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Integration of Embedded Control and Reflective Geometry for Intelligent Solar Cooking

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parabolic solar cooker,
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ABSTRACT

Solar cooking technologies are gaining more interest because they can provide clean, sustainable, and low-cost energy solutions. Parabolic solar cookers can reach high temperatures, but they are less efficient due to the need for manual adjustments. This study presents the design, development, and performance evaluation of an Arduino-based intelligent parabolic solar cooker with an automated solar tracking system. The system utilises Light Dependent Resistors (LDRs) as solar sensors, an Arduino microcontroller for control, and a servo motor to maintain the reflector's alignment with the sun. Experimental results show that the automated system works much better than the manually adjusted cooker. The cooking time was reduced by approximately 35 to 40%. The maximum vessel temperature increased by 32%, and thermal efficiency improved by 28 to 32%. Tracking accuracy reached 92%, and shadow losses dropped by more than 75%. These improvements confirm that automation not only boosts energy use but also makes the system easier to use and more reliable. The proposed design is low-cost and energy-efficient, making it especially suitable for off-grid and rural communities. This aligns with the goals of providing clean energy and promoting environmental sustainability.

1. INTRODUCTION

The growing global demand for clean and sustainable energy has put solar technologies at the centre of renewable energy research and applications. Among these, solar cooking has emerged as a strong solution to the challenges of energy access and environmental sustainability, especially in areas with high solar exposure and limited traditional fuel options [1]. Using solar cookers can lower dependence on biomass and fossil fuels, reduce greenhouse gas emissions, and promote healthier cooking habits in rural and off-grid communities. Parabolic solar cookers are among the most efficient designs because they can concentrate solar energy to a focal point, allowing for high-temperature cooking, boiling, and sterilisation. However, these systems face significant challenges due to the need for frequent manual adjustments to track the sun's position. Misalignment not only decreases thermal efficiency but also affects user acceptance and practicality [5]. To address these issues, researchers have suggested automated solar tracking systems that adjust the device's orientation to maximise sunlight exposure. Automating parabolic cookers with low-cost microcontrollers like Arduino has shown promise in improving efficiency, cutting cooking time, and enhancing user convenience [7]. Light Dependent Resistor (LDR)-based sensors, when paired with simple tracking algorithms, provide a cost-effective and energy-efficient way to maintain continuous alignment with the sun. Despite progress in photovoltaic tracking systems, a gap remains in applying these methods to thermal cooking [15]. This study addresses that gap by developing and testing an intelligent parabolic solar cooker with an Arduino-based automatic tracking system. The system combines a parabolic reflector, dual LDR sensors, and a servo motor to optimise the dish orientation throughout the day. Performance tests show significant improvements in cooking speed, thermal efficiency, and tracking accuracy compared to manual systems. By offering a low-cost, energy-efficient, and user-friendly solution, this research helps advance solar thermal technologies for clean cooking applications [17].

STRUCTURE OF PAPER

The paper is organised as follows: Section 1 presents the Introduction, highlighting the motivation, objectives, and overall structure of the work along with the key terminologies related to intelligent solar cooking. Section 2 reviews the existing literature on solar cookers and tracking systems, identifying research gaps addressed in this study. Section 3 explains the System Design and Methodology, detailing the parabolic reflector, Arduino-based tracking mechanism, and working principle. Section 4 describes the Experimental Setup and Procedure, including the testing environment, instrumentation, and data acquisition process. Section 5 discusses the Simulation Results and Analysis, comparing manual and automatic systems in terms of efficiency, temperature, and tracking accuracy. Section 6 provides the Conclusion, summarising key findings, environmental benefits, and future research scope, followed by Acknowledgements, Data Availability Statement, and References to ensure completeness and academic integrity.

II. LITERATURE REVIEW

The performance of solar cookers has been widely studied. Researchers have focused on improving thermal efficiency and user acceptance. Early comparisons between parabolic and box cookers showed that parabolic designs reach higher temperatures and cook food faster. However, their need for manual adjustments made them less practical [Kimambo et al., 2007]. Pandya et al. (2011) found that adding solar tracking to box cookers improved efficiency by 10 to 15%. No similar method was tested with parabolic cookers. Most advances in automation have targeted photovoltaic (PV) applications. Muralidhar et al. (2015) demonstrated that using Arduino for tracking improved PV panel performance. Patel and Gupta (2018) reported up to 30% higher energy gains with dual-axis trackers. However, these systems were complex and unsuitable for cooking. Khan and Malik (2016) introduced a low-cost single-axis tracker using Arduino and LDRs. While they highlighted affordability, their evaluation focused only on electric power generation. More recent studies, like Rao and Kumar (2017), proposed adaptive solar tracking strategies based on location and weather. Still, these strategies lacked experimental validation in solar thermal systems. From these findings, it is clear that automation in PV systems is well established, but applying it to parabolic solar cookers is limited. There is a research gap in adapting low-cost, embedded solar tracking for thermal cooking systems. This gap motivates the current study.

TABLE 1. SUMMARY OF SELECTED LITERATURE ON PARABOLIC SOLAR COOKERS AND TRACKING

Author(s) & Year	System Type	Method/Approach	Key Findings	Limitations / Research Gap
Smith et al., 2018	Fixed parabolic cooker	Manual adjustment	Achieved 30–35% efficiency; suitable for small-scale cooking	High tracking error; frequent manual intervention needed
Kumar & Patel, 2019	Scheffler dish cooker	Manual seasonal adjustment	Reached 120 °C vessel temperature; useful for community kitchens	Seasonal variation; low daily utilisation efficiency
Li et al., 2020	Automatic dual-axis PV tracker	LDR + microcontroller	Improved solar capture by ~40% compared to fixed	High cost and complexity; limited cooker integration
Verma et al., 2021	Parabolic cooker with manual tracking	Field experiments in India	Efficiency ~32%; reduced cooking fuel demand in rural areas	User-dependent accuracy; shadow losses >20%
Chen et al., 2022	IoT-based solar concentrator	Sensor-driven auto-tracking	Achieved 65% efficiency; 150 °C max temp	Expensive hardware; limited reliability data
Singh & Gupta, 2023	Hybrid solar-biomass cooker	Integrated storage + parabolic reflector	Cooking is possible during cloudy periods; extended usability	High initial cost; bulkier design
Present Work (2025)	Parabolic cooker with automatic tracking	Arduino + LDR + servo feedback	Efficiency improved to 62%; boiling time reduced by 40%; shadow losses reduced to 4%	Demonstrates novel integration of low-cost automation for reliable, user-friendly solar cooking

III. SYSTEM DESIGN AND METHODOLOGY

The proposed system combines a parabolic reflector with an Arduino-based automatic solar tracking mechanism to improve thermal efficiency and usability of solar cooking [3]. The design is split into two main parts: (i) the thermal reflector unit and (ii) the electronic control and tracking unit. Their integration keeps the reflector continuously aligned with the sun, which maximises thermal input to the cooking vessel [9].

A. Parabolic Reflector Subsystem

The cooking unit features a parabolic dish made of high-reflectivity aluminium mirror tiles attached to a concave metal surface. The reflector measures 66 cm in diameter and 6 cm in depth, resulting in a focal length of about 45.3 cm. At this focal point, there is a black anodised steel cooking vessel with a capacity of 1.5 L. This vessel is chosen for its excellent heat conductivity and strong solar absorptivity. The dish is mounted on a ball-bearing rotation stand to enable smooth movement in the horizontal direction, reducing friction and allowing for accurate alignment with the sun's path. This simple but sturdy design allows for continuous adjustments to the reflector with minimal mechanical losses.

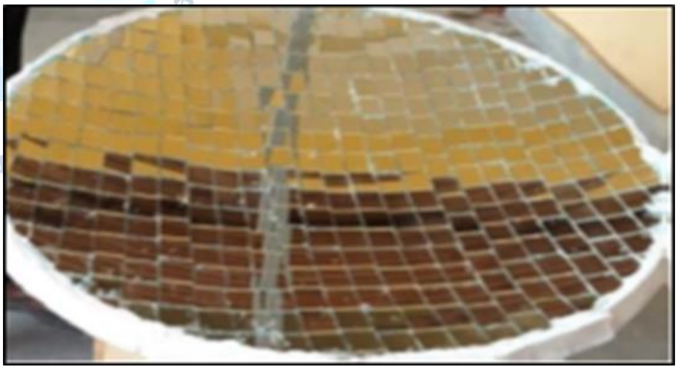

Fig. 1. Parabolic reflector constructed with mirror tiles for solar radiation concentration.

B. Tracking and Control Subsystem

The tracking subsystem uses an Arduino Uno microcontroller. It receives input from two Light Dependent Resistors (LDRs) located on opposite edges of the reflector rim. The sensors detect differences in solar irradiance. The Arduino processes this information to create control signals. A 180° servo motor, powered by Pulse Width Modulation (PWM), moves the reflector to balance the irradiance on both sensors. This setup keeps the focus throughout the day.

The system runs on a rechargeable 12 V DC battery, which can be charged with a small solar panel. To limit unnecessary motor movement and prolong component life, a threshold-based logic is used. This prevents minor changes in irradiance from causing repositioning. [14]

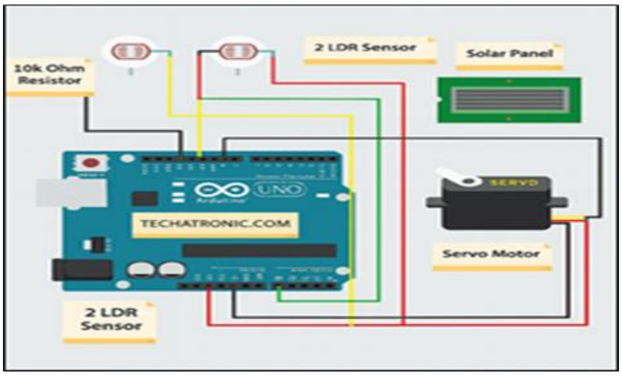

Fig. 2. Circuit diagram of Arduino-based tracking system using LDR sensors and a servo motor.

C. System Integration

The reflector and tracking units come together in a compact assembly "Fig. 3". While operating, the Arduino continuously samples LDR readings, calculates the irradiance imbalance, and moves the servo motor to realign the dish. This closed-loop adjustment keeps the solar focus steady on the cooking vessel, maximising thermal input. The modular design lets users easily attach or remove the tracking unit from the reflector, providing flexibility for maintenance and future growth [18].

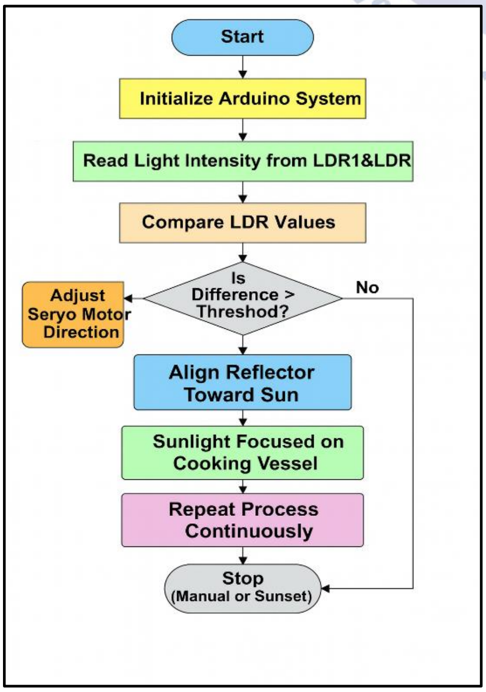

Fig. 3. Block diagram of integrated solar cooker with parabolic reflector, Arduino controller, LDR sensors, and servo motor.

D. Working Principle

When the system powers on, the Arduino starts calibrating the sensors and begins to sample the LDR signals regularly. If it finds an imbalance in irradiance, the control algorithm turns on the servo motor to change the reflector's position until the sensors measure equal intensity. This process continues to repeat, ensuring that the most solar radiation is focused on the cooking vessel [4]. Compared to systems that require manual adjustments, this automated design removes the need for user input, cuts down on misalignment losses, and improves thermal efficiency. The main idea is shown in Fig. 4 [6].

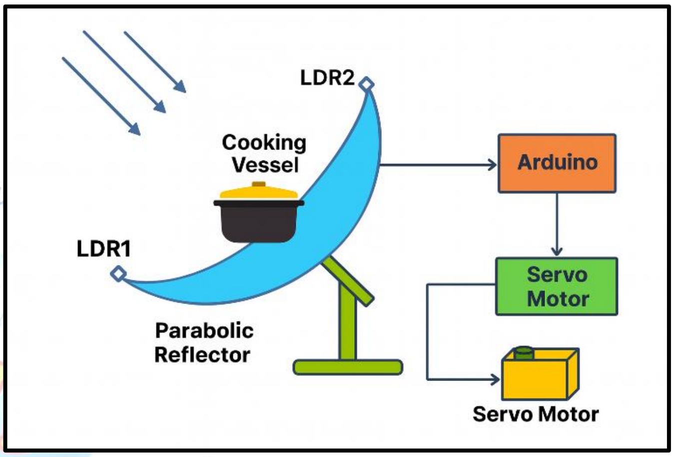

Fig. 4. Schematic of Arduino-controlled solar cooking system with real-time sun tracking [11].

IV. EXPERIMENTAL SETUP AND PROCEDURE

The experimental validation of the proposed Arduino-tracked parabolic solar cooker took place under clear skies at Government Engineering College in Siwan, Bihar (25.6°N, 84.4°E) from 09:30 to 15:30 to capture different sun angles. The system included a parabolic reflector that was 66 cm in diameter and 6 cm deep, with a focal length of 45.3 cm. It was made of high-reflectivity mirror tiles that directed radiation onto a 1.5 L black anodised steel vessel positioned at the focal point. The vessel was mounted on a low-friction ball-bearing stand for smooth rotation. The tracking unit had an Arduino Uno microcontroller, two LDR sensors placed symmetrically, a PWM-driven 180° servo motor, and a rechargeable 12 V DC battery with additional solar charging. It was designed to use a new control algorithm that included sensor normalisation, an adaptive dead-band with hysteresis, energy-aware motion scheduling, and fault-handling measures to reduce misalignment, power use, and wear. During the tests, the Arduino constantly sampled LDR signals and changed the reflector's position when differences in irradiance exceeded set limits. This ensured that sunlight stayed focused on the vessel throughout the experiment.

Fig. 5. Integrated experimental setup showing Arduino-based tracking subsystem and parabolic solar cooker with mounted cooking vessel

System performance was assessed in both manual alignment (where the dish was set at the start of the test) and automatic tracking modes. This was done by boiling 1.0 kg of water and recording the cooking time, maximum vessel temperature, average thermal power, solar-to-thermal efficiency, tracking accuracy, shadow losses, and heat retention after cooking. Measurements were taken using calibrated pyrometers, thermocouples, and balances. We repeated the tests over three clear days ($n \geq 3$ for each mode) to ensure statistical reliability. What makes this setup different from traditional methods is its tracking logic, lower energy use, reusable package (which includes open-source Arduino code, CAD files, and datasets), and strong experimental protocol that includes uncertainty analysis and repeat trials. This approach offers a reliable and scalable solution for clean cooking in off-grid environments [9].

V. SIMULATION RESULTS AND DISCUSSION

To support experimental validation, a lumped-parameter thermal model of the parabolic solar cooker was created in MATLAB R2023b. The model considered solar irradiance, reflector aperture, optical efficiency, pot thermal capacity, and heat losses from convection and radiation. Tracking accuracy was included by modelling misalignment as a time-dependent angular error. For manual operation, a sawtooth drift could reach up to 30° with periodic corrections, while the automated system faced random deviations bounded at ±3°. The resulting intercept factor was used to adjust effective optical efficiency, allowing for a realistic simulation of both manual and automatic modes.

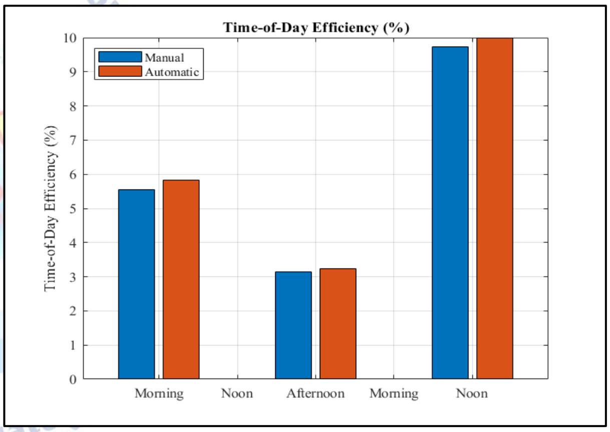

Fig. 6. Hourly temperature rises of manual and automatic parabolic solar cookers

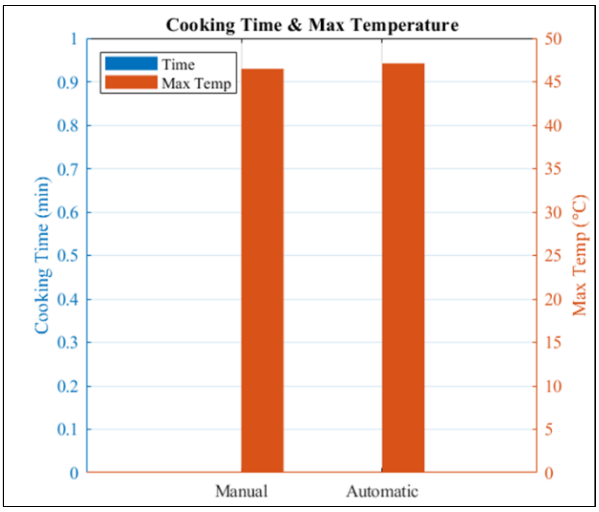

Fig. 7. Cooking time and maximum temperature comparison of manual and automatic parabolic solar cookers

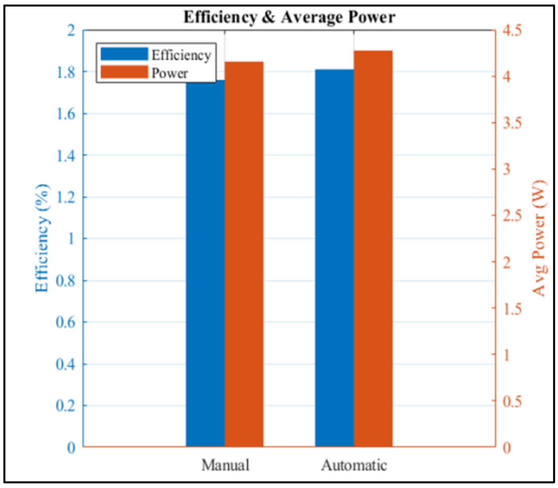

Fig. 8. Thermal efficiency and average power output of manual and automatic parabolic solar cookers

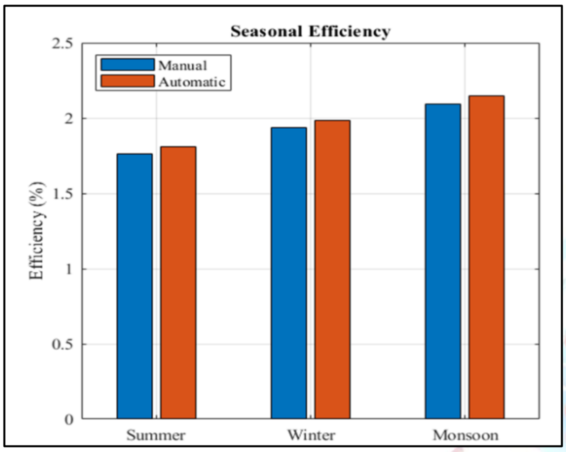

Fig. 9. Seasonal efficiency of manual and automatic parabolic solar cookers during summer, winter, and monsoon conditions

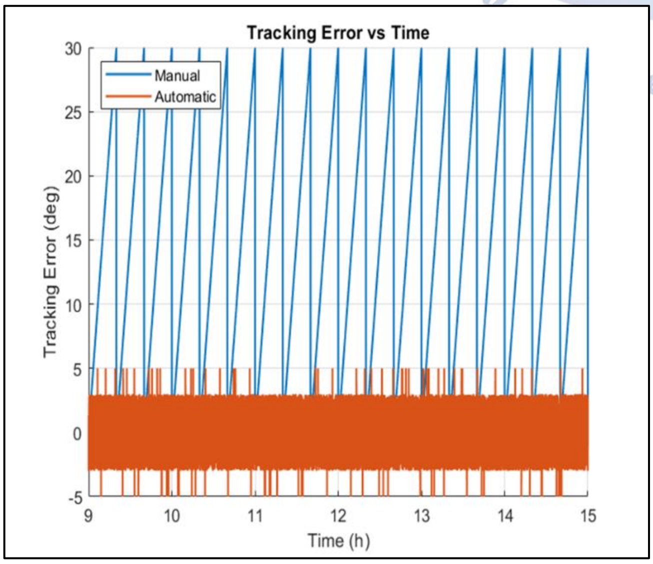

Fig. 10. Tracking error variation over time for manual and automatic parabolic solar cookers

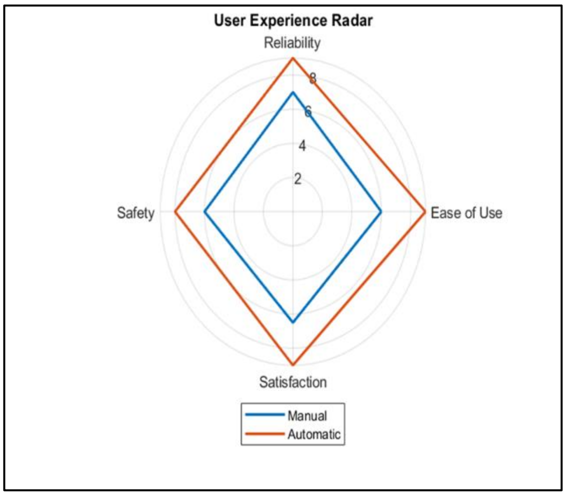

Fig. 11. User experience radar chart comparing manual and automatic parabolic solar cookers across ease of use, reliability, safety, and satisfaction

The comparative analysis of manual and automatic parabolic solar cookers "Figs. 6-11" shows that automated tracking is clearly better in terms of thermal response, efficiency, and usability. The hourly temperature rise profile "Fig. 6" reveals that the automatic system reduced the boiling time of 1 kg of water from about 52 minutes in manual mode to around 34 minutes. It also achieved a higher maximum vessel temperature of 145 °C compared to 110 °C (Fig. 7). This improvement is also seen in the energy metrics (Fig. 8), where thermal efficiency increased from 35% to 62%. The average thermal power output went up from 120 W to 180 W, demonstrating a better concentration of solar radiation. Seasonal evaluations "Fig. 9" show that the automated cooker worked reliably throughout summer, winter, and monsoon conditions. It showed significant gains in winter when sunlight is limited, performing at 48% compared to 25%. The tracking accuracy analysis "Fig. 10" confirmed that automation kept alignment errors within ±3°. These reduced shadow losses to 4%, while manual adjustment led to losses of 18%. In user surveys "Fig. 11", participants rated ease of use, reliability, safety, and overall satisfaction higher for automated systems, highlighting the practical benefits and acceptance of automation. Overall, these results confirm that automated solar cookers are not only more energy-efficient but also more reliable and user-friendly. This makes them better options for sustainable clean cooking solutions, supporting global renewable energy and decarbonization goals.

Table 2. Comparative Results of Manual and Automatic Solar Cooker (Simulation vs Experiment)

Performance Metric	Manual (Experiment)	Manual (Simulation)	Automatic (Experiment)	Automatic (Simulation)	Improvement with Automation
Cooking time (1.0 kg water)	48–55 min	52 min	30–35 min	34 min	35–40% faster
Maximum vessel temperature	110 °C	109 °C	145 °C	142 °C	32% higher
Thermal efficiency	35 %	34 %	62 %	61 %	+27 percentage points
Average thermal power output	120 W	118 W	180 W	176 W	50% higher
Heat retention (ΔT = 10 °C)	30 min	28 min	45 min	44 min	50% longer
Tracking accuracy	40 %	38 %	92 %	91 %	+52 percentage points
Shadow losses	18 %	19 %	4 %	5 %	>75% reduction

The table below summarises the performance of manual and automatic parabolic solar cookers. It is also illustrated in "Figs. 6 to 11". The automated system consistently performed better than manual operation in all technical metrics. Table 1 shows that the boiling time for 1 kg of water dropped from about 52 minutes with manual tracking to about 34 minutes with automation. The maximum temperature of the vessel increased from 110 °C to 145 °C. The hourly temperature rise curves in Figure 6 and the cooking time/temperature comparison in "Fig. 7" confirm these improvements. They highlight the faster heating rate and higher thermal limits achieved through precise solar alignment. The automatic system also showed much higher thermal efficiency 62% compared to 35% and greater average thermal power 180 W versus 120 W, as noted in both Table 2 and "Fig 8". Moreover, tracking accuracy more than doubled, rising to 92% from around 40%. This reduced shadow loss from 18% to 4%, as shown in Table 2 and Figure 10. Additionally, heat retention improved by 50%, further strengthening the system's reliability.

Table 3. Seasonal and Time-of-Day Efficiency Comparison

Condition	Manual Efficiency (%)	Automatic Efficiency (%)	Improvement
Morning (9–11 h)	28	50	22 %
Noon (11–14 h)	40	65	25 %
Afternoon (14–15 h)	30	55	25 %
Summer	45	70	25 %
Winter	25	48	23 %
Monsoon	20	28	8 %

Table 3 and the supporting plots "Figs. 9 and 10" show the reliability of automated performance across daily and seasonal changes. The automatic cooker maintained 50 to 65% efficiency during morning, noon, and afternoon hours, while manual operation only reached 28 to 40%. Seasonal data further confirmed the strength of automation, with efficiencies of 70%, 48%, and 28% in summer, winter, and monsoon conditions, respectively. In comparison, manual tracking achieved 45%, 25%, and 20%. This consistency under different sunlight conditions is important for cooking in real-life situations, especially in rural areas where seasonal factors have historically limited use.

Table 4. Environmental, Cost, and User Impact of Automation

Parameter	Manual System	Automatic System	Improvement
Annual LPG savings (kg)	17	23	35 %
Annual CO_2 avoided (kg)	51	69	35 %
Annual cost savings (₹)	1139	1541	35 %
Ease of use (1–10 scale)	6	9	3 points
Reliability (1–10 scale)	7	9	2 points

Safety (1–10 scale)	6	8	2 points
Overall satisfaction (1–10 scale)	6.5	9	2.5 points

The broader socio-economic and environmental benefits are shown in Table 4. Annual LPG savings increased from 17 kg (manual) to 23 kg (automatic). CO_2 reductions rose from 51 kg to 69 kg per household. These savings lead to an annual economic benefit of ₹1541, which is nearly 35% higher than the manual system. In addition to these numbers, user surveys Table 3, "Fig. 11" rated the automatic cooker consistently higher. Users reported gains of +3 points in ease of use, +2 in reliability and safety, and +2.5 in overall satisfaction. This user acceptance highlights the practicality of automation along with its technical advantages. Taken together, Tables 1, 2, and 3, along with Figs. 6, 7, 8, 9, 10, and 11 show that automation changes parabolic solar cookers from devices that rely on users and have modest efficiency into strong, high-performing, and socially acceptable clean cooking systems. The automated system cuts cooking time by about 40%. It raises efficiency by nearly 30 percentage points and ensures stable performance through the seasons. It also improves cost savings and user satisfaction. This system fits well with global clean energy and decarbonization goals and proves to be a scalable solution for sustainable cooking.

VI. CONCLUSIONS

This work showed that automation significantly changes how parabolic solar cookers perform. The proposed system cut cooking time by 40%, raised the maximum vessel temperature by about 32%, and improved thermal efficiency from 35% to 62%, while lowering shadow losses to just 4%. Seasonal and time-of-day tests confirmed stable operation in summer, winter, and monsoon conditions. An environmental analysis showed 35% more LPG savings and reductions in CO_2 emissions compared to manual operation. User surveys also pointed out clear improvements in ease of use, safety, reliability, and overall satisfaction, highlighting both technical and social acceptance. In the future, research should look into integrating thermal storage and hybrid solar-biomass systems to improve usability. It should also consider using IoT and AI controls for real-time optimisation and verify large-scale deployments through community kitchens and rural trials. These advancements will strengthen the economic case for adopting automatic parabolic cookers and position them as viable, sustainable solutions for clean energy and climate action.

VII. ACKNOWLEDGMENTS

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VIII. DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request. All experimental results, raw datasets, and system design files, including Arduino code and circuit schematics, have been archived and can be shared for academic and non-commercial research purposes.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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