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Research Article

Experimental evaluation of a dual-use solar cooker for indoor and outdoor applications

Faiq SAID[1,*], Qazi Muhammad YASEEN[2], Sahibzada Naveed Inayat ULLAH[2], Muneeb AHMAD[2], Farhan AHMED[2], Zakir ULLAH[2], Mir Muhammad Mehran KHAN[2], Ibrar HUSSAIN[2]

[1]Department of Mechanical Engineering, University of Engineering and Technology, Mardan 23200, Pakistan
[2]Department of Mechanical Engineering, University of Engineering and Technology, Peshawar 25120, Pakistan

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ABSTRACT

The design, construction, and experimental assessment of a portable parabolic solar cooker intended for both indoor and outdoor use in Peshawar, Pakistan, are presented in this study. The cooker boiled one liter of water in 12 minutes (from 34 to 94 degrees Celsius), boiled an egg in 12 minutes, and fried an egg in just one minute. It also reached a maximum temperature of 200.6 degrees Celsius. An optical efficiency of 48.69% ± 2.5% and a thermal efficiency of 46.72% ± 2.8% were obtained from performance testing under average solar irradiance of 937.75 W/m² (787.49 W/m² at 60° tilt). In sunny conditions, it was shown to operate continuously for up to eight hours. This cooker exhibit better thermal concentration, portability (8.5 kg), and user-friendliness than previous parabolic designs (usually < 140 °C peak temperature and longer boiling times). These findings demonstrate its potential as an affordable, sustainable, and clean cooking option for both urban and rural populations.

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INTRODUCTION

A solar cooker is a type of cooking appliance that uses solar radiation to cook food [1]. In underdeveloped nations, cooking uses a significant amount of energy in rural areas [2]. With the UN establishing targets for 2030 and offering guidelines on the use of sustainable energy for cooking, solar cookers are crucial to achieving the Sustainable Development Goals (SDGs) [3]. Solar cookers are a cost-effective and environmentally friendly method of using solar energy for cooking in sunny climates all over the world [4]. Both developed and underdeveloped nations, as well as refugee camps, can utilize solar cookers. Its main purpose is to focus sun energy and use various reflective materials to transform it into heat. A few other crucial factors were taken into account, such as the need for a shining, smooth reflector surface and control (loading, tracking, temperature sensing, wind, and

*__Corresponding author.__
*E-mail address: engr.faiq.said@uetmardan.edu.pk

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ambient temperature) [5]. Global demand is predicted to exceed the annual supply of non-renewable energy sources (like petrol, and coal) in the next 20 years. For food cooking, solar cookers (SCs) offer a renewable supply. However, the biggest disadvantage of SCs is that they are ineffective when there is no sunlight [6]. Researchers from all around the world are now focused on renewable energy sources due to the depletion of conventional energy sources such as petrol, diesel, coal, etc., and their negative environmental effects. Solar energy is widely available, abundant, and efficient for use in a variety of home and commercial applications. Cooking, being one of the largest energy consumers is a necessary part of human existence. Cooking using wood or cow dung as the main source of thermal energy causes pollution and unhygienic conditions worldwide [7].

Despite extensive work on box-, panel-, and parabolic-type cookers, most parabolic solar cookers reported in the literature achieved maximum temperatures around 140 °C, required 30-60 min for boiling, or lacked portability and long-term durability. Furthermore, experimental indoor validation has been limited, as most studies focused only on outdoor trials. To address these gaps, the present study introduces a parabolic solar cooker that is lightweight, portable, fabricated with durable polished stainless steel, and experimentally validated in both indoor and outdoor environments under real solar conditions.

Solar energy offers a clean, abundant, and sustainable solution for cooking, reducing fuel scarcity, deforestation, and pollution. Solar cookers improve health, lower costs, and cut greenhouse gas emissions, making them especially valuable in developing regions. When combined with efficient stoves, they meet growing cooking energy needs while minimizing environmental and economic impacts [8-13].

In Pakistan, the total energy mix comprises 180 MW of renewable energy, and the estimated potential for solar energy is more than 100,000 MW. According to a research conducted by USAID and the National Renewable Energy Laboratory (NREL) in the United States, Pakistan has 2.9 million MW of solar energy potential. Figure 1. shows direct normal sun energy while Figure 2. shows the SUNY solar model for Pakistan. Conventional cooking in Pakistan uses expensive and harmful fuels, and solar potential is still underutilised, thus increasing the importance of this research. There is a need for a useful, effective, and user-friendly design that has been proven in practical applications because existing cookers frequently lack mobility and practical validation. [14].

There are many different designs for solar cookers; these designs frequently mimic the geometry and type of heat exchanger setups that are crucial. Solar box cookers

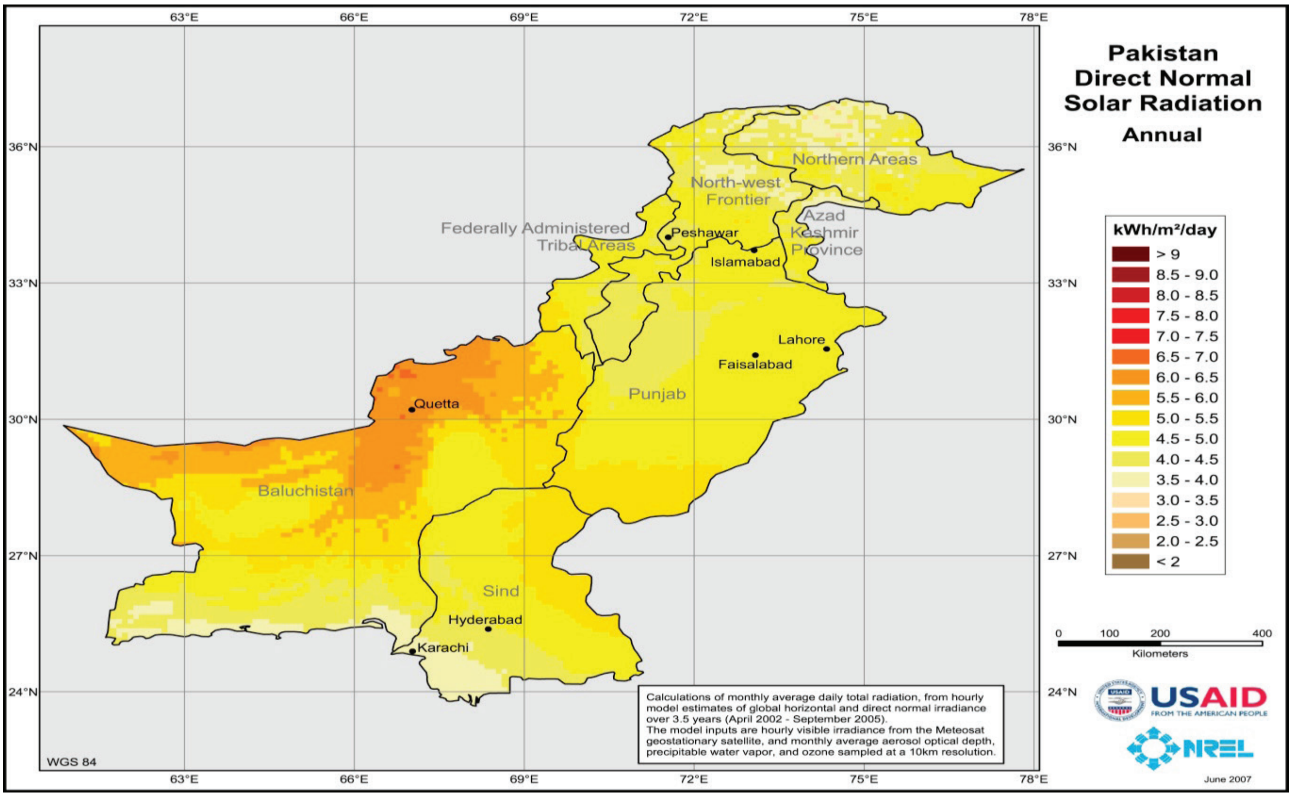

Figure 1. Direct Normal Sun Energy in Pakistan showing high annual insolation [14]

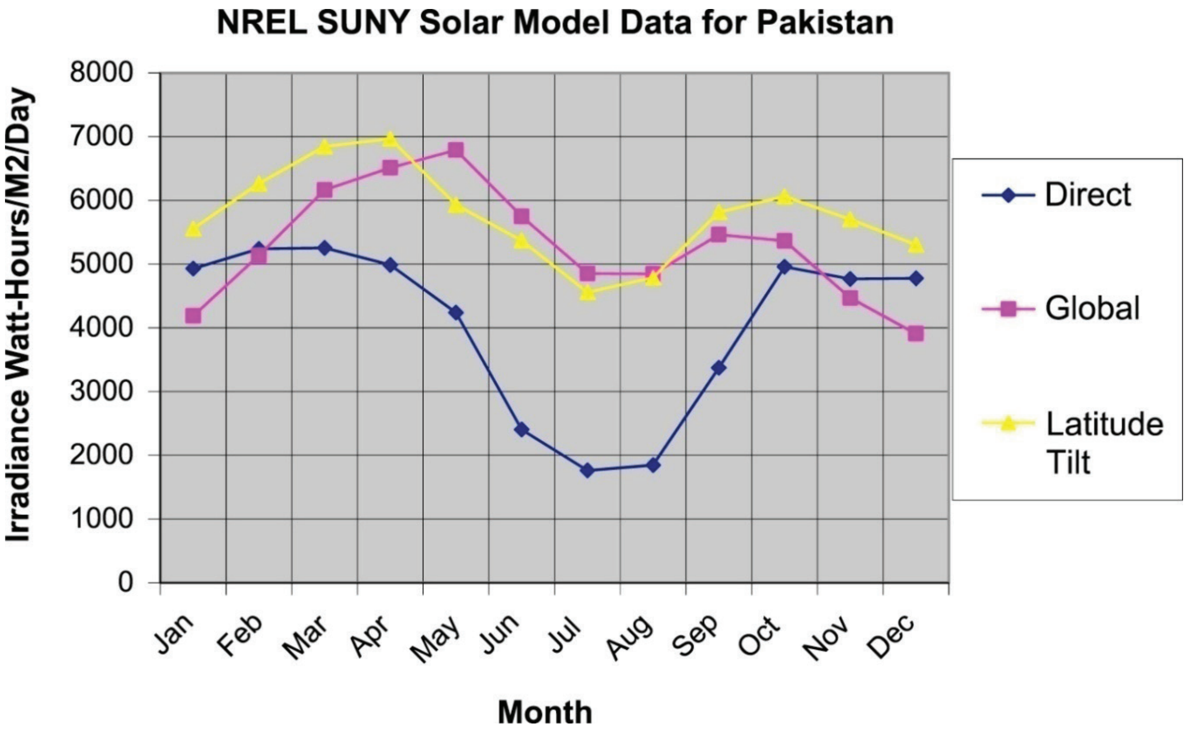

Figure 2. Data from the NREL Sunny Solar Model for Pakistan [14]

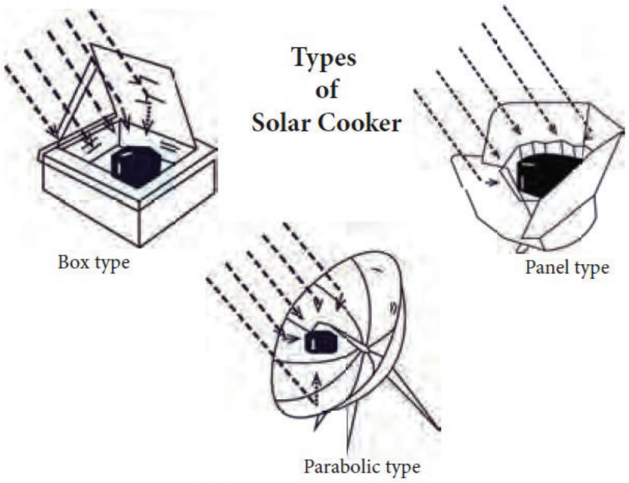

Figure 3. Classification of Solar Cooker(Box, Panel and Parabolic Type) [15]

often use direct box-type heat exchangers, whereas storage systems typically use shell and tube designs shown in Figure 3 [15].

LITERATURE REVIEW

According to Arunachala et al., cooking has a major impact on greenhouse gas emissions and world energy consumption, hence solar cooking is a practical solution. Their review discusses several solar cooker designs, such as box, panel, funnel, and parabolic models. It indicates that panel cookers are cheaper and reach 60-70% efficiency compared to box cookers. They highlight the need to come up with designs and materials that can make low-cost solar cookers efficient and long lasting, which has been highly overlooked in the past studies. The authors advocate the use of photovoltaic panels in the capture of solar energy, and effective indoor solar cooking systems even though the latter are very expensive. The final objectives of the review are to establish international testing criteria of solar cookers and stimulate access to the improvement of solar cooking commercials [16]. Vishwakarma and Sinha present a review of box-type solar cookers (BSC) equipped with thermal storage units (TES), in which case they are promising as alternatives to biofuels such as wood and animal dung that are still viewed as clean and low-cost cooking fuels. BSCs are small in size and cheap, but their cooking can only be limited in respect to off-peak hours. To improve the performance, the addition of phase change materials (PCM) like paraffin and stearic acid gives a chance to cook twice or even three times a day and reach temperatures above 100°C, with some systems reaching 164.12 °C to deep fry. To improve BSCs, it is recommended to improve thermal insulation, add artificial intelligence, and popularize them as an auxiliary gadget in the country to make them more popular [17].

Saxena et al. have conducted an experimental study of modified solar box cooker (SBC) to be operated continuously with high efficiency in cooking. To realize thermal energy storage (TES) with the use of cylindrical copper tubes, the study used three materials including paraffin wax, grainy carbon powder, and a mixture of the two. The redesigned SBC had a thermal efficiency of 53.81%, cooking power of 68.81 W and a heat transfer coefficient of 56.78 W/m²°C, which was higher than the conventional designs. This is both economical and geographically flexible because the cooker is estimated to cost about $39.11. The findings show that such a special construction enhances the efficiency of solar cooking and offers a lightweight and economical piece of equipment that would suit a family of four to five people throughout the year [18].

Aliyu, S. J., et al. evaluate the capabilities of a parabolic solar multi-cooker, which is intended to cook using clean, renewable solar energy. It surpassed its design goals and successfully reached a temperature of 140°C, efficiently cooking food at 100°C. The cooker consumes less fossil fuels, is less expensive, and has a smaller environmental impact because it is simple to use and constructed using local materials. In order to direct solar energy toward the pot, it effectively monitors the sun. However, you might have to decide between sun concentration and angle tolerance, depending on the pot›s size. Since the multi-cooker uses renewable energy and is more environmentally friendly than conventional stoves, it is ultimately a suitable option for locations with erratic electricity [19]. Patil, R., et al. Using energy and exergy ideas, this research evaluates the thermodynamic performance of three parabolic solar cookers with the same aperture areas but varied geometries. It examines important thermal characteristics such as figure of merit, cooking power, efficiency, and change in water temperature. The manufactured and segmented rectangular dish cookers produced energy outputs ranging from 234 to 1139 kJ, while the traditional circular dish cooker produced energy outputs between 184 and 1072 kJ. The averages of energy and exergy efficiency were found to be 40%–48% and 2%–3%, in that order. According to the study's findings, the segmented rectangle dish cooker performed better overall and had higher thermal efficiency than the traditional circular dish cooker [20]. Milikias, E., et al. presented that the design, development, and testing of an enhanced box-type solar cooker with thermal energy storage is the main goal of this project. Heat storage capacity and sunlight concentration are two important improvements. Compared to a normal cooker with the same solar intercept area, the enhanced cooker has an inner surface area that is 20% smaller. Based on performance tests carried out in compliance, every variant of the upgraded cooker received an 'A' rating, with the first figure of merit (F1) values higher than 0.12. Concrete and black stone, two thermal storage materials, have a noteworthy capacity to retain heat [21].

Apaolaza-Pagoaga, X., et al. investigated solar funnel cookers that aim to be broadly available and reasonably priced. It tests the FC1 and FC2 funnel cooker designs to see if they can boil water above their boiling point. FC1 lacks a glass enclosure, but FC2 has one. The Cooker Opto-thermal Ratio (COR) and total cooking efficiency are used to compare the performance of the two cookers using glycerin as the test load. The results indicate that FC2 is excellent for high-temperature cooking because it can attain temperatures between 140 and 150°C. Compared to FC1, which has a COR of 0.110 and an efficiency of 10.2%, FC2 has a higher COR (0.157) and a greater overall cooking efficiency (11.8%) [22]. Hebbar, G., et al. research goal includescreating a zero-emission solar cooker that, in comparison to traditional models, requires less maintenance and cooks food faster. A heat transfer fluid (HTF) fills the space between the two hollow stainless-steel cylinders that make up the cooking pot. To facilitate cooking during the hours when the sun doesn't shine, phase change material (PCM)-filled copper tubes are positioned around the pot. Hose pipes are used to connect the HTF to evacuated tubes. A thermo siphon cycle transfers heat from the evacuated tubes to the HTF, heating the cooking pot and PCM in the process, and guaranteeing effective energy utilization and heat retention [23]. Gupta, P. K., et al. conducted a study on a low-cost solar cooker that uses reflecting panels and is composed of affordable materials. This panel cooker's two designs were put to the test and contrasted with a traditional solar cooker in the form of a box. After taking temperature readings in both cookers at different times, it was discovered that the panel-type cooker produced cooking pot temperatures that were lower than those of the box-type cooker. Nevertheless, with a few adjustments, the panel cooker might prove to be a practical and affordable substitute for conventional box-style solar cookers [24].

Using aluminum fins, Vengadesan et al. tested the thermal performance of a box-style solar cooker. Four fin-equipped and finless cylindrical aluminum vessels were put to the test. With a heat transfer coefficient of 58.54 W/m²°C, the 45 mm finned vessel had the highest thermal efficiency, at 56.03% [25]. Ebersviller et al. looked at solar cookers for homes and measured their cooking power at 50°C. They discovered that parabolic cookers had a standard cooking power of 198 W, box-type cookers had 65 W, and panel-type cookers had 25 W. The study showed that water heating times, thermal efficiency, and cooking power are important performance metrics. It also suggested that wind speed changes and water evaporation problems should be looked into [26].

Tibebu and Hailu looked into a solar cooker that was made from old satellite dishes, tires, steel, and aluminum foil. The cooker had a 1.8m aperture and a concentration ratio of 123.46. The cooker was tested in terms of cooking time and energy costs versus conventional fuels including firewood, charcoal, kerosene, and electricity. It also can follow the movement of the sun. The performance metrics showed that the system had an efficiency of 10.75% and a power output of around 0.3 kW/hr, with an output energy of 0.182 kW/m^2, an input energy of approximately 1.691 kW/m^2, and an average solar radiation of 0.665 kW/m^2. Better cooking results were shown by the parabolic solar cooker, which also uses no energy [27]. A study on the development, construction, and testing of a parabolic solar cooker intended for usage in rural homes and refugee camps was carried out by Ahmed, S. M., et al. Stainless steel, aluminum foil, and Mylar tape were among the reflecting materials used in the study to gauge how well the solar cookers worked. Regarding the use of Mylar tape, the third tested design demonstrated the highest temperatures and the quickest cooking rate. The study indicates that additional enhancements in insulation and materials could augment the efficacy of these cookers, rendering them scalable, cost-effective, and especially advantageous in emergency contexts [5]. Using parabolic dish solar concentrators, Mawire et al. tested two solar cooking storage pots. They employed two thermal energy storage materials sunflower oil and erythritol and varied the cooking loads of water and oil. Water used more heat than sunflower oil, but sunflower oil was marginally more efficient in storage. The dependability of sunflower oil was demonstrated by the significant water evaporation that took place during solar frying. The findings provide fresh information about how well different TES materials work in solar cooking applications [28]. Patel's study highlighted the benefits of using solar energy as an alternative to fossil fuels by comparing the thermal performance of box-style and hexagonal solar cookers. The study emphasizes the significance of solar cookers in fuel consumption trends by pointing out that cooking uses more than 75% of energy in rural developing nations. Additionally, the study shows that energy absorption is influenced by the sun's position, indicating that solar cookers may lessen reliance on conventional fuels [29]. In order to dry coriander seeds, Kumar et al. designed and constructed a photovoltaic thermal collector with solar dryer (PVTCSD). They evaluated features like moisture removal, outlet air temperature, and solar radiation intensity while testing forced, open, and natural sun drying modes. The superior efficiency of PVTCSD for real-world agricultural applications was demonstrated by the results, which showed that forced convection solar drying performed better than natural and open sun modes [30].

E. Raghavendrakumar et al. analyzed SABER data from 2002-2022, finding significant atmospheric oscillations influencing ozone loss. Temperature changes reached 260 K in the middle atmosphere between 15 and 40 km altitude. They observed small but significant tropospheric ozone variation and attributed harmful gases from industrial and automotive emissions to negatively impact the atmosphere [31]. In Nasiriyah, Iraq, Koban et al. evaluated the cooking power, heat gain, collector efficiency, and optical efficiency of three parabolic solar cookers. The findings revealed cooking power of up to 740 W and efficiencies between 53-60%. Wind speed, solar tracking accuracy, reflector quality, and dish diameter all affected performance. Cooking performance and cooker efficiency were enhanced by wider apertures and precise alignment [32].

Alshehri et al. used a lab-scale setup to compare the solar-thermal performance of a multilayer selective metafilm absorber to that of a black absorber at different sun concentrations. Heat transfer analysis and steady-state testing revealed that the metafilm on stainless steel foil had outstanding spectral selectivity and thermal stability, achieving 57% efficiency at 371°C under 10 suns, with potential for up to 83% efficiency in practical solar thermal systems. The study demonstrated the ability of innovative absorber materials to greatly improve high-temperature solar energy conversion for concentrating solar power applications [33]. Vadiya et al. developed a novel inclined sidewall box-type solar cooker. Compared to a traditional cooker, the optimised design achieved a greater maximum plate temperature (76 °C vs. 65 °C), pot temperature (86 °C vs. 60 °C), and a cooking temperature of 90 °C for 2 hours, whereas the conventional cooker only maintained 60 °C for the same duration. The figures of merit were also greatly enhanced, with F1 values of 0.15 vs. 0.11 and F2 values of 0.59 vs. 0.30, indicating improved thermal response and cooking capabilities. Cooking trials revealed that food was thoroughly cooked in the newly designed cooker but overcooked in the conventional type, demonstrating the practical utility of the optimised sidewall geometry [34].

The literature shown in table 1, on solar cookers reveals various designs and methods, each with varying efficiencies and performance characteristics. Panel cookers achieve 60-70% efficiency but require design improvements, while box-type cookers can exceed 100°C. Parabolic cookers show promise but face challenges in portability and practical application. This study presents a parabolic solar cooker designed for Peshawar, Pakistan, achieving 46.75% usage efficiency and running for up to eight hours per day. This project aims to provide a sustainable substitute for fossil fuels and tackle energy scarcity in the area. The cooker boiled one liter of water in twelve minutes, reached a peak temperature of 200.6°C, and showed 46.72% thermal efficiency. There is a gap in developing solar cookers that combine high efficiency, faster cooking, and practical usability for real-world applications. Also, these studies standardized testing revealed that parabolic cookers had cooking outputs of about 198 W, but box-type and panel-type cookers only had 65 W and 25 W, respectively. These comparisons show how the current design of parabolic solar cooker goes beyond the constraints of previous designs by combining a high working temperature, efficiency, and quick cooking with portability and dual indoor-outdoor application.

Table 1. Comparative Review of Solar Cooker Designs, Performance, and Key Findings

Author	Methods	Performance	Key Findings	Limitations	References
Arunachala et al.	Review of solar cooker designs	60-70% efficiency (panel)	Panel cookers are more affordable; require design/material advancements	Limited designs reviewed; lack of experimental data	[15]
Vishwakarma and Sinha	Review of box-type solar cookers	Achieves >100°C	PCM integration improves performance; recommend enhanced insulation	Limited off-peak cooking; scalability issues	[16]
Saxena et al.	Experimental modified solar box cooker	68.81 W, 53.81% efficiency	Cost-effective and adaptable for household use	Small sample size; regional limitations	[17]
Aliyu et al.	Evaluation of parabolic multi-cooker	140°C cooking temperature	Environmentally friendly; utilizes local resources	Size constraints for portability	[18]
Patil et al.	Thermodynamic performance evaluation	Energy outputs: 184-1139 kJ	Segmented rectangle dish cooker outperforms traditional designs	Limited testing conditions; ideal only for specific locations	[19]
Milikias et al.	Design of enhanced box-type cooker	'A' rating	Effective heat storage materials retain heat	High material costs; limited market availability	[20]
Apaolaza-Pagoaga et al.	Investigation of funnel cookers	FC2: 140-150°C	FC2 outperforms FC1 in efficiency	Only focused on two designs; limited comparative analysis	[21]
Hebbar et al.	Zero-emission solar cooker development	Efficient heat transfer	PCM improves cooking efficiency	Lack of practical user trials; limited geographical scope	[22]
Gupta et al.	Low-cost panel cooker comparison	Lower temperature than box cooker	Practical alternative with adjustments	Limited performance under adverse weather	[23]
Vengadesan et al.	Thermal performance of box cooker	56.03% efficiency	Finned vessels outperform unfinned designs	Single design focus; limited performance data across designs	[24]
Ebersviller et al.	Evaluation of various solar cookers	Power: 198 W (parabolic)	Established performance metrics	Lack of long-term performance data	[25]
Tibebu and Hailu	Development of solar cooker	10.75% efficiency	Parabolic cooker outperforms conventional fuels	Limited thermal testing; potential user biases	[26]
Ahmed et al.	Testing of parabolic solar cookers	Highest temperatures noted	Mylar tape enhances performance	Results may vary with different materials	[5]
Mawire et al.	Testing of storage pots	Better heat consumption	Erythritol pot demonstrates superior performance in solar cooking	Limited to specific material; not widely available	[27]
Patel et al.	Comparison of box-style and hexagonal cookers	Highlights solar energy value	Importance of solar cookers in rural energy utilization	Focused on specific regions; limited design variations	[28]
Kumar et al.	Photovoltaic thermal collector with solar dryer	32°C to 59°C	Forced convection solar drying outperformed natural convection and open sun drying	No Scalability and only single crop tested	[30]

MATERIALS AND METHODS

Design Requirements

In addition to dependability, portability, and compactness, the parabolic solar cooker must be flexible enough to cook in a range of sun intensities. All components that come into touch with food must be made of food-grade materials and be able to operate both indoors and outdoors. The design limitations prioritize cost-effectiveness, safety, lightweight construction, and ease of use and setup. Because the external surface might get extremely hot when in use, extra care must be taken to prevent users from coming into touch with it. A key part of the solar cooker, the reflector is always in contact with the atmosphere and ought to be able to be adjusted according to changing circumstances. It must possess corrosion resistance, excellent reflectivity, and be readily available in the market.

We had the following objectives to fulfill the requirements using the given design that are given below.

- The objective of this study is to design a type of product offered with the aim of reducing air pollution, utilizing clean renewable energy, and increasing awareness about alternative energy solutions..
- The design aims to foster an understanding of environmental issues and the rational use of natural resources, highlighting the importance of conservation efforts.
- The goal is to design and fabricate an efficient and user-friendly solar cooker suitable for cooking food and heating purposes in both indoor and outdoor settings.
- We seek to diminish reliance on traditional stoves that consume wood and other energy resources, addressing the challenges associated with energy resource depletion.
- The objective is to have alternative energy solutions identified, particularly for individuals and communities with low income.

Conceptual Design

The satellite-dish-shaped parabolic solar cooker directs sunlight onto a central cooking pot using polished stainless steel. Because of its absorptivity, the polished stainless steel absorbs the remaining energy while reflecting 60% of the incoming solar radiation. Cooking materials are positioned in a receptor at a focal point that receives solar radiation from the concentrator. Any direction of movement is possible thanks to the movable holding mechanism. The pot›s bottom is heated by the heat from the parabolic concentrator, which transforms solar energy into cooking heat energy for uniform and efficient cooking.

Detailed Design

A parabolic concentrator, frame, receptor, and stand are among the various components that make up the parabolic solar cooker. The parabolic solar cooker›s operating parameters are 60 C to 400 C for the working temperature (T), 1.1 m for the focal length (f), and 8.5 kg for the weight (W).

Material selection

All the cooker components are crafted using a certain material. In the case of reflectors, a number of materials were taken into factor such as parabolic mirror, exterior aluminum foils and polished stainless steel. Stainless steel was eventually decided upon due to its durability, beauty and maintenance free qualities. Mirrors were also not preferred simply because the cooker was to be taken outside and easily broken. Polished stainless steel is a durable reflective surface that needs minimum maintenance particularly when polished frequently to maintain the finish. It also increases the service of life of the product and general life of the product. The parabolic concentrator has the mirror-like finishing with extra polishing. To promote and preserve its reflective-ness, a protective surface is taken into consideration, and regular polishing is made to remove all the scratches that may interfere with performance. The suitability of stainless steel to this purpose is due to its ability to resist rust, strength, and suitability out-of-door, as well as to its high reflectivity and low emissivity. To make it easy to use, the reflector is made by having a diameter of 6 feet with a quarter of the entire circumference open so that the user can easily view, put and take out the cooking dish at any time. The reflector is constructed out of 15 different sheets of stainless steel of the same thickness as depicted in Table 2. & 3. which are, respectively, cut together and riveted together.

The supporting frame was designed using mild steel because it is strong, can be used in various structures, and it is easily fabricated hence it was considered the best choice of material to be used in the structural parts of the solar cooker. The parabolic desired frame acts as a critical support element to the concentrator material which is fixed using rivet joints.

Table 3. Parameters of the Parabolic Concentrator

Parameter	Value	Unit
Aperture Diameter (Da)	1.6	m
Aperture Area (Aa)	1.5072	m^2
Reflectivity of Concentrator	0.58	-
Absorptivity of Concentrator	0.42	-

Table 2. Stainless Steel Sheet Composition

No of Sheets	Material	Sheets Diameter	Sheet Reflectivity
15	Stainless Steel	2 mm	60%

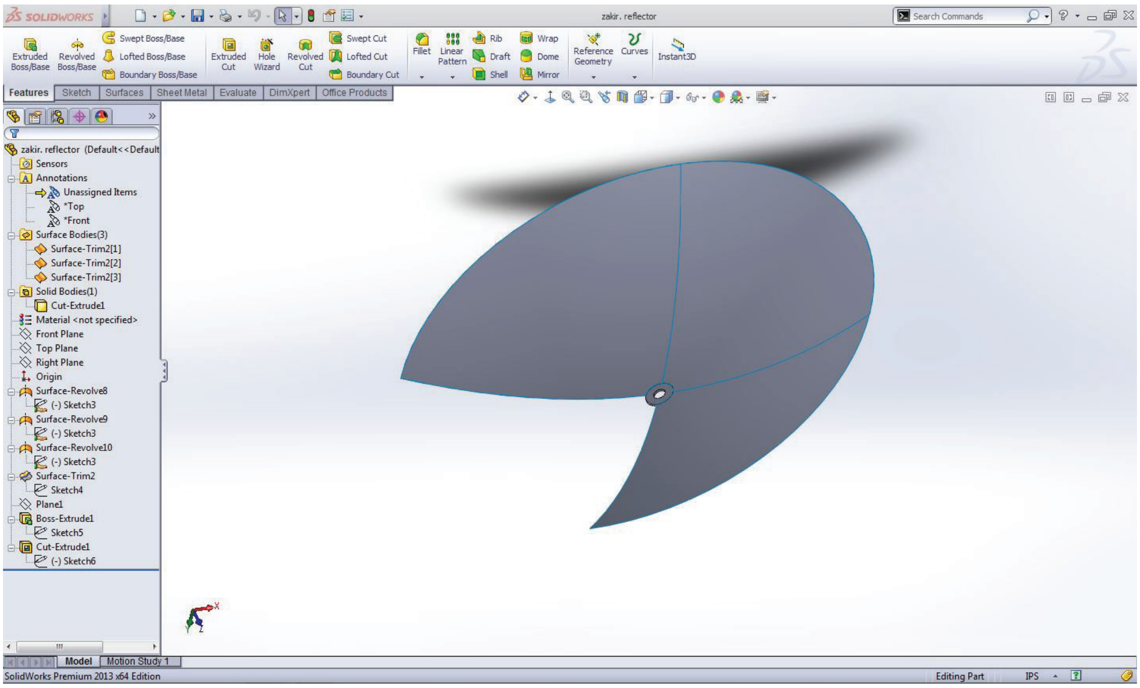

Figure 4. CAD Model of Parabolic Concentrator.

It is designed with eighteen arc-shaped supports and is made of three units at 90 degrees to the other which are joined with nuts and bolts to make it more stable.

The receptor itself is produced out of silver and it has been black painted thus increasing its capacity to absorb the solar radiation. The use of black painting also enhances its capacity to absorb the solar energy greatly. It has a cylindrical shape, positioned at the focus point of the parabolic

Table 4. Parameters of the Receptor

Parameter	Value	Unit
Radius of receptor	0..0762	m
Emissivity of receptor	0.5	-
Absorptivity of receptor	0.85	-
Area of receptor (Ar)	0.048	m^2

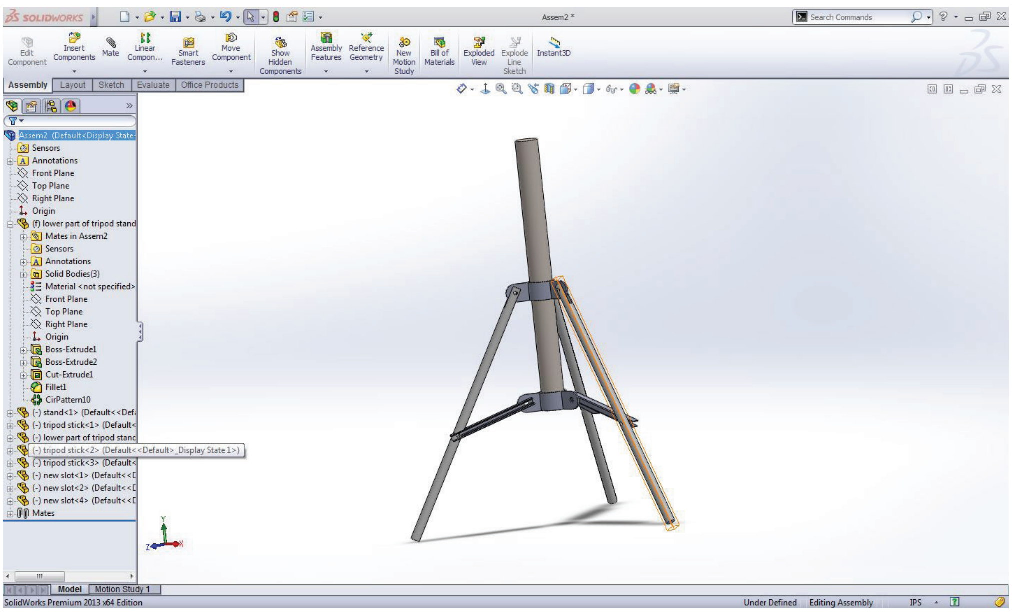

Figure 5. CAD Model of Stand.

concentrator that allows it to efficiently capture and utilize the concentrated solar energy.

The stand comprises of two parts;

The **upper part** consists of several pieces made from mild steel and is fully adjustable. These components are assembled using various sizes of nuts and bolts. For proper adjustment, sliders are utilized, which can be securely fixed using screws specific to each slider. Most of its parts are comprised of cylindrical mild steel pipes with specific dimensions.

The **lower part** of the stand is constructed from stainless steel and consists of several sub-components including a central support, an adjustable slider, three supporting legs and arms connecting the legs to the central support. To adjust and set up the solar cooker, the slider screw is loosened, allowing the slider to be pushed downward before being tightened again. As the leg supports expand, they provide increased stability to the stand, allowing it to support more load.

Theoretical analysis of solar dish concentrator

A mathematical study was done to determine the values that meet the design parameters, such as diameter, aperture angle, and concentration ratio, to calculate the parabola. For analysis, the Figure. 6 is displayed below.

Aperture Angle:

$$\phi = 2tan^{-1}\left(\frac{D_a}{4f}\right) \quad (1)$$

Φ = 40°= 0.6975 radian (Using Equation 1)

Where;

Φ = Aperture angle (radian)

Da = Diameter of the aperture (m)

f = Focal length of the parabolic dish (m)

Edge Radius:

$$\gamma_r = \frac{2f}{1 + \cos\phi} \quad (2)$$

γ_r = 1.245m (Using Equation 2)

Where;

γ_r = Edge radius or maximum distance between focal point and parabolic edge (m)

Φ = Aperture angle (radian)

f = Focal length of the parabolic dish (m)

To find the area of the receptor theoretically, it is necessary to consider the aperture angle (ϕ), radius of the receiver, radius of edge and angle supported by the sun from the earth. From the Earth, the sun is seen as a circular dish that subtends 0.53° Angle α.

From the Figure 7, "C" is produced by the hypotenuse between point B, the focus and Φ = 40°.

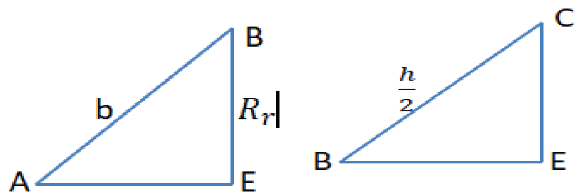

Figure 7. Receptor Area Determinations.

$$C = \frac{a}{\sin\phi} \quad (3)$$

C = 0.1186m (Using Equation 3)

Where;

C = Hypotenuse length from the focus to point B on the parabola (m)

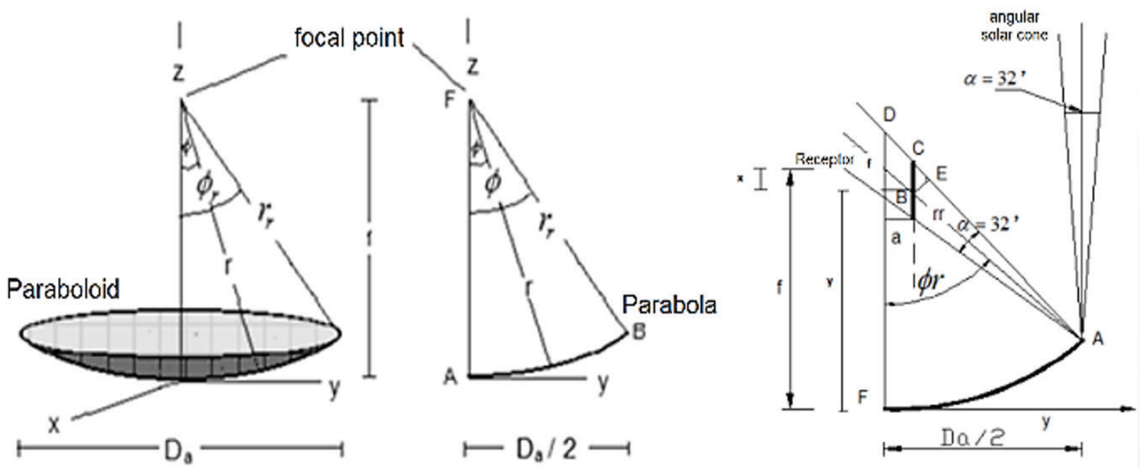

Figure 6. Theoretical Analysis of Solar Dish Concentrator [35].

a = Distance between point B and the receptor base (m)
Φ = Aperture angle (radian)

Now point B would be equal to;

$$b = \gamma_r - C \tag{4}$$

b = 1.1264m (Using Equation 4)

From Figure 7., the geometric ratio of points ABE & BCCA is;

$$R_r = \frac{b}{2}\sin\left(\frac{\alpha}{2}\right) \tag{5}$$

$R_r = 2.6 \times 10^{-3}$ m (Using Equation 5)

Using Figure 7. of the triangle BCE, we can find the half of contact surface of the receiver cylinder as,

$$\frac{h}{2} = \frac{R_r}{\cos(\theta - \phi)} \tag{6}$$

We obtain the angle formed between $h/2$ & R_r as; θ = 90.265° =1.575421 radian

h = 0.00836 m (Using Equation 6)

Where h is the contact surface of the receiver cylinder.
The area of a receiver is;

$$A_r = 2\pi a h \tag{7}$$

$A_r = 4 \times 10^{-3}$ m^2 (Using Equation 7)

The net aperture area can be calculated as;
Net aperture area (A_p)= Tota aperture area ($(A_p)_t$) – area of sector (A_s)

$$A_p = \frac{\pi D_a{}^2}{4} - \frac{\theta}{360} \times \pi r_a{}^2 \tag{8}$$

As $r_a = 0.8$, θ = 90° and D_a=1.6 m^2;

$A_p = 1.5071$ m^2 (Using Equation 8)

There is another parameter in the solar collector system which is a concentration ratio (C) defined as the ratio between the area of the aperture (A_p)and area of receiver (A_r). The higher the concentration ratio, the higher the temperature will be.

$$C = \frac{A_p}{A_r} \tag{9}$$

C = 376.8 (Using Equation 9)

There is angular dispersion in the receptor. The dispersion is due to inappropriate solar monitoring, poor quality in polishing of reflection material and complete accurate curate curvature of concentrator surface. The angular dispersion & considering that all the specular radiation reflected is on the angular cone with (0.53° + δ). So, the value of the contact surface of the receptor considering angular dispersion is;

$$h_1 = \frac{2R_r}{\cos\left(\theta - \phi + \frac{\delta}{2}\right)} \tag{10}$$

$h_1 = 8.40 \times 10^{-3}$ m (Using Equation 10)

Then, the actual maximum concentration ratio would be given as

$$C_{max} = \frac{\pi D_a{}^2}{4} \times \frac{1}{2\pi a h_1} \tag{11}$$

C_{max} = 499.3 (Using Equation 11)

By using equation (11), we can find Da1 as;

$$D_{a1} = \sqrt{8 a h_1 C_{max}} \tag{12}$$

D_{a1}=1.59 m (Using Equation 12)

The optimal focal distance (f_o) is;

$$f_o = \frac{D_{a1}}{4\tan\left(\frac{\phi}{2}\right)} \tag{13}$$

f_o = 1.09 m (Using Equation 13)

Table 5. Solar Dish Concentrator Calculations

Calculated Value	Description	Calculated Value	Description
ϕ = 40° = 0.6975 radian (Using Equation 1)	Aperture angle	$A_r = 4 \times 10^{-3}$ m^2 (Using Equation 7)	Receiver area
γ_r = 1.245 m (Using Equation 2)	Edge radius	A_p = 1.5071 m^2 (Using Equation 8)	Net aperture area
C = 0.1186 m (Using Equation 3)	Receptor distance	C = 376.8 (Using Equation 9)	Concentration ratio
b = 1.1264 m (Using Equation 4)	Point B distance	$h_1 = 8.40 \times 10^{-3}$ m (Using Equation 10)	Receptor height with angular dispersion
$R_r = 2.6 \times 10^{-3}$ m (Using Equation 5)	Geometric ratio	C_{max} = 499.3 (Using Equation 11)	Maximum concentration ratio
θ = 90.265° = 1.5754 radian, h = 0.00836 m (Using Equation 6)	Angle and receiver height		

FABRICATION

Quality Control

Material quality control

Mild steel and stainless steel were selected due to their mechanical properties and performance requirements. To make sure that the mild steel and stainless steel fulfilled the requirements for strength, corrosion resistance, and reflectivity, quality assurance measures were put in place during the material selection process. To ensure maximum solar radiation reflection, the stainless-steel sheets which were specially selected for their 60% reflectivity were examined for consistent thickness and surface polish.

Fabrication process control

Ensuring precise and reliable construction, several machining processes were involved in the fabrication of solar cooker including bending, drilling, welding, riveting and finishing.

- In order to give the frame a desired parabolic shape we used a gear bending machine as in Figure 8 below which is calibrated to bend with a specific angle which would give the best concentration of the energy. It is a machine that is meant to bend pipes and sheets to the needed shapes. The gears are spaced so as to allow different sizes of bars and pipes here the gap between the gears can be adjusted to suit the different sizes and they are then attached to motors which convert electrical power to mechanical power to power the bending process. With help of this method we managed to bend the rectangular metallic strip to form the frame of the solar cooker. (Fig. 9)
- The process of permanently joining two metal components is called welding. The structure of the solar cooker is divided into three major sections, each of which is composed of smaller components. The main frame sections are created by welding these subparts together, and they are then fused to create a single, integrated frame.
- A sheet metal cutting machine was used to precisely cut the reflective stainless-steel sheet into smaller pieces. To guarantee that every little sheet could be correctly riveted onto the frame rods, this precision was crucial. Each cut sheet's length matched the separation between two successive frame rods, ensuring a tight fit for the best alignment and stability.
- Drilling was used to build the solar cooker, and it was a crucial step in making accurate holes in the stand, frame, and reflective sheets. To guarantee that the proper hole sizes were made for every component, a drill machine was equipped with the proper drill bits. The bit sizes were selected according to the particular requirements of the drilled pieces. The holes were carefully measured and aligned because any misalignment could jeopardize the stand's and the parabolic frame's structural stability, which would have a direct impact on the solar cooker's overall performance.
- As seen in Figure 10 below, riveting is a permanent mechanical fastening technique used to attach two metal plates. Usually, a rivet is made out of a short metal pin with a cylindrical tail on one end and a head on the other. As seen in Figure 11 below, an impact riveting machine was used to secure the stainless steel reflective sheets to the frame of our solar cooker project. The reflective sheets were securely fastened to the frame by this machine, which pressed the rivet's head downward. Every joint was carefully examined for longevity and secure fastening, and the impact riveting technique guaranteed a strong and long-lasting bond. Because impact riveting is more accurate and efficient than manual riveting, it was selected.
- By smoothing metal surfaces, finishing lowers friction and improves the components' visual appeal. We finished every component of the solar cooker, paying special attention to the lower portion of the stand. By reducing wear and tear during use, this step not only guarantees improved functionality but also enhances the cooker's overall appearance.

Figure 8. Bending Machine used fot Parabolic Shape.

Figure 9. Holes using a Drilling Machine

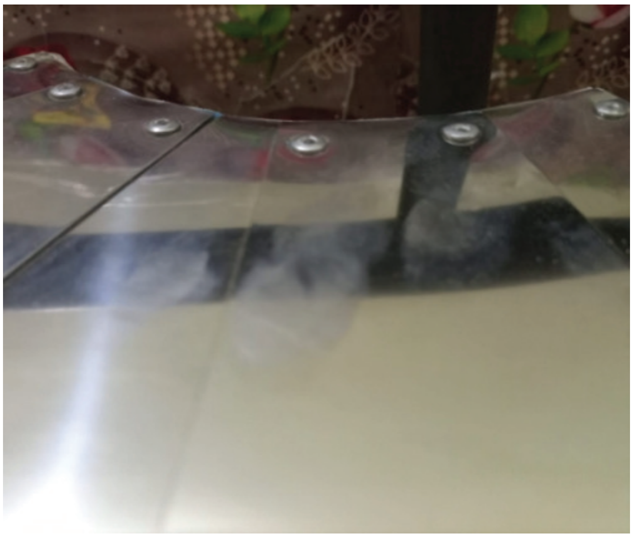

Figure 10. Rivets using Riveting.

Figure 11. Rivet Machine.

Reflective Surface Control

An essential part of the solar cooker›s operation is its reflecting surface. The surface›s smoothness and reflectivity are examined following the cutting and riveting of the stainless-steel sheets. Any imperfections, like dents or scratches, could make the reflector less effective. The sheets were kept highly reflective by cleaning and polishing them.

Assembly Procedure

The upper part of the stand shown in Figure 12 with an adjustable slider shown in Figure 13. consists of cylindrical mild steel pipes shown in Figures 14 below, assembled using nuts and bolts of varying sizes. The three leg support shown in Figure 15. of the stand plays a critical role in supporting the overall load of the solar cooker and maintaining stability in the design. Like the upper part, it is securely assembled using nuts and bolts. The frame, as shown in Figure. 16, of the solar cooker has reflecting sheets riveted onto it. The receptor is carefully assembled to be positioned at the focal point of the parabolic concentrator, optimizing energy concentration for efficient cooking. Figure 17. below shows the final product of our research.

RESULTS AND DISCUSSION

Testing Procedure

The experiment procedure entailed carrying out five different tests in the most favorable sunny weather conditions with ambient temperatures of 30°C to 35°C. During

Figure 12. Cylindrical Mild Steel Pipes

Figure 13. The upper part of the Stand

Figure 14. Adjustable Slider.

Figure 15. Three Leg Support

Figure 16. Frame of Solar Cooker

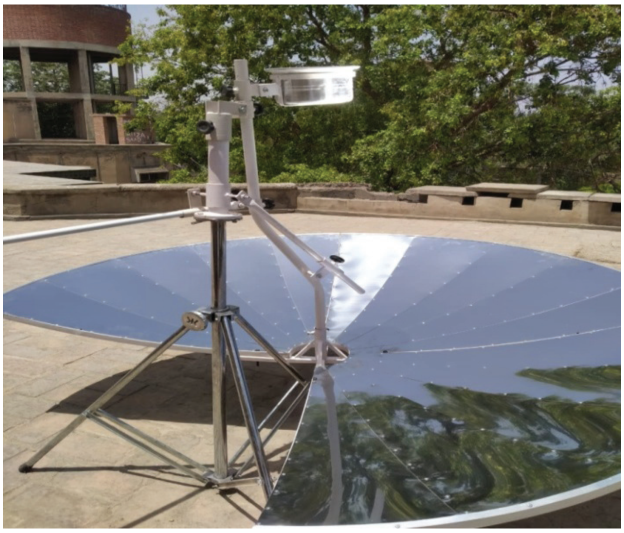

Figure 17. Parabolic Concentrator

the experiment, the solar cooker was oriented at an angle facing the sun so as to maximize the amount of solar captured. Among the five experiments, three were devoted to boiling water under various conditions of the time of the day, one was devoted to boiling an egg and the last experiment was devoted to frying an egg. All experiments were properly observed, a thermocouple was used to record the changes in temperature with time, and it could be taken into account as a good way to understand how the cooker works in different conditions. Such tests presented a viable analysis of the solar cooker and its usefulness in performing everyday cooking chores that it was effective in utilizing solar energy to perform domestic tasks. This study has developed a lightweight parabolic solar cooker with high thermal efficiency and versatility to be used both indoors and outdoors and tested them in real life conditions. The idea is confirmed by the experiments of practical cooking which proves the high speed of boiling and possibility to work all day long up to 8 hours. This is unlike earlier research which could only carry out simulations or test in a single environment. This holistic design has made solar cooking technology go a notch higher than the traditional designs by offering both effectiveness and practicality.

For indoor testing, the cooker was positioned near large south-facing windows to capture direct solar radiation. No artificial light sources were used. Solar irradiance was measured during these runs to ensure comparability with outdoor experiments.

Experiment No.1

In Experiment No. 1, we experimented to determine the time taken to boil water with the help of a solar cooker and the experiment was started at 9:00 AM. This was meant to find the efficiency with which the cooker would be able to raise the temperature of the water to boiling point. The experiment was successful in boiling water in 18 minutes time as measured by a thermocouple that was positioned inside the receptor. The readings of the temperatures after certain intervals of time show the gradual rise starting with the temperature at 31.2°C and reaching 89°C by 9:18 AM. The in-depth temperature records, presented in Table 6., address the efficiency of the solar cooker in collecting the solar energy to attain the intended heating, and as such, it can be utilized in practical ways in heating water and cooking.

Table 6. Results for Experiment No.1

Time (minutes)	Temperature (°C)
9:00 AM	31.2
9:03 AM	39
9:06 AM	48.5
9:09 AM	60
9:12 AM	71
9:15 AM	78
9:18 AM	89

Experiment No.2

Experiment No. 2, we tested the efficiency of solar cooker by boiling water at 12:30 PM, with the aim of determining the efficiency of this item in regard to heat transfer when fully exposed to the sun. The findings indicated that the water boiled within 12 minutes, which was impressive as it boiled very fast. A thermocouple was used to record the variations of temperature in the receptor with the values showing a steady increase in temperature of an initial temperature of 34°C to 94°C by 12:51 PM. Table 7. shows that the measured temperatures demonstrate a uniform rise, which highlights the ability of the solar cooker to use solar energy in quick boiling. The latter experiment also highlights the practical value of solar cookers in terms of providing energy efficiency in the process to heat water.

Table 7. Results for Experiment No.2

Time (minutes)	Temperature (°C)
12:30 PM	34
12:33 PM	46
12:36 PM	59
12:39 PM	74
12:42 PM	83
12:51 PM	94

Experiment No.3

Experiment No. 3 tested the ability of the solar cooker to boil an egg, and the experiment was conducted at 1:00 PM. The process took only 12 minutes to boil and this showed the efficiency of the cooker to transfer heat. A thermocouple was installed in the receptor to keep an eye on the temperature variations giving the correct values throughout the cooking process. Table 8. demonstrates that the temperature was measured initially at 38°C and then increased to 66°C after 6 minutes and finally to 87°C at the termination of the experiment at 12 minutes. These findings show how the solar cooker can make good use of solar energy to cook, and this proves that it is a viable option of preparing foods as a sustainable solution.

Table 8. Results for Experiment No.3

Time (minutes)	Temperature (°C)
1:00 PM	38
1:06 PM	66
1:12 PM	87

Experiment No. 4

Experiment No. 4 was conducted to test the solar cooker performance in boiling water whereby the experiment commenced at 3:00 PM. It boiled in 16 minutes showing that the cooker was effective in the utilization of sun energy during the day. A thermocouple was also installed in the receptor to measure the temperature in the boiling process accurately. The initial temperature was taken to be 35°C at 3:10 PM and then gradually rose to 47°C at 3:14 PM, 73°C at 3:22 PM, and finally to 85°C at the conclusion of the experiment. These findings also confirm the ability of solar cooker to harness the use of solar energy efficiently in cooking and this explains why solar cooker is a viable and sustainable product.

Table 9. Results for Experiment No.4

Time (Minutes)	Temperature (°C)
3:10 PM	35
3:14 PM	47
3:18 PM	61
3:22 PM	73
3:26 PM	85

Figure. 18 shows that the temperature curve of the parabolic solar cooker has a rapid thermal response. Raising the water temperature initially at 34°C, it gradually increased to 94°C in approximately 12 minutes with maximum sunlight exposure, which depicts the high concentrating power and energy transfer efficiency of the system. Above this temperature, the temperature curve leveled off at a higher

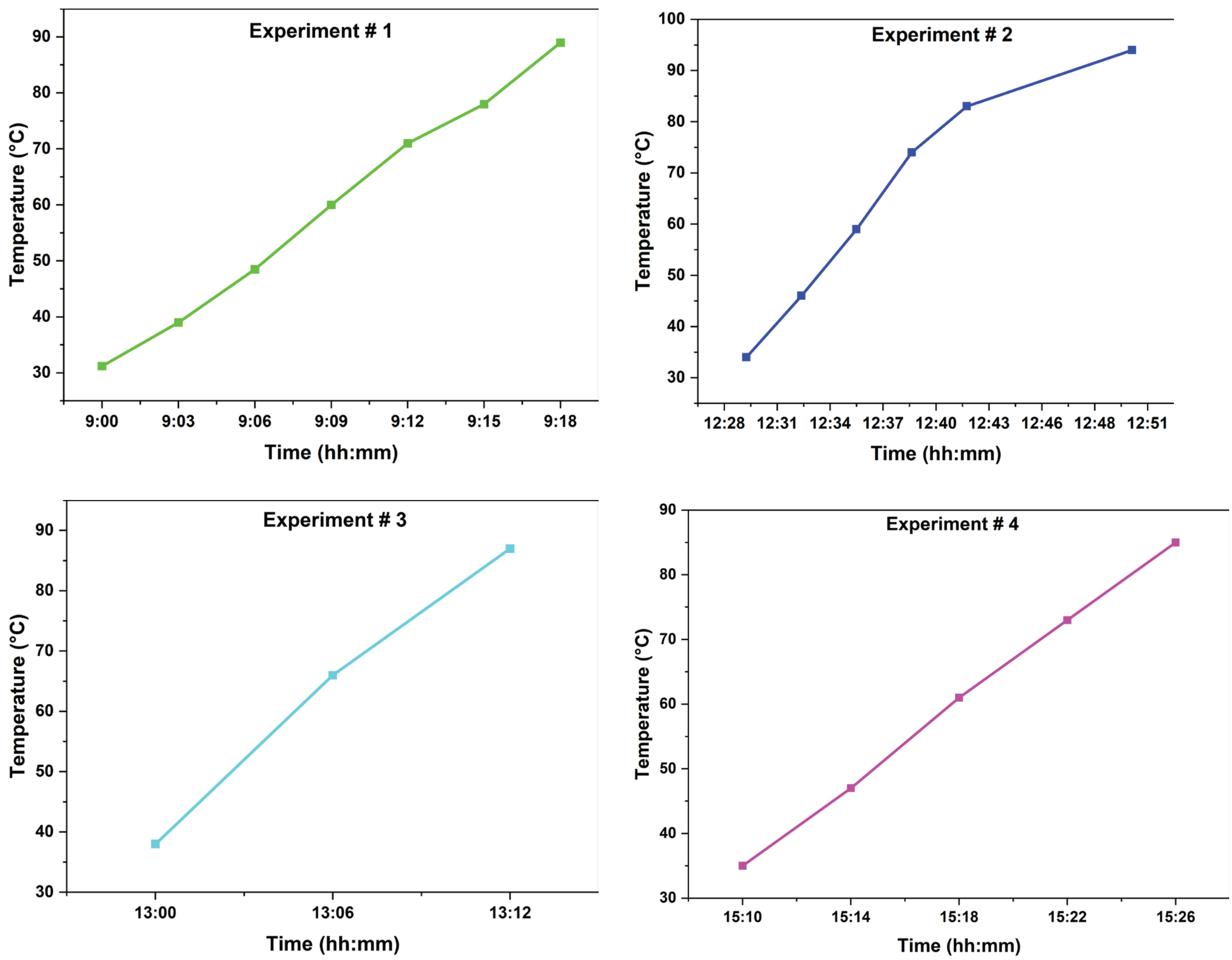

Figure 18. Temperature Variation in Solar Cooker During Cooking Tests showing a rapid rise in temperature at peak irraditaion.

temperature of over 80°C and it was found to be a stable temperature condition at which the heating was to be conducted continuously. This is due to this constant temperature zone where food can be cooked in a proper and consistent way that does not have the ups and downs that normally affect performance in other systems. The design is quite quicker in heating and has a greater maximum temperature compared to the previous experiments of box-type cooker which could require more than an hour to boil water. The high slope of the heating curve is a sign of the enhanced thermal concentration offered by the parabolic geometry and smooth reflective surface, which makes the cooker suitable in the context of the need to achieve the thermal concentration on the one hand and the long-term thermal stability on the other.

Experiment No.5

In Experiment No. 5, we tested the solar cooker's ability to cook an egg, initiating the process at 3:00 PM. The egg was cooked for a duration of one minute, showcasing the cooker's effectiveness in applying concentrated solar energy for quick cooking tasks. The egg was successfully cooked in such a short amount of time, despite the fact that no temperature data was recorded during this quick experiment. This shows the potential for quick food preparation using solar technology. This further emphasizes the versatility and efficiency of the solar cooker in meeting various cooking needs, particularly in regions with abundant sunlight.

RESULTS AND DISCUSSION

Total Solar Irradiation on Solar Cooker

Total solar irradiation refers to the rate at which solar radiation strikes a surface per unit area of that surface. The solar radiation that strikes the parabolic solar cooker in its entirety is provided by.

$$I_{i\theta} = I_{DN} cos\theta + I_{d\theta} + I_{r\theta} \quad (14)$$

The earth›s position (l), the time of day (h), and the day of the year (d) all affect the angle of incidence (θ).

When the Solar Cooker is Horizontal

When the solar cooker is horizontal, the angle of incidence θ is equal to the Zenith angle (Ψ).

$$\theta = \Psi = 90 - \beta \tag{15}$$

$$\beta = sin^{-1}[cosl \text{ x } \text{cosd} + \text{sinl sind}] \tag{16}$$

β = 34.0151° (latitude angle for Peshawar = 34.0151°
hour angle h = 0° (noon)

The declination angle is;

$$\text{d} = 23.47\sin 360\ \frac{(284 + \text{N})}{365} \tag{17}$$

N=161 (11 June)

d = 23.03° (Using Equation. 17)

β = 79.01° (Using Equation. 16)

θ = 10.78° (Using Equation. 15)

$$\text{I}_{DN} = Ae^{\frac{-\beta}{sin\beta}} \tag{18}$$

Where A = 1080 w/m^2 for Mid-summer and β = 0.21 for summer.

I_{DN} = 872 w/m^2 (Using Equation. 18)

$$\text{I}_{d\theta} = C.\text{I}_{DN}\text{ F} \tag{19}$$

Where C = 0.135 for summer and F is a view factor which is a function of orientation of surface only.

$$F = \frac{1 + cos0}{2} = 1$$

$\text{I}_{d\theta}$ = 117.72 w/m^2 (Using Equation. 19)

$$\text{I}_{r\theta} = (\text{I}_{DN} + \text{I}_d)\delta_g F_{SG} \tag{20}$$

Where δ_g = 0.5, $F_{SG} = \frac{1-cos0}{2}$=0

$\text{I}_{r\theta}$ = 0 w/m^2 (Using Equation. 20)

So, it means that when the solar cooker is placed horizontally to the ground, no solar radiation is reflected toward the solar cooker.

$\text{I}_{i\theta}$ = 937.75 w/m^2 (Using Equation. 14)

In this study, the performance of a solar cooker positioned horizontally was investigated. The angle of incidence was found to be equivalent to the zenith angle, indicating a significant alignment with solar radiation at noon. For the specific latitude of Peshawar, the calculated declination angle confirmed that solar exposure was optimal during the mid-summer period. According to the analysis, the cooker did not receive any reflected solar radiation when positioned horizontally, even though the direct normal irradiation was significant. As a result, the cooker received about 937.75 W/m² of total solar radiation. This research highlights how important positioning is for improving solar energy absorption, which in turn increases the effectiveness of solar cooking applications.

When a Solar Cooker is Placed Inclined

The solar cooker›s concentrator receives the most sunlight when it is angled 60 degrees from the horizontal surface. With the tilt angle Σ = 60°., we will now examine the total amount of solar radiation that reaches the solar cooker. The angle of incident "θ" is given by the formula;

$$\theta = cos^{-1}[sin\beta\ cos\Sigma + cos\beta cos\alpha sin\Sigma] \tag{21}$$

Latitude l = 34.0151° (Peshawar)
hour angle h = 0° (solar noon)
N = 162 (12 June)
d = 23.1° (Using Equation. 17)

β = 79.08° (Using Equation. 16)

$$\alpha = 180\text{-}\Upsilon \tag{22}$$

$$\Upsilon = \cos^{-1}\left[\frac{cosl\ sind - cosd\ \text{cosh}\ sinl}{cos\beta}\right] \tag{23}$$

ϒ = 178.29°(Using Equation. 23)

α = 1.87° (Using Equation. 22)

θ = 49.08° (Using Equation 21)

I_{DN} = 880.97 w/m^2 (Using Equation. 18)

Since $F = \frac{1+cos\Sigma}{2}$ = 0.75

$\text{I}_{d\theta}$ = 89.19 w/m^2 (Using Equation. 19)

$$F_{SG} = \frac{1 - cos\Sigma}{2} \tag{24}$$

F_{SG} = 0.25

$\text{I}_{r\theta}$ = 121.27 w/m^2 (Using Equation. 20)

$\text{I}_{i\theta}$ = 787.49 w/m^2 (Using Equation. 14)

In order to maximize the concentration of solar radiation, the solar cooker was positioned in this analysis at an inclined angle of 60° from the horizontal surface. Maximum solar radiation could reach the concentrator because of the inclination. The computed angle of incidence, which took the tilt angle into account, was 49.08°, guaranteeing effective solar energy capture. Additional diffuse and reflected components contributed to the total energy, which was measured at 880.97 W/m² for direct normal irradiation. An inclined position greatly increases solar energy absorption, which is essential for optimizing the performance of solar cookers. The inclined cooker's total solar irradiation received was calculated to be 787.49 W/m².

Optical and Thermal Efficiencies:

The collector›s optical efficiency is;

$$\eta_o = \tau_v \delta_c \delta S \quad (25)$$

$$S = \frac{A_p - A_t}{A_p} \quad (26)$$

$A_{nd} = A_p$ - *Area base recibidor* $= A_p - A_t$

$$A_{nd} = \left(\frac{\pi D^2{}_a}{4} - \frac{\pi \theta {r_p}^2}{360}\right) - \pi a^2 \quad (27)$$

$A_t = 1.5072\text{-}3.14 \text{ x } 0.0762^2$

$A_t = 1.4889$

$S = 0.9878$ (Using Equation. 26)

$\eta_o = 48.69\%$ (Using Equation. 25)

$$T_r = \frac{T_{amb} + T_{sum}\left[(1-\eta)\eta_o X \frac{C_{max}}{46311 \, X \, \epsilon_r}\right]}{2} \quad (28)$$

Where $T_{amb} = 40$ °C and $T_{sun} = 5726.8$ °C

$T_r = 200.60$ °C (Using Equation. 28)

$$Q_{abs} = A_r \tau_v \delta_c \delta I_d \quad (29)$$

$I_d = 872 \; w/m^2$ (already calculated in the radiation section)

$Q_{abs} = 640.03$ watt (Using Equation. 29)

$$Q_{loss} = A_r u (T_r - T_{amb}) \quad (30)$$

$$u = \left(\frac{1}{h_{in} + h_{out}}\right)^{-1} \quad (31)$$

$$h_{out} = 4\Delta \epsilon_r {T_{amb}}^3 \quad (32)$$

$h_{out} = 3.477 \; w/m^2 \, K$ (Using Equation. 32)

$$h_{in} = \frac{K_{air} N_u}{D_{out}} \quad (33)$$

$$R_e = \frac{V_{air} D_{out}}{\nu} \quad (34)$$

Since 40 °C + 273 = 313 K, then $D_{out} = 0.1524 \; m$

$R_e = 37{,}293.17$ (Using Equation. 34)

$$N_u = 0.30 \, {R_e}^{0.66} \quad (35)$$

$N_u = 165.99$ (Using Equation. 35)

$h_{in} = 29.62 \; w/m^2 \, K$ (Using Equation. 33)

$u = 33.097 \; w/m^2 \, K$ (Using Equation. 32)

$Q_{loss} = 25.939$ *watt* (Using Equation. 31)

$$Q_{net} = Q_{abs} - Q_{loss} \quad (36)$$

$Q_{net} = 614.091$ watt (Using Equation. 35)

This is the net quantity of heat that cooks the food ingredients inside the receiver.

Using the useful energy delivered, it is possible to calculate the system instantaneous thermal efficiency of the solar cooker. The result is given as follows:

$$\eta = \frac{Q_{net} \times 100}{A_p I_d} \quad (37)$$

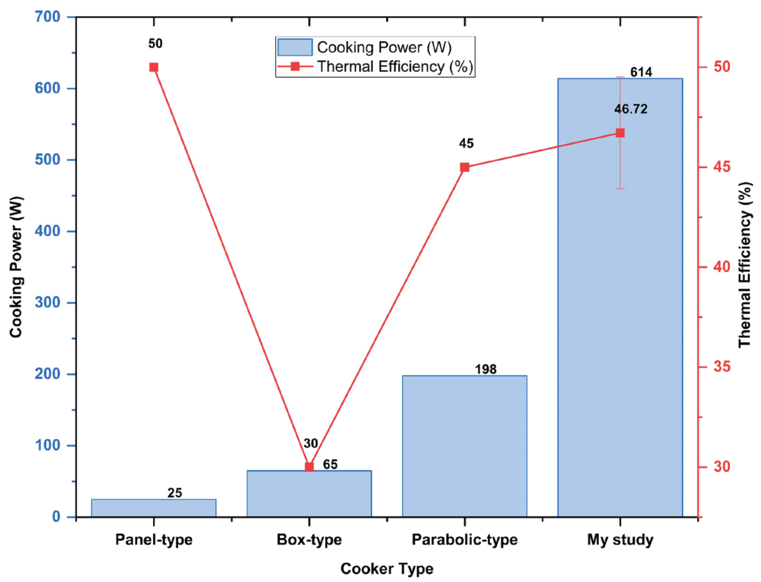

Figure 19. comparison of solar cookers' performance in terms of thermal efficiency and cooking power.

η = 46.72% (Using Equation. 37)

Together with the current design, Figure 19 compares the cooking power and thermal efficiency of several types of solar cookers that have been documented in the literature. Conventional parabolic cookers can reach approximately 198 W with 40–50% efficiency, whereas panel and box cookers usually have low cooking power (25–65 W). The current design›s superior performance is demonstrated by its significantly higher cooking power (614 W) and comparable thermal efficiency (46.72% ± 2.8%).

Uncertainity Analysis

To guarantee the repeatability and dependability of the outcomes, each experiment involving the solar cooker (water boiling, egg boiling, and frying) was carried out three times. High experimental consistency was indicated by the measurements› low variation between repetitions.

- **Temperature measurement uncertainty**
  Thermocouples with a resolution of 0.1°C and a calibration accuracy of ±0.5°C were employed. The combined uncertainty in temperature measurement, taking into account multiple trials, is estimated to be ±0.6°C. The reproducibility of the thermal response data is confirmed by the minimal deviation over the course of three trials.
- **Time measurement uncertainty**
  A digital stopwatch with an uncertainty of ±1 s was used to record the time. This uncertainty is minimal considering that the experiments lasted between 12 and 18 minutes in total.
- **Solar irradiation uncertainty**
  Calculations of solar radiation took into consideration direct, diffuse, and reflected components. An estimated ±3% uncertainty is introduced by variations in atmospheric conditions.
- **Derived efficiencies (Optical and Thermal)**
  Using measured temperatures, irradiance, and geometric parameters, optical efficiency (ηo) and thermal efficiency (η) were computed. An overall combined uncertainty of roughly ±2.5% for optical efficiency and ±2.8% for thermal efficiency is obtained by propagating uncertainties from temperature (±0.6°C), irradiation

Table 10. Analysis of Solar Cooker Performance: Thermal and Radiative Factors

Calculated Values	Description	Equation Number	Calculated Values	Description	Equation Number
937.75 W/m²	Total solar irradiation on the solar cooker when placed horizontally.	14	$I_{r\theta}$ = 121.27 W/m²	Reflected radiation falling on the solar cooker (inclined).	20
β = 34.0151°	Latitude angle for Peshawar.	16	$I_{i\theta}$ = 787.49 W/m²	Total incident radiation on the solar cooker (inclined).	14
d = 23.03°	Declination angle for 11 June (N = 161).	17	η_o = 48.69%	Optical efficiency of the solar cooker.	25
θ = 10.78°	Angle of incidence when the solar cooker is horizontal.	15	S = 0.9878	Solar energy absorption factor.	26
I_{DN} = 872 W/m²	Direct normal irradiation at noon.	18	A_t = 1.4889 m²	Area of the solar cooker's receiver.	27
$I_{d\theta}$ = 117.72 W/m²	Diffuse radiation falling on the solar cooker.	19	T_r = 200.60°C	Receiver temperature.	28
$I_{r\theta}$ = 0 W/m²	Reflected radiation falling on the solar cooker (horizontal).	20	Q_{abs} = 640.03 W	Absorbed heat by the solar cooker.	29
$I_{i\theta}$ = 937.75 W/m²	Total incident radiation on the solar cooker (horizontal).	14	u = 33.097 W/(m²·K)	Overall heat transfer coefficient (u).	31
θ = 49.08°	Angle of incidence when the solar cooker is inclined at 60°.	21	Q_{loss} = 25.939 W	Heat loss from the solar cooker.	30
I_{DN} = 880.97 W/m²	Direct normal irradiation when the solar cooker is inclined at 60°.	18	Q_{net} = 614.091 W	Net heat retained by the solar cooker for cooking.	36
$I_{d\theta}$ = 89.19 W/m²	Diffuse radiation falling on the solar cooker (inclined).	19	η = 46.72%	Instantaneous thermal efficiency of the solar cooker.	37
F_{SG} = 0.25	View factor for reflected radiation when inclined.	24			

(±3%), and surface area (~±0.5%). The dependability of these efficiency values is further supported by the small variations between repeated experiments.

The inclusion of this analysis confirms that the performance of the solar cooker is consistently reproducible and shows the high repeatability and confidence in our experimental results.

Table 10 demonstrate the radiative and thermal parameters of the cooker. The solar cooker's ability to efficiently catch and concentrate solar radiation was confirmed by its 48.69% optical efficiency. A net heat of 614.09 W was retained by the receiver, which is enough for normal cooking requirements in a household. Its 46.72% instantaneous thermal efficiency shows a high conversion rate of solar energy into usable heat, which is in line with the highest range of parabolic cookers that have been documented. These results show how reliable and effective the system is at using solar energy for practical cooking applications.

The efficiencies were calculated with error margins to account for measurement uncertainties. It was determined that the thermal efficiency was 46.72% ± 2.8% and the optical efficiency was 48.69% ± 2.5%. These uncertainties came from the propagation of errors in geometric measurements (~±0.5%), solar irradiance variation (±3%), and thermocouple calibration (±0.6 °C). The robustness of the solar cooker's performance evaluation is confirmed by the comparatively small deviations, which show high repeatability and reliability of the experimental results.

This cooker lowered the boiling time to 12 minutes instead of 30 to 60 minutes, increased the peak temperature to 200.6 °C from 120 to 140 °C in previous parabolic cookers, and guaranteed durability by using polished stainless-steel reflectors instead of brittle foils or mirrors. Compared to traditional bulky designs, it is more portable and useful for household use because it is lightweight (8.5 kg) and has a foldable stand.

CONCLUSION

This study effectively illustrated the design and construction of an easy-to-use parabolic solar cooker that is specifically suited to the climate of Peshawar, Pakistan, where daily solar insolation averages between 5.5 and 6.5 kWh/m². The main goal was to use locally accessible materials to create a cooking solution that was effective, portable, and sustainable. Its practical performance was also assessed through experiments conducted in real-world settings.

- Based on the sensible heat that the water gained during the boiling tests, the solar cooker's maximum thermal efficiency was determined to be 46.72%.
- One liter of water boiled in just 12 minutes from an ambient temperature of 28°C, demonstrating the cooker's quick thermal response in real-world cooking tests. Furthermore, under ideal solar conditions, the cooker's high thermal concentration and effective heat retention were evident from the fact that eggs were fried in about a minute and vegetables were cooked through in 20 to 25 minutes.
- Under clear sky conditions, the cooker could run for up to eight hours a day (from 9:00 AM to 5:00 PM), offering a practical way to meet everyday cooking needs without using gas or electricity.
- In order to minimize thermal losses and ensure optimal energy convergence on the cooking vessel, the focal point accuracy was kept at ±2 cm.
- With a foldable and adjustable frame that allows tilt angle adjustment between 30° and 60° depending on the solar altitude throughout the year, the cooker weighed about 8.5 kg in total.
- The parabolic shape (diameter: 1.2 m, depth: 0.2 m) guaranteed effective focus and heat delivery, while the use of stainless steel with a reflectivity of roughly 60% improved solar concentration.
- In terms of the environment, the solar cooker takes the place of traditional liquid petroleum gas use. An estimated 0.25 kg of liquid petroleum gas could be saved per session of use, which translates to a daily reduction of 0.75 kg of carbon dioxide emissions per household.
- This study placed a strong emphasis on real-world testing, which confirms the design's effectiveness and dependability in real-world cooking situations, in contrast to many earlier studies that only looked at simulations.
- In comparison to earlier designs, our solar cooker performed better, reaching 200.6°C, boiling one liter of water in 12 minutes, and achieving a maximum thermal efficiency of 46.72%. Its practical relevance and wider impact for sustainable cooking solutions are highlighted by its quick cooking, high efficiency, and dual indoor-outdoor applicability.

The suggested solar cooker is an economical and sustainable substitute for conventional cooking methods because of its high thermal efficiency, rapid boiling capacity, and 8-hour continuous operation. It offers useful advantages by reducing reliance on fossil fuels, encouraging sustainability, and enabling adaptable use in both indoor and outdoor settings. The performance of the cooker is restricted by its reliance on clear skies, the requirement for manual solar tracking on a regular basis, and the durability of reflective surfaces over time. In order to further improve performance and applicability, future work should concentrate on developing lightweight, high-reflectivity materials, scaling the design for community-level kitchens, integrating phase change materials (PCM) for cooking during off-sun hours, and integrating reasonably priced automated tracking systems.

NOMENCLATURE

$I_{i\theta}$ *Total solar irradiation of a surface (w/m²)*
I_{DN} *Direct radiation from sun (w/m²)*

$I_{d\theta}$ *Diffuse radiation from sky (w/m²)*
$I_{r\theta}$ *Reflected radiation from other surfaces (ground)*
Θ *Angle of incident (degree)*
β *Altitude angle which is linked with the surface angle*
F_{SG} *View factor from ground to surface of solar cooker*
α *Wall solar azimuthal angle.*
Υ *Azimuthal angle.*
τ_v *Trasnmittance of glass coating (If not given then equal to* 1)
δ_c *Receptor absorbance* (0.85)
δ *Reflectivity of concentrator* (0.58)
S *Shape factor* (0.9878)
C *For summer* (0.135)
I_d *Mean direct radiation from the sun to parabolic concentrator*
F *View factor (F is a function of orientation of surface only)*
δ_g *Reflectivity ofground* (0.5)
η_{opt} *Optical Efficiency* (0.4869)
η_{th} *Thermal Efficiency range* (0,4-0.6)
ϵ_r *Emmicivity of reciever* (0.5)
K_{air} *Thermal conductivity ofair* (0.072 *w/mK*)
v *Kinetic viscosity* (17×10^{-6} m^2/s)
V_{air} *Velocity of air* (4.16 *m/s*)
h_{in} *Inner convection heat transfer coefficient*
h_{out} *Outer convection heat transfer coefficient*
u *Overall heat transfer coefficient*
Q_{abs} *Estimated energy absorbed by the receptor*
Q_{loss} *Heat lost in receiver*
Q_{net} *Net heat gain*
T_r *Average temperature in the receiver*
Q_e *Useful Energy Delivered*
I_b *Solar Irradiance*
A_c *Collector Aperture Area*
m *Mass of Water*
ΔT *Temperature Rise*
Δt *Heating Time*

Da *Aperture diameter*
f *Focal length*
Ar *Receiver area*
Ap *Aperture area*
C *Concentration Ratio*
h *Reciever height*
b *Distance from focus to point*
θ *Angle in triangle BCE*
γ_r *Edge radius*
ϕ *Aperture angle*

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