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IoT-Based Real-Time Monitoring and Thermal Performance Evaluation of A Box-Type Solar Cooker

Badri N. Panigrahi[a], Satyam S. Mahanta[b], Jayashree Nayak[b], Sudhansu S. Sahoo[c,*], & Balaji K. Choudhury[d]

[a]*Department of Mechanical Engineering, Biju Patnaik University of Technology, Rourkela, India*
[b]*Department of Mechanical Engineering, Indira Gandhi Institute of Technology, Sarang, India*
[c]*School of Mechanical Sciences, Odisha University of Technology and Research, Bhubaneswar, India*
[d]*Department of Mechanical Engineering, Parala Maharaja Engineering College, Berhampur, India*

Abstract

This work presents the development and evaluation of an IoT-based real-time monitoring system integrated with a box-type solar cooker to assess its thermal performance. The system incorporates an ESP8266 microcontroller interfaced with a DHT11 sensor for ambient temperature and humidity, a DS18B20 sensor for absorber plate temperature, and a MAX6675 with a K-type thermocouple for vessel (water) temperature measurement. All of the sensor data is transmitted to the ThingSpeak cloud platform, enabling real-time visualization and remote analysis. Thermal performance indicators were derived from the recorded data, including the first figure of merit (F1), second figure of merit (F2), thermal efficiency (η), and the overall heat loss coefficient (UL). Under clear-sky conditions, the cooker reached a stagnation temperature of approximately 130°C, with ambient conditions near 35°C and solar irradiance around 850 W/m². The calculated F1 (~0.11 °Cm²/W), F2 (~0.41), average thermal efficiency (~30 %), and average heat loss factor (~4.8 W/m²C) signify a reasonably efficient solar cooker design. Additionally, real-time insights into heat retention and loss were made possible through continuous monitoring. The integration of IoT with the solar cooker not only improves data acquisition and performance evaluation but also demonstrates the viability of smart sustainable cooking technologies in modern applications. It allows for easy and better evaluation of the cooker by the general user.

Keywords: ESP8266, IoT, renewable energy, real-time, solar cooker, thermal evaluation.

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1. Introduction

Energy-saving technology based on renewable natural energy sources is essential to the modern growth of the business. In affluent nations, solar collectors, heat producers, and wind and solar power plants are widely distributed. A gadget that converts solar energy into thermal energy is one of them. These gadgets are expensive and have poor durability and dependability. Thus, lowering the cost of the solar energy conversion equipment and improving its dependability and durability are the real challenges of this project (Rout et al., 2017). There are several uses for solar energy. In addition to materials, solar radiation is a crucial factor in determining whether solar-assisted devices are feasible (Shafa, Rhakasywi, & Fahrudin, 2023; Suryo, Rhakasywi, & Fahrudin, 2023). The increasing demand for clean and sustainable energy sources has intensified interest in solar cooking technologies, particularly in regions with abundant solar radiation. Among the various types of solar cookers, the box-type solar cooker stands out due to its simplicity, low cost, and ease of construction and use. It is especially suitable for domestic applications in rural and semi-urban areas, where access to conventional fuels may be limited or expensive. A box-type solar cooker typically consists of an insulated box with a transparent glass cover and one or more reflective surfaces to concentrate sunlight into the cooking chamber. The trapped solar energy raises the internal temperature (Fig. 1), allowing food to cook through retained heat. While this type of cooker is ideal for slow cooking and retains nutrients effectively, its performance can be influenced by several factors, including solar intensity, ambient temperature, insulation quality, and cooker orientation. Numerous works have

* Corresponding author.
E-mail address: sudhansu@outr.ac.in

been carried out on traditional and modern approaches. An investigation into a tiltable box-type solar cooker intended for a typical household in Sana'a, Yemen, has been conducted, with experimental results validated by CFD (Suryo, Rhakasywi, & Fahrudin, 2023). Two modified solar cookers have been compared and presented: one with a regular design and the other with an inclined cover (Goyal & Muthuswamy, 2023). Detailed different kinds of solar thermal-based box-type solar cookers are reviewed (Sarangi et al., 2024). A solar cooker design with an absorber plate integrated with paraffin wax heat storage and a tracking-type bottom parabolic reflector is an effective method for better performance (Tawfik et al., 2022). The Dwarf Mongoose Optimization Algorithm (DMOA), which was inspired by the social behavior of dwarf mongooses, is presented in this study. The approach was evaluated against various optimization techniques and tested on benchmark functions (Agushaka et al., 2022).

Using a comprehensive Taguchi and machine learning-based optimization approach, the ideal design parameter combinations for a trapezoidal solar cooker that produces the lowest heat loss coefficient have been identified (Panigrahi et al., 2024). Recent years have seen the development of a novel solar cooking system (SCS) with rock-bed thermocline storage, in which thermal oils release heat into the cooktop unit for cooking and transport heat from the collectors to the rocks during charging (Zhou et al., 2023). The thermal performance of two modified transparent sun cookers in Prayagraj, India: the modified sun cooker (MSC) and the modified solar cooker with an inclined cover has been investigated recently (Koshti et al., 2023). All types of heat losses are predominant in solar cooker cavities, and the CFD method is an effective method to find out quantitative heat losses based on different parameters (Sarangi et al., 2023).

A hybrid cooking oven with electric, solar, and combination modes is shown in the study. The hybrid mode achieves an efficiency of 63%, which is much greater than the 35% in electric mode and the 4% in solar mode, according to experimental and computational fluid dynamics (CFD) assessments (Saini et al., 2023). To optimize numerous objectives in WSNs, this research proposes a sophisticated control mechanism that combines a PID controller with NSGA-III. By reducing congestion, the strategy seeks to enhance the network's overall performance and data transfer efficiency (Bhatti et al., 2024). The design and functionality of a tiltable box-style solar cooker with a tracking system are covered in the article (Al-Nehari et al., 2021). The efficiency of the tracking mechanism in improving cooking performance was validated by numerical simulations using ANSYS-FLUENT, which demonstrated good agreement with experimental data.

A control technique is essential for addressing the unpredictability and significant disruption of linear solar thermal power generating systems, and one of the most successful approaches is sliding mode predictive control (Lu, Sun, & Fan, 2022). Recently, an MLP architecture comprising a power signal forecast architecture and a meteorological signal forecast architecture was presented to mine REGF signal patterns in renewable energy power systems (SPM-REPS) (Tian et al., 2024).

Inspired by previous research, it was discovered that performance studies were never employed and were primarily focused on the steady-state method and the usage of IoT for continuous assessment. Solar cookers operate outside and are exposed to high temperatures, wind, dust, and rain. Research is necessary to develop a low-cost, durable, and reliable IoT-based box-type solar cooker to withstand these conditions for extended periods. Data like temperature, solar irradiance, and weather conditions can be used to develop predictive models for forecasting cooking times. Some existing systems focus on monitoring, but there is a knowledge gap in developing IoT IoT-based box-type solar cooker in which different parameters can be dynamically adjusted based on real-time sensor data to optimize cooking performance. Knowledge gap for an IoT-based box-type solar cooker lies in optimizing its thermal performance and usability in diverse environmental conditions and with varying cooking needs like heat retention and distribution within the cooker cavity. With the mentioned research gaps and motivation, the objectives of the present studies are mainly to evaluate the thermal performance of a box-type solar cooker, an Internet of Things-based real-time monitoring system. The results are intended to encourage the wider use of box-type solar cookers as a sustainable cooking solution by enhancing their practical feasibility and informing design changes. Real-time understanding of the heat losses through various components from the cooker cavity will help to minimize energy losses and maximize energy absorption (optimizing heat retention). Developing and using reliable sensors for temperature, solar radiation, and humidity that can withstand the cooker’s environment is needed.

2. Experimentation and Methodology

2.1. Experimentation

A trapezoidal solar cooker (Fig.1) has been used for experimentation in this work. The details of the geometrical configuration are found in our earlier work [8]. The experimental procedure began with the proper placement of the sensors. The DHT11 sensor has been installed in a shaded position near the cooker to avoid direct solar radiation and ensure accurate ambient measurements. The DS18B20 was mounted securely on the absorber plate using thermal adhesive to ensure efficient heat transfer, while the thermocouple was immersed in the center of the water vessel during loaded tests. During the no-load(stagnation) tests, the solar cooker was placed facing true south and tilted at an angle approximately equal to the local latitude.

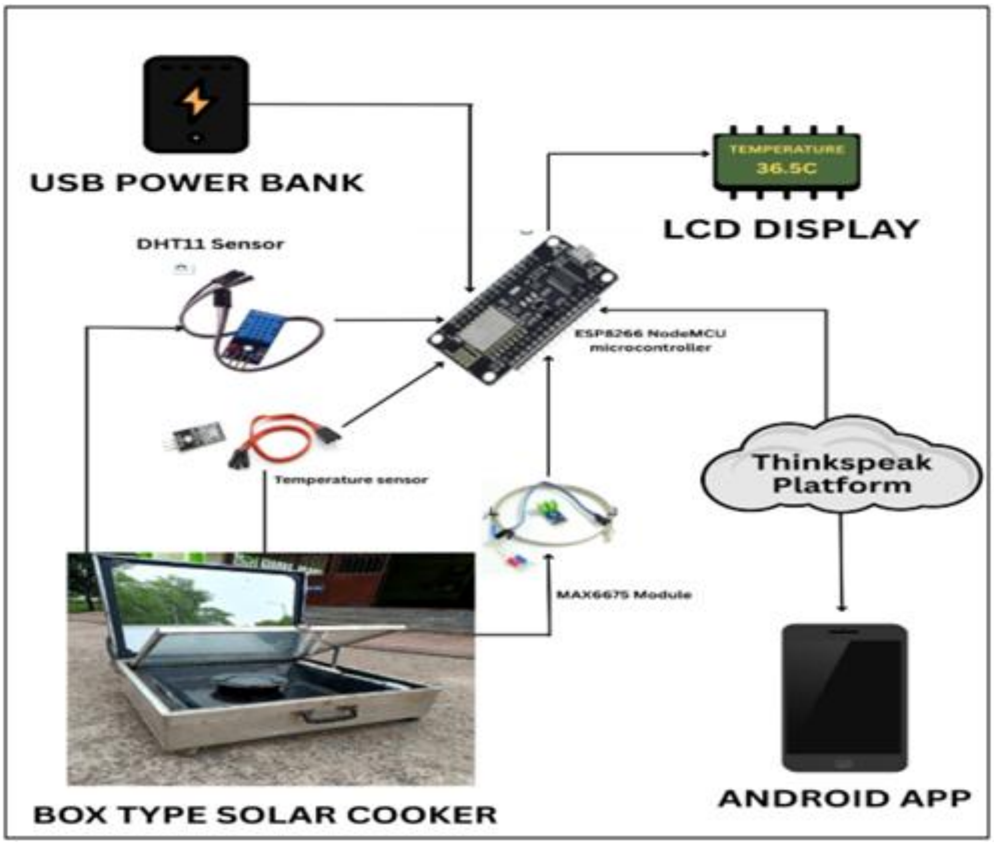

Fig. 1. Box-type solar cooker and IoT-enabled setup for experimentation

Experiments were conducted between 08:00 AM and 5:00 PM under clear sky conditions to maximize solar input. The cooker was left empty, and the temperatures were monitored until a stable maximum absorber plate temperature (stagnation temperature) was achieved. Real-time data logging on the ThingSpeak platform allowed for later retrieval and analysis. The work aimed to comprehensively monitor, record, and evaluate the real-time thermal performance of the box-type solar cooker under realistic environmental conditions.

2.2. IoT implementation

The integration of Internet of Things (IoT) technologies into solar energy systems has opened new frontiers in data-driven optimization, real-time monitoring, and intelligent performance analysis. Traditionally, assessing the thermal performance of a box-type solar cooker required manual temperature readings at intervals, often leading to gaps in data, human error, and delayed performance evaluation. By embedding IoT-based monitoring systems, the operation and evaluation of solar cookers can be made much more efficient, precise, and autonomous.

In this work, an ESP8266 Node MCU microcontroller serves as the central IoT platform. It is connected to multiple sensors that monitor key thermal parameters in real-time: (1) A DHT11 sensor measures the ambient temperature and humidity, providing environmental context. (2)A DS18B20 digital sensor measures the plate (absorber) temperature to track the cooker's heat absorption capacity. (3) A MAX6675 thermocouple interface module connected with a K-type thermocouple measures the vessel (water) temperature, providing load condition data.

These sensor readings are transmitted wirelessly via Wi-Fi to the ThingSpeak cloud platform, where the data is logged, visualized, and made accessible remotely through graphs and dashboards. This real-time monitoring enables continuous tracking of the cooker's performance without the need for manual intervention and allows detailed analysis based on parameters like: Variation of absorber temperature with time, Rate of water heating, Influence of ambient conditions on performance, Continuous calculation of figures of merit and efficiency.

Furthermore, the IoT system allows easy detection of anomalies (e.g., unexpected heat loss due to lid opening, cloud shading, etc.) and provides insights into cooker behavior over different days and weather conditions. Thus, IoT integration transforms the solar cooker from a passive thermal device into an economical, smart, connected system, enhancing both its scientific evaluation and practical usability in real-world scenarios. The complete setup of the IoT-enabled solar cooker for experimentation and the flow chart of the IoT implementation procedure are shown in Fig. 1 and Fig. 2, respectively.

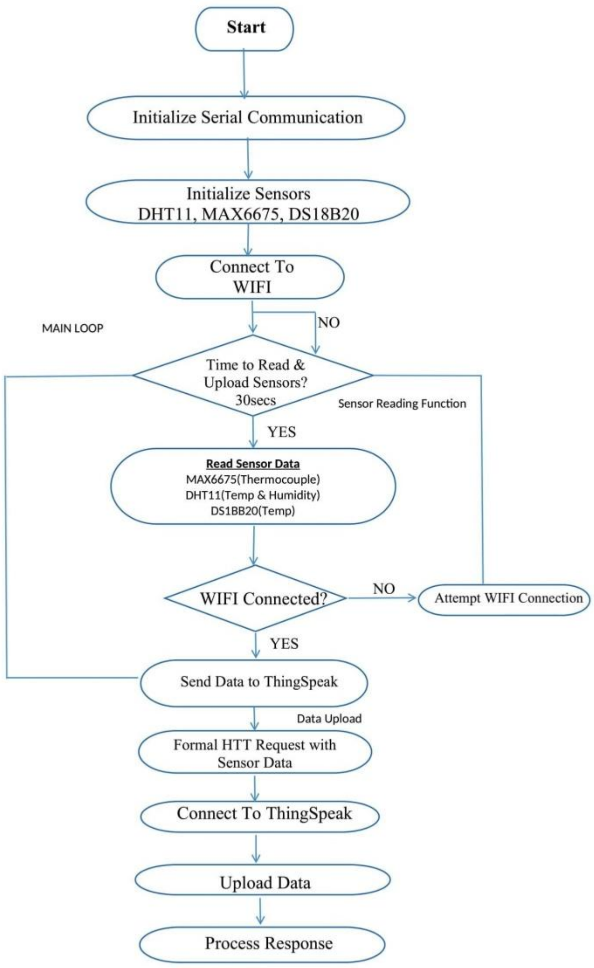

Fig. 2. IoT Implementation procedure

2.3. Performance parameters to be obtained

The first figure of merit (F_1) of a solar cooker represents the combined effect of its optical efficiency and thermal insulation under no-load conditions- that is, when the cooker is empty and allowed to stagnate. It is a direct indicator of how well the cooker converts incident solar radiation into absorbed heat, while simultaneously minimizing heat losses. It is mathematically given by:

$$F_1 = \frac{T_{ps} - T_a}{G} \tag{1}$$

The second figure of merit (F_2) provides a more practical evaluation by measuring the actual cooking performance of the solar cooker under load conditions, usually by heating a certain quantity of water. It tells how efficiently the cooker can transfer absorbed solar energy into useful heat energy that increases the temperature of the food or water.

$$F_2 = \frac{F_1\,(MC)_w}{A\tau} ln \left[\frac{1-(1-F_1)(\frac{T_{w1}-T_a}{G})}{1-(1-F_1)(\frac{T_{w2}-T_a}{G})}\right] \tag{2}$$

The thermal Efficiency (η) of a solar cooker expresses the percentage of the incoming solar energy that is utilized for heating the load (e.g., water or food).

$$\eta = \frac{mc_p(T_{w2} - T_{w1})}{AI\Delta t} \tag{3}$$

The Heat Loss Factor (U_L) is a critical parameter that quantifies how much heat escapes from the solar cooker to the external environment. Even under full sun, some of the captured thermal energy is inevitably lost due to conduction, convection, and radiation.

$$U_L = \frac{IA\eta_s}{A(T_{ps} - T_a)} \tag{4}$$

3. Results and Discussion

The performance of the IoT-based real-time monitored box-type solar cooker was evaluated based on experiments conducted over 2 months (March-April). The data collected through the integrated DHT11, DS18B20, and MAX6675 thermocouple sensors via the ESP8266 microcontroller were uploaded live to the ThingSpeak platform for analysis.

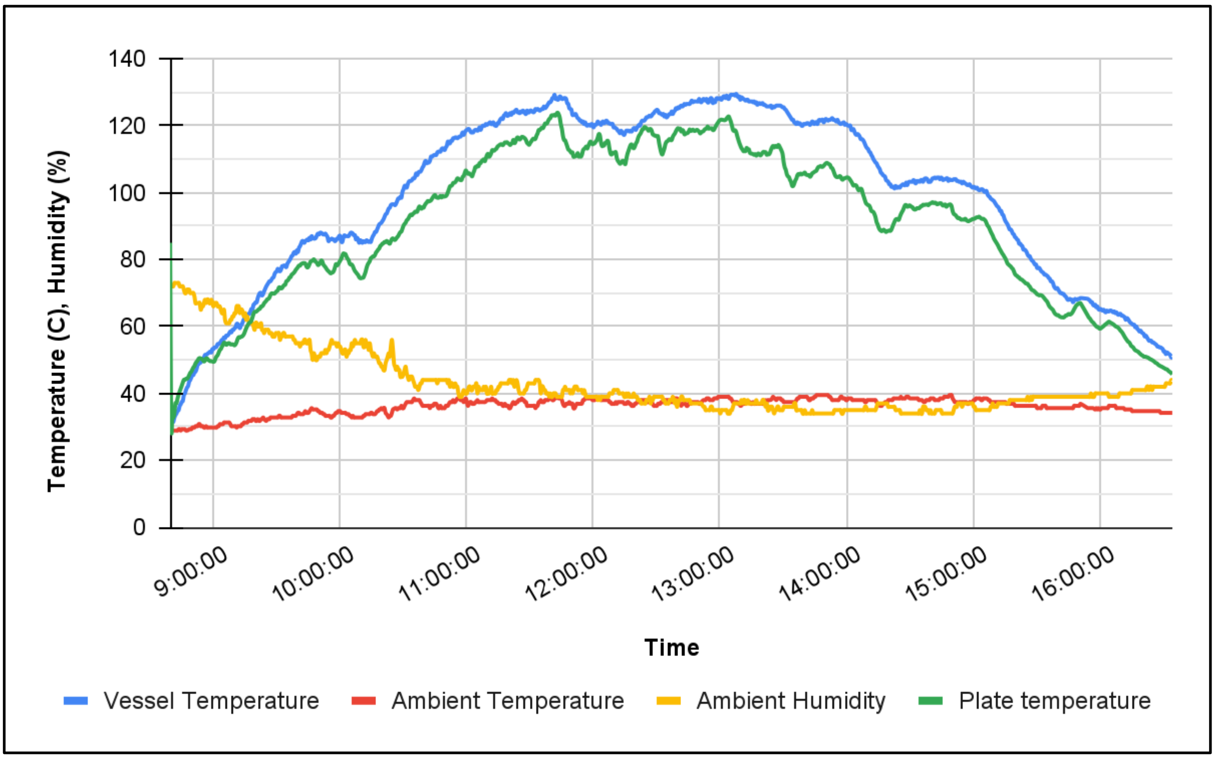

Fig. 3. The temperature data related to 21st March

Ambient Temperature, Ambient Humidity, Plate Temperature, and Vessel Temperature were recorded on 21st March, 2025 (Figure 3) using different equipment in the setup region.. It is seen that vessel temperature rises from 9AM to 12.30 PM, peaking at about 130°C..The data remains almost stable till 2 PM after which it follows a decreasing trend. It can be inferred that the stagnation temperature is 130°C. The absorber plate temperature follows the same trend. This is because after 2.30 PM, there is a sharp fall in solar intensity. Throughout the day ambient temperature varies between 30-35°C. Humidity drop is correlated with heating. From the stored data, performance was calculated. They were then plotted for better visualisation of the cooker's performance. The average solar irradiation during the testing period was 731.39 W/m². This substantial solar resource provided adequate energy input for the cooker's operation. The specific daily irradiation values would help contextualize the performance metrics on individual testing days, especially when analyzing efficiency variations.

As the system heats up and reaches steady state, i.e., in the peak temperature period, there is reduced heat loss (Figure 4). The heat loss coefficient hovers around 4W/m^2-C.This aligns with vessel temperature and plate temperature variation. With increasing temperature, the heat loss factor is reduced. This is a positive trend, and the cooker lies in the stability phase during this period. Heat loss rises in the cooling-down phase. This happens due to an increasing temperature gradient. In the peak operating temperature period, the heat loss factor is minimum and hence, thermal efficiency is maximum. This period is an optimal time for cooking.

The heat loss factor measurements (Fig. 4) from the 27th to the 29th averaged 4.8752. The values showed some fluctuation (5.9708, 4.0860, and 4.5687), with the highest losses recorded on the 27th. This suggests that environmental conditions (like wind speed or ambient temperature) may have influenced the thermal insulation properties of the cooker. The decreasing trend in heat loss factors indicates potential improvements in the cooker's thermal retention as testing continued

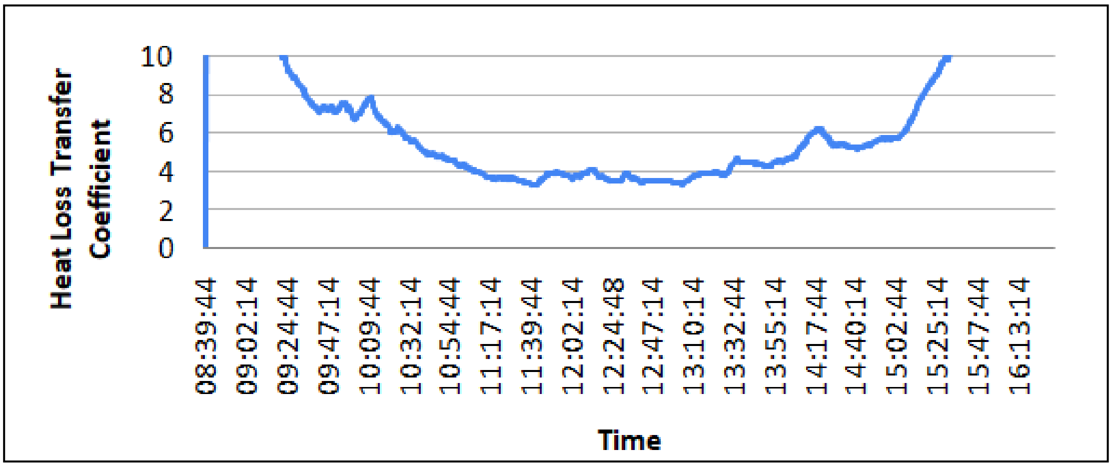

Fig. 4. Overall heat loss coefficient related to solar cookers considered

The efficiency data (Figure 5) shows high variability throughout the day. It is visible that the thermal efficiency varies between 0-40 %. The operating period can be considered as a heating up period (9 AM to 12 noon), peak temperature period (12 Noon to 2.50 PM), and then cooling down period (after 2.30 PM). Thermal efficiency remains stable around 30 % during the peak temperature period, and this is the most suitable time to cook.

The thermal efficiency measurements taken on the 30th through the 1st averaged 29.98 %. The values showed minimal variation (30.32 %, 30.44 %, and 29.17 %), indicating consistent overall performance. This thermal efficiency represents the percentage of incident solar energy that was converted to useful heat for cooking purposes. The nearly 30% efficiency is considered good performance for a box-type solar cooker under standard testing conditions.

The F_1 factor, which measures the optical efficiency of the solar cooker, showed consistent performance over the three-day testing period (27th-29th). Values ranged from 0.0941 on the 27th to 0.1253 on the 29th, with an average value of 0.1136. This indicates that approximately 11.36% of the incoming solar radiation was effectively transmitted through the glazing and absorbed by the cooking vessel. The increasing trend in F_1 values suggests improved optical performance as testing progressed, due to better alignment based on the previous values. The F_2 factor, representing the heat transfer efficiency from the absorber to the cooking vessel, was measured from the 30th to the 1st. Values remained relatively stable at 0.4006, 0.4200, and 0.4218, respectively, with an average of 0.4142. This consistency demonstrates good reliability in heat transfer mechanisms within the cooker. The higher F_2 values compared to F_1 indicate that once solar energy enters the cooker, a significant portion (approximately 41.42%) is effectively transferred to the cooking vessel.

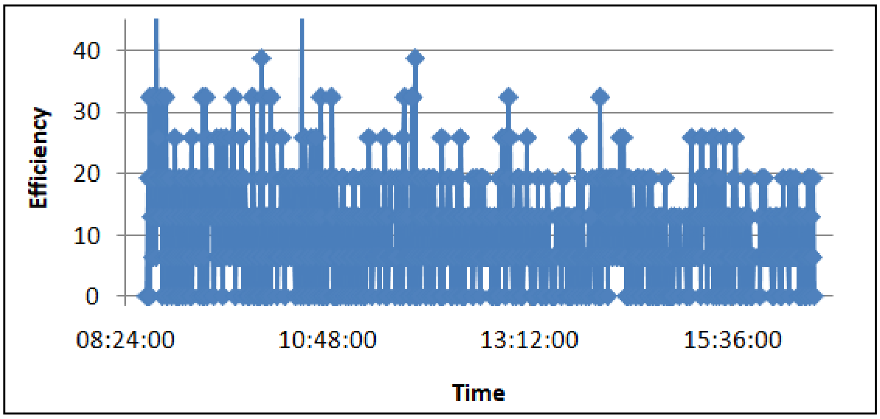

Fig. 5. Thermal efficiency derived throughout the day of experimentation

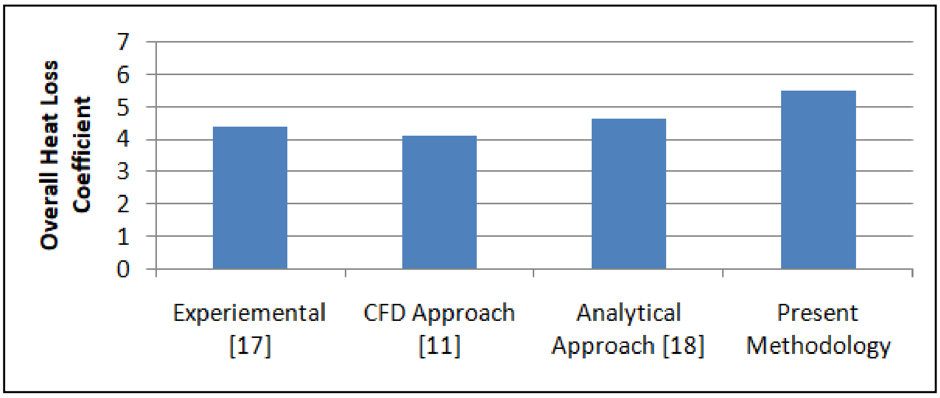

Fig.6. Comparison of the overall heat transfer coefficient with the mentioned literature values

To better understand the thermal performance of the designed box-type solar cooker, a comparative analysis of the Overall heat loss coefficient or heat loss factor was conducted against previously published studies. The results (Fig. 6) obtained in the present work were compared with experimental findings by Singh et al. (2020), a CFD-based study by Sarangi et al. (2023), and an analytical method proposed by Nayak et al. (2018). The comparison is illustrated in Figure 6, where it can be observed that the present result shows a slightly higher Heat Loss Factor compared to earlier studies. This slight increase is reasonable considering the material characteristics, design specifics, and ambient environmental factors influencing the present experimental setup. The comparative analysis validates the accuracy of the developed IoT-based real-time monitoring system and provides valuable insights into areas of further design optimization. The heat loss factor determines the rate at which thermal energy is lost to the surroundings under no-load conditions. It is a complex phenomenon involving a number of factors like material properties of the box (insulation, absorber plate, no of glazing), ambient conditions (solar radiation intensity, ambient temperature, wind speed). For this, there is a minor difference in the value of the heat loss factor between the present work and previous studies. Performance parameters like figures of merit, thermal efficiency, and heat loss factors are compared with standard literature and presented in tabular form (Table 1).

Table 1. Comparsion of performance parameters

Parameter	Present study	References
F_1	0.113	0.1-0.14 Singh et al. (2020) ≥ 0.12 (Solar Cookers International., n.d.)
F_2	0.41	0.1-0.14 Singh et al. (2020) ≤ 0.41 (Solar Cookers International., n.d.)
Thermal Efiiciency	29.98	≥ 25% (Solar Cookers International., n.d.)

Parameter	Present study	References
Heat Loss Factor	4.87	4.64 Singh et al. (2020)

The combined results demonstrate that the box-type solar cooker achieves reasonable efficiency levels for its design category. The optical efficiency (F1) is lower than the heat transfer efficiency (F2), suggesting that improvements to the glazing system could yield the most significant performance gains. The nearly 30% thermal efficiency indicates effective conversion of solar energy to cooking heat, while the heat loss factors identify opportunities for enhanced insulation.

Though the integration of the Internet of Things to box box-type solar cooker is encouraging, there are some challenges like sensor accuracy, battery life for field application, reliability of data transmission, and real-time monitoring in low connectivity regions. These limitations have significant potential for improvement. Box-type solar cookers operate outdoors and are thus exposed to high temperatures, humidity, wind, dust, and rain. If the IoT components are not designed to withstand such conditions, there is a chance of inaccuracy. Sensor accuracy affects the accuracy of the data collected. For Remote monitoring and data storage, reliable internet connectivity is necessary. Regular maintenance, like sensor calibration, can increase the life of IoT IoT-based solar cooker. Though battery lifespan is affected by temperature and charge-discharge cycles, a Small solar panel can be used to recharge batteries. Ensuring long-term reliability and robustness is crucial. The challenges can be addressed by careful consideration in the design and implementation phases, like selecting appropriate components to withstand harsh environments, robust power management solutions, reliable connective technology, proper sensor calibration, and positioning. By addressing the respective challenges, IoT can significantly contribute to the performance of box box-type solar cooker. In the future, this can facilitate better design, efficient usage, and wide adoption of this cooker. There are many places where potential improvement can be made. Advanced machine learning techniques can be applied to gain further insights into solar cooker performance, optimize energy usage, and detect maintenance issues. Study [20] has already found that the payback period is shorter when a solar cooker is used instead of wood or LPG. The integration of IoT can further reduce this.

The costs associated with adding IOT are very low. A temperature sensor, a Radiation sensor, and an ESP8266 microcontroller were purchased from the local market and used in this particular setup, which costs a thousand INR. Initial costs for designing IOT system include hardware costs and the cost of integrating hardware and software. Satellite-based IOT connectivity can be considered for remote areas. Open-source hardware and software platforms can be used for data storage, visualization, and analytics to reduce costs. A rechargeable battery has been used to power IOT components. Protective covering and necessary wiring have been done with minimal cost. While used on a large scale, the local community can be engaged in assembly and maintenance, and thus can create economic opportunity for the local community. The initial investments in sensors, communication modules, and power systems can increase the cost of the solar cooker. Though the initial cost is a little high, long-term viability, economic benefits with fuel savings, enhanced efficiency, better health outcomes, actual cost of deployment and maintenance, fuel savings and particularly a sustainable model with connectivity are to be noted. Government support and pilot projects can play a vital role in making IoT IoT-based box-type solar cooker economically feasible. Capitalizing on existing infrastructure, keeping an eye on the benefits of the integrated cooker, the IoT integration is the call of the day. There are many economic advantages, like real-time monitoring that optimizes cooking times, ensuring efficient energy use, and reducing the need for supplementary fuel.

4. Conclusion

The present project successfully demonstrated the design, real-time monitoring, and thermal performance evaluation of a box-type solar cooker integrated with IoT technology.

By utilizing DHT11, DS18B20, and MAX6675 thermocouple sensors connected to an ESP8266 NodeMCU, continuous and automated data acquisition was achieved. The collected data was efficiently transmitted to the ThingSpeak cloud platform, enabling real-time remote monitoring and detailed performance analysis.

Through multiple experimental trials, the cooker's thermal behavior was characterized using important parameters such as the First Figure of Merit (F_1), Second Figure of Merit (F_2), Thermal Efficiency (η), and Heat Loss Factor (U_L). The average values obtained were:

- $F_1 = 0.1137$ °C·m²/W,

- $F_2 = 0.4142$,
- Thermal Efficiency = 29.9809 %, and
- Heat Loss Factor = 4.88 W/m²°C,

thereby indicating satisfactory thermal performance for a simple, non-concentrating box-type cooker.

The integration of IoT technology significantly improved the accuracy, reliability, and accessibility of data, eliminating manual recording errors and enabling precise calculation of thermal parameters. Additionally, the system's cloud-based data logging enabled better visualization of trends, helping to correlate cooker performance with environmental conditions like solar irradiation and ambient temperature. IoT-based approach offers a breakthrough over traditional solar cooker evaluation methods by more precise, continuous data collection and comprehensive performance analysis. Real-time monitoring can transform traditional solar cooking to smart cooking with data-driven improvement. It can be concluded that IoT IoT-based box-type solar cooker can ease the way in moving from manual, intermittent, and limited data collection to continuous and comprehensive data collection along with remote monitoring and advanced analytical capabilities. This helps in a deeper understanding of box-type solar cooking in the real world. In the future, techniques to train AI models can be explored on decentralized data while preserving privacy

Thus, the project highlights that IoT-enabled solar cookers have the potential to not only enhance cooking efficiency but also serve as effective educational and research tools for thermal evaluation studies, promoting the development of smart renewable energy devices.

Nomenclatures:

T_{ps}	Plate Stagnation Temperature (°C)	τ	Time Interval
$\underline{T_a}$	Ambient temperature (°C)	T_{w1}	Initial temperature of water
G	Solar irradiance (W/m²)	T_{w2}	Final temperature of water
F_1	First Figure of Merit	U_L	Heat loss factor (W/m²°C)
F_2	First Figure of Merit	I	Solar irradiance (W/m2)
M_w	Mass of water (kg)	η_s	Measured Stagnation efficiency
C_w	Specific heat capacity of water (KJ/kgK)	T_{ps}	Maximum Absorber plate temperature
A	Absorber area (m2)		

Data availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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