2$ = Residual Degrees of Freedom; F = Statistical Significance Parameter for Comparison.

It is however noted that the confidence interval (α) considered was 0.05 in view of determining the $F_{Critical}$ value using the df_1 and df_2

Conclusion is centered at two key ultimate parameters namely the determined F value and the Critical F value based on the below points:

i. If F value is greater than $F_{Critical}$, Null Hypothesis is rejected, meaning statistical significant evidence exists to show strong relationship between or among parametric groups at the confidence level (α) considered.
ii. If F value is less than $F_{Critical}$, Null Hypothesis is accepted, ultimately depicting the absence of statistical significant evidence to show clear relationship between or among parametric groups at the considered confidence level (α).

RESULTS AND DISCUSSION

Geometric Parameters Results

The geometric parameters as evaluated using the provided models and the measured geometric parameters have been presented below:

Focal Length for the positioning of the collector and the receiver (f) = 0.309 m (Equation 1)

Area of the Concentrator Aperture ($A_{aperture}$) = 0.4657 m^2 (Equation 3)

Area of the Parabolic Dish Solar Collector ($A_{Collector}$) = 0.5206 m^2 (Equation 5)

Area of the Receiving Pot ($A_{receiver}$) = 0.112 m^2 (Equation 4)

Geometric Concentration Ratio (CR_g) = 4.15 (Equation 2)

To briefly discuss the geometric parameters, the determined focal length gives the exact point from the tip center of the parabolic dish, also known as the focus or focal point, where the reflected rays from the solar irradiance incident on the parabolic dish converge for the thermal impact. The determined areas are clearly observed to be in line with expectations based on their sizes, although, the geometric concentration ratio, being 4.15 is obviously low. This makes it fall under the lower concentration ratio classification for a solar concentrating system, being less than 10 (Fedkin, n.d). However, the geometric concentration ratio as an indicator or a strong determinant for a thermal efficiency of the system can be improved by making geometric adjustments by increasing the size of the solar collector and lowering further the size of the solar receiver.

Thermal Performance Parameters Results

For the conducted water heating tests, the results of the different thermal parameters for the varied time interval have been presented in table 3. It was accompanied by graphical description of the thermal performance parameters in figure 1 and figure 2.

Table 3: Results for the Time Variations with the Accompanied Thermal Performance Parameters

Time	Ambient Temperature (°C)	Water Temperature (°C)	Water Heat Gain (J)	Thermal Power Delivered (W)	Time Interval (sec)
12:00 PM	34.7	29.3	0	-	0
12:15 PM	34.5	44.0	61534.2	68.37	900
12:30 PM	36.3	50.0	86650.2	48.14	1,800
12:45 PM	33.6	54.0	103394.2	38.29	2,700
1:00 PM	34.2	57.0	115952.2	32.21	3,600
1:15 PM	35.6	62.7	139812.4	31.07	4,500
1:30 PM	36.4	65.3	150696.0	27.91	5,400
1:45 PM	36.9	69.2	167021.4	26.51	6,300
2:00 PM	36.0	71.4	176230.6	24.48	7,200
2:15 PM	36.0	76.0	195486.2	24.13	8,100
2:30 PM	36.5	81.4	218090.6	24.23	9,000

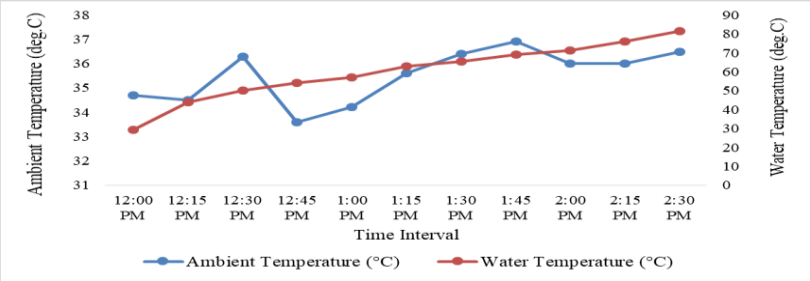


Figure 1: Ambient temperature and water temperature against the time interval

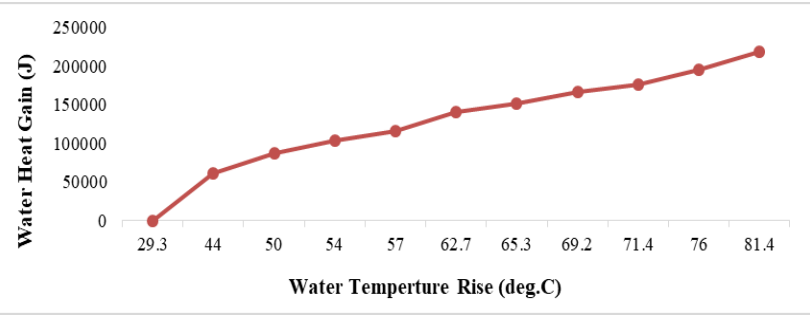


Figure 2: Water heat gain against the water temperature rise

Note:

i. Reference Time: 12:00pm equivalent to 0 seconds interval
ii. Reference Water Temperature Prior to Heat Gain: 29°C
iii. Mass / Quantity of Water Used: 1.0 kg / 1.0 L
iv. Specific Heat Capacity of Water (C_p) = 4.18 kJ/kg.K (Water Science School, 2026)

From the observed water temperature over the time intervals, temperature of up to 81.4°C has been obtained, although, could even be greater by time increment to a certain limit on the experimental trials. Improving the design from the existing state by adjustment to geometric parameters, ensuring adequate tracking mechanism, improved finishing for better smoothness and better foil wrapping for lowered rays scattering could also impact the temperature positively, ultimately impacting the other thermal performance parameters.

It is noted that due to the absence of a pyranometer, solar irradiance values were estimated using typical dry-season irradiance data for northern Nigeria, where midday values commonly range between 145.83 W/m² and 312.50 W/m² (Idris et al., 2024).

Maximum System Energy and Power Generated

i. Hence, with 1.0 L of water heated from 29.3°C to 81.4°C, the temperature rise was 52.1°C, giving a useful thermal energy gain of 2.18×10^5 J (Equation 6).
ii. The average power delivered to the water during the 2.5 hr. heating period was evaluated as 24.2 W (Equation 7).

Thermal Efficiency

i. The instantaneous solar irradiance during the experiment was not measured directly. Therefore, an assumed irradiance of 229.17 W/m² was used, as obtained by taking the average of the presented extreme power flux values from literature. This assumption is due to the absence of pyranometer data.
ii. The thermal efficiency (ηth) was computed from the already presented model (Equation 8), based on the overall heat generated value of 2.18×10^5 J, the assumed solar irradiance value on average of 229.17 W/m^2, the area of the aperture being 0.4657 m^2, and the overall time for the maximum temperature generation being 9000 seconds. The evaluated thermal efficiency of the parabolic dish cooker was approximately 22.7%.

Lastly, to compare the geometric and thermal performance parameters with one of the previous studies for instance, Aririguzo (2023), in a study at eastern Nigeria considered a dish diameter of 1.7 m, leading to a focal length of 0.747 m, and obviously a higher aperture area, ultimately leading to a thermal efficiency of 33% above the estimated efficiency in this study.

Figure 3 showed the fabricated parabolic solar cooking system set-up for the water heating tests, accompanied by figure 4, showing the 3D engineering drawing view.



Figure 3: The Fabricated Parabolic Solar Cooker Outdoors for the Water Heating Tests



Figure 4: Isometric (3D View) of the Parabolic Solar Cooker Design

Statistical Evaluation Results

The results for the extensive statistical evaluations for data treatment based on inferential statistics have been presented in table 4, 5, and 6.

Table 4: ANOVA Results Summary 1 (Ambient Temperature vs. Water Temperature)

H_0 = Null Hypothesis: $\mu_1 = \mu_2$ (Equal Means) H_1 = Alternative Hypothesis = Unequal Means				
Variation	**Sum of Square (SS)**	**Degrees of Freedom (df)**	**Mean Square (MS)**	**F**
Between Treatment (B)	3134.49	$df_1 = 1$	3134.49	$F_{critical} = 4.35$
Error / Residual (E)	2136.08	$df_2 = 20$	106.80	$F_{evaluated} = 29.35$
$\therefore F_{evaluated} > F_{critical}$				

Table 5: ANOVA Results Summary 2 (Water Temperature vs. Corresponding Heat Gain)

H_0 = Null Hypothesis: $\mu_1 = \mu_2$ (Equal Means) H_1 = Alternative Hypothesis = Unequal Means				
Variation	**Sum of Square (SS)**	**Degrees of Freedom (df)**	**Mean Square (MS)**	**F**
Between Treatment (B)	$9.09*10^{10}$	$df_1 = 1$	$9.09*10^{10}$	$F_{critical} = 4.35$
Error / Residual (E)	$4.04*10^{10}$	$df_2 = 20$	$2.02*10^{9}$	$F_{evaluated} = 44.97$
$\therefore F_{evaluated} > F_{critical}$				

Table 6: ANOVA Results Summary 3 (Heat Gain vs. Corresponding Thermal Power)

H_0 = Null Hypothesis: $\mu_1 = \mu_2$ (Equal Means) H_1 = Alternative Hypothesis = Unequal Means				
Variation	**Sum of Square (SS)**	**Degrees of Freedom (df)**	**Mean Square (MS)**	**F**
Between Treatment (B)	$2.0005*10^{11}$	$df_1 = 1$	$2.0005*10^{11}$	$F_{critical} = 4.41$
Error/Residual (E)	$2.2233*10^{10}$	$df_2 = 18$	$1.2352*10^{9}$	$F_{evaluated} = 161.96$
$\therefore F_{evaluated} > F_{critical}$				

From table 4, it is obvious the evaluated F value being 29.35 based on the different ANOVA models and the assumption considered was greater than the critical F value which was obtained from the ANOVA table as 4.35. This is clear to draw a conclusion that at the considered confidence interval, which was 0.05, statistical significant evidence exist in showing a strong relationship between the ambient temperature and the water temperature. Similar argument exist in table 5 and table 6 for the other dual-group thermal parameters treatments, such that their evaluated F values being 44.97 and 161.96 were all greater than their corresponding critical F values of 4.35 and 4.41 respectively, which goes back to same conclusion like that drawn of table 4 data.

Conclusion

A parabolic solar cooker was designed, fabricated and evaluated under outdoor conditions in Sokoto city, Nigeria. The fabricated system had an aperture diameter of 0.77 m, an estimated focal length of 0.309 m and a low geometric concentration ratio of 4.15. During the water-heating experiment, 1.0 L of water was heated from 29.3 °C to 81.4 °C within 150 minutes, corresponding to a calculated useful energy gain of approximately 2.18×10^5 J and average useful thermal power of 24.2 W. These findings demonstrate the ability of the fabricated cooker to provide useful solar heating under the investigated conditions. A thermal efficiency of approximately 22.7% was estimated using assumed solar irradiance; therefore, this value should be interpreted cautiously. The absence of direct irradiance measurements and repeated experimental trials limits the reliability of the performance assessment. Statistical significance tests on the thermal performance parameters based on the Analysis of Variance (ANOVA) showed existence of statistical significant evidence in ascertaining a strong relationship among the dual group-based compared thermal performance parameters as a result of all the evaluated F values being greater than the corresponding critical F values. Further investigations incorporating measured solar radiation, repeated standardised tests, uncertainty analysis and improved solar tracking with automations are recommended to establish exact and improved thermal efficiency and practical suitability for domestic cooking applications. Also, the use of phase change materials (PCM) for the thermal energy storage may serve for utilizing stored thermal energy during the night as a further recommendation.

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