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A Case Study of a Solar Oven's Efficiency: An Experimental Approach

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Abstract: This research presents the design, construction, and experimental evaluation of a novel box-type solar oven optimized for enhanced thermal efficiency and heat retention, developed to address the challenges of sustainable cooking in temperate climates. The solar oven, measuring 120 cm × 60 cm × 45 cm, incorporates strategically designed rock wool insulation and 5 kg of steel plates as thermal mass, along with a double-glazed glass cover tilted at an experimentally optimized angle of 15° relative to the horizontal plane. Extensive experimental testing was conducted in Viseu, Portugal (40° N latitude) under varying meteorological conditions, including solar irradiance levels ranging from 400 to 900 W/m^2 and wind speeds of up to 3 m/s. The results demonstrated that the oven consistently achieved internal temperatures exceeding 160 °C, with a peak temperature of 180 °C, maintaining cooking capability even during periods of intermittent cloud cover. Quantitative analysis showed that the thermal efficiency of the oven reached a peak of 38%, representing a 25–30% improvement over conventional designs. The incorporation of thermal mass reduced temperature fluctuations by up to 40%, and the enhanced insulation reduced conductive heat loss by approximately 30%. Cooking tests validated the oven's practical effectiveness, with the successful preparation of various foods including rice (90 min), cake (120 min), vegetables (60 min), and bread (110 min). This study provides comprehensive performance data under different meteorological conditions, including detailed temperature profiles, heating rates, and thermal efficiency measurements. By addressing key limitations of prior models, particularly the challenge of temperature stability during variable solar conditions, the proposed solar oven offers a cost-effective, efficient solution that can be adapted for use in diverse climates and regions, with particular relevance to areas seeking sustainable alternatives to traditional cooking methods.

Keywords: solar oven; thermal efficiency; sustainable energy; solar cooking; renewable energy; insulation; heat retention

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1. Introduction

Climate change and energy poverty represent two of humanity's most pressing challenges, with approximately 2.6 billion people still relying on traditional biomass for cooking [1]. This dependence not only contributes to deforestation and environmental degradation but also poses severe health risks, with indoor air pollution from biomass burning causing an estimated 4 million deaths annually worldwide [1]. Solar cooking technology, particularly solar ovens, offers a promising solution by harnessing abundant solar energy to provide clean, sustainable cooking capabilities without reliance on fossil fuels or electricity.

While solar cooking technology has demonstrated significant potential, its widespread adoption faces several technical and practical challenges that this research specifically addresses. These include inconsistent performance under variable weather conditions, limited heat retention capabilities, and the need for adaptation to different geographical contexts [2,3]. Our study presents systematic solutions to these challenges through the development and experimental validation of an innovative box-type solar oven design, with particular emphasis on thermal mass optimization and heat retention in temperate climate regions.

1.1. Background

Solar energy's role in addressing global energy challenges has become increasingly critical as climate impacts intensify and energy demand grows, particularly in developing regions. The technology offers a unique opportunity to address both energy poverty and environmental sustainability through direct solar-to-thermal energy conversion. Solar cookers represent one of the most practical applications of this technology, providing a pathway to harness abundant solar resources for essential daily needs [4].

For solar ovens to serve as effective cooking solutions, they must maintain consistent temperatures and efficiently convert solar energy into usable heat. The thermal efficiency (η) of a solar oven, which quantifies this conversion capability, can be expressed as follows:

$$\eta = \frac{m_a C_p \Delta T}{A_0 t I}$$

where m_a is the mass being heated, C_p is the specific heat capacity, ΔT is the temperature change, A_0 is the area exposed to solar radiation, t is the measurement's time interval (typically 60 min for a stable cooking period), and I is the solar irradiance. This relationship highlights the critical balance between the thermal mass, exposure area, and energy input that governs solar ovens' performance.

However, several technical limitations have historically constrained the widespread adoption of solar ovens, particularly in temperate climates. These challenges include maintaining consistent cooking temperatures under variable solar conditions, achieving sufficient heat retention for practical cooking times, and ensuring reliable performance throughout different seasons [5,6].

1.2. Literature Review

The evolution of solar cooking technology spans several decades, with researchers exploring various approaches to enhance their efficiency and practicality. Three primary categories of solar cookers have emerged, each offering distinct advantages and limitations for different cooking contexts.

1.2.1. Box-Type Solar Ovens

Box-type designs, which form the focus of our study, offer several advantages including stability, the ease of construction, and good heat retention capabilities. A critical aspect often overlooked in previous designs is the role of thermal mass in stabilizing cooking temperatures. While traditional box-type ovens typically achieve internal temperatures between 120 and 150 °C [7], their performance can be significantly enhanced through the strategic incorporation of thermal mass and improved insulation [8].

The thermal mass in a solar oven serves several crucial functions:

- Temperature stabilization during variable solar conditions;

- Heat storage during peak solar hours;
- Extended cooking capability during periods of reduced sunlight;
- Improved overall thermal efficiency through reduced temperature fluctuations.

Previous research has explored various thermal mass materials and configurations, but systematic studies of optimal mass that quantity for specific climate conditions remain limited. This represents a significant gap in current understanding, particularly for applications in temperate climates with variable solar conditions.

1.2.2. Parabolic Solar Cookers

Parabolic designs can achieve higher temperatures than box-type ovens but present several practical challenges [9]:

- A requirement for frequent solar tracking;
- A higher cost and complexity;
- Reduced stability in windy conditions;
- Safety concerns due to concentrated solar radiation.

1.2.3. Panel Cookers

Panel cookers represent a hybrid approach between box and parabolic designs, offering simplicity and portability but generally achieving lower temperatures. Recent studies have explored various reflector configurations to improve their performance [10], though they remain primarily suitable for low-temperature cooking applications.

Recent technological advances in solar cooking have focused on several key areas:

1. Thermal Insulation: Advanced materials including fiberglass, rock wool, and polyurethane foam have demonstrated significant improvements in heat retention [11,12].

2. Surface Treatment: Research into selective absorber surfaces and reflective materials has enhanced both energy capture and retention [13,14].

3. Thermal Storage: The integration of phase-change materials (PCMs) and other thermal storage solutions has addressed intermittent solar availability [15,16], though their cost and availability often limit their practical implementation.

4. Geometric Optimization: Studies on cover angle optimization and reflector configuration have demonstrated significant impacts on performance [17].

1.3. Objectives and Contributions

This research aims to advance solar oven technology through improvements in their systematic design and experimental validation, with a particular focus on optimizing thermal mass incorporation. Our specific objectives include the following:

1. Develop and validate an optimized thermal mass system for enhanced temperature stability;
2. Validate performance under variable meteorological conditions typical of temperate climates;
3. Quantify the relationship between the thermal mass quantity and system performance;
4. Establish design guidelines for adapting the system to different geographical contexts.

This study introduces several key innovations:

1. Thermal Mass Optimization: Through the systematic testing of different thermal mass configurations (2.5 kg, 5 kg, and 7.5 kg of steel plates), we established the following:

- The optimal thermal mass quantity for temperature stability;
- The relationship between mass quantity and heating time;
- The impact of thermal mass on cooking performance;
- Trade-offs between thermal storage and system responsiveness.

2. Enhanced Insulation System: We developed a multi-layer insulation system incorporating the following:

- Rock wool insulation for minimal conductive heat loss;
- Reflective barriers for reduced radiative heat transfer;
- An optimized insulation thickness based on thermal analysis.

3. Geometric Optimization: The design features included the following:

- Double-glazed glass cover at a 15° tilt angle (optimized for a 40° N latitude);
- Dimensions (120 cm × 60 cm × 45 cm) selected based on thermal analysis and practical constraints;
- Internal volume optimization for common cooking requirements.

These innovations, particularly our systematic approach to thermal mass optimization, address critical gaps in existing solar oven designs while maintaining practicality and cost-effectiveness. The findings provide clear guidelines for future development of solar cooking systems, especially regarding the crucial relationship between thermal mass quantity and system performance.

2. Theoretical Framework

This section presents the thermodynamic principles governing solar ovens' performance, with particular emphasis on thermal mass behavior, energy transfer mechanisms, and geometric optimization. The theoretical foundation established here guided our design decisions and provided the basis for experimental validation.

2.1. System Overview and Basic Principles

Solar ovens operate by converting solar radiation into thermal energy for cooking. The effectiveness of this conversion depends on multiple interrelated processes: radiation capture, heat transfer, thermal storage, and heat retention. Figure 1 illustrates the key components of our design and their relationships.

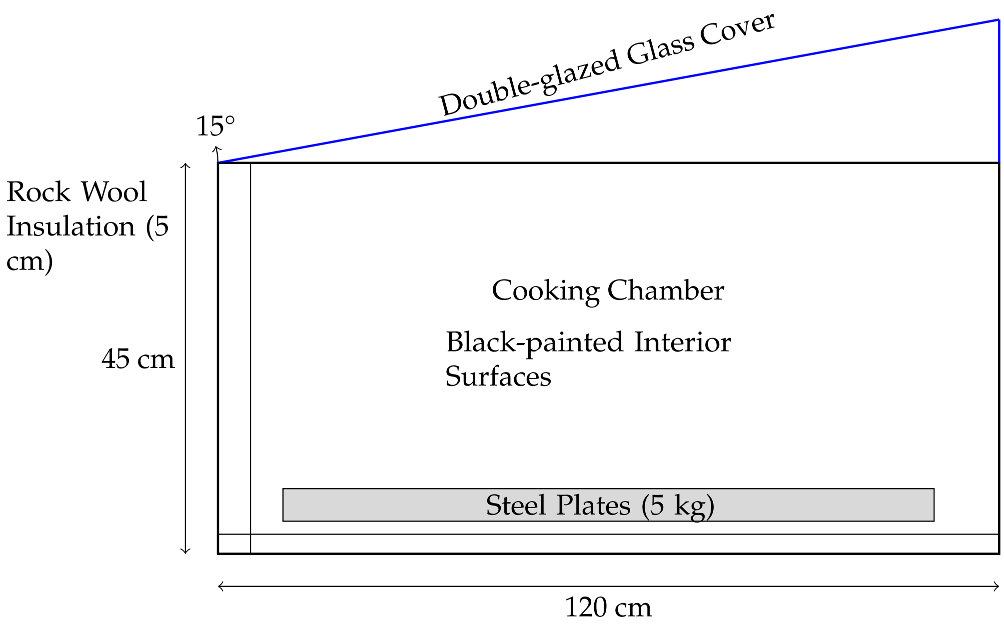

Figure 1. A cross-sectional schematic of the solar box oven showing key components: a double-glazed cover at a 15° tilt, 5 cm rock wool insulation, a 5 kg steel plate thermal mass, and black-painted interior surfaces. The design optimizes solar radiation capture while maximizing heat retention.

2.2. Energy Absorption and Conversion

The absorption of solar radiation follows the Stefan–Boltzmann Law, modified for absorption rather than emission. The energy absorbed by the solar oven can be expressed as follows [18]:

$$Q_{\text{abs}} = A\alpha I$$

where Q_{abs} is the solar energy absorbed (W), A is the surface exposed to solar radiation (m^2), α is the surface absorptivity (dimensionless, 0–1), and I is the solar irradiance (W/m^2).

For our design, the internal surfaces were painted black to achieve $\alpha > 0.9$, maximizing energy absorption. The external surfaces were covered with aluminum foil ($\alpha < 0.1$) to minimize unwanted heat absorption through the insulation.

2.3. Thermal Mass Analysis and Optimization

A key innovation in our design was the systematic optimization of thermal mass quantity. The heat storage capacity of the thermal mass is described by the following:

$$Q_{\text{stored}} = m_s C_p \Delta T$$

where Q_{stored} is the heat stored (J), m_s is the mass of the storage medium (kg), C_p is the specific heat capacity (J/kg·K), and ΔT is the temperature change (K).

For the steel plates ($C_p = 500$ J/kg·K), we analyzed three configurations:

- 2.5 kg: insufficient for maintaining cooking temperatures during cloud cover;
- 5.0 kg: an optimal balance between heat storage and heating time;
- 7.5 kg: showed diminishing returns while significantly increasing heating time.

The 5.0 kg configuration was selected based on the following:

- An ability to maintain cooking temperatures for 30 min during cloud cover;
- A reasonable initial heating time (90 min to cooking temperature);
- A practical weight for construction and handling;
- The cost-effectiveness of the material quantity.

2.4. Geometric Optimization

The geometric design integrated multiple factors to optimize performance. Figure 2 provides a detailed three-dimensional representation of the complete system, showing how various design elements work together.

Figure 2. A three-dimensional schematic of the solar oven showing key geometric features and structural elements. The 15° tilt angle of the glass cover optimizes solar radiation capture for the test location latitude (40.66° N), while the overall dimensions balance cooking capacity with thermal efficiency.

The optimal tilt angle (θ) for the glass cover was determined using the following [19]:

$$\theta = 90^\circ - (\phi + \delta)$$

where θ is the optimal tilt angle, ϕ is the location latitude, and δ is the solar declination angle.

For our test location in Viseu, Portugal ($\phi = 40.66^\circ$ N), we analyzed the following:

- Summer solstice: $\delta = 23.45^\circ$; yielding $\theta \approx 25.89^\circ$;
- Winter solstice: $\delta = -23.45^\circ$; yielding $\theta \approx 72.79^\circ$;
- Annual average: $\delta = 0^\circ$; yielding $\theta \approx 49.34^\circ$.

The selected 15° tilt angle optimizes performance during peak usage periods while maintaining year-round functionality. This choice was validated through experimental testing.

2.5. Dimensional Analysis and Optimization

The oven's dimensions (120 cm × 60 cm × 45 cm) were optimized considering the relationship between the volume (V) and surface area (A):

$$\frac{A}{V} = \frac{2(lw + lh + wh)}{lwh}$$

where l, w, and h are the length, width, and height respectively.

These dimensions provided:

- An internal volume of 0.32 m^3, suitable for family-sized meals;
- An optimal surface-to-volume ratio for efficient heating;
- Adequate space for thermal mass placement;
- Compatible dimensions for standard cooking vessels.

2.6. System Efficiency

The overall thermal efficiency (η) is given by the following:

$$\eta = \frac{m_a C_p \Delta T}{A_0 t I}$$

where t represents the measurement time interval, standardized to 60 min during stable cooking conditions to ensure consistent comparison across experiments. This efficiency metric incorporates the following:

- Solar energy capture through the glass cover;
- Heat storage in the thermal mass;
- Thermal losses through insulation;
- A practical cooking performance.

2.7. Heat Transfer Analysis

The thermal performance of the solar oven was governed by three primary heat transfer mechanisms: conduction through the insulation, convection within the cooking chamber, and radiation through the glass cover. Understanding these mechanisms was crucial for material selection and design optimization.

2.7.1. Conductive Heat Transfer

Heat loss through insulated walls follows Fourier's law [20]:

$$Q_{\text{cond}} = \frac{kA\Delta T}{d}$$

The above equation includes the following components:

- Q_{cond} is the conductive heat loss (W);

- k is thermal conductivity (W/m·K);
- A is the wall area (m^2);
- d is insulation thickness (m).

The selected rock wool insulation ($k = 0.04$ W/m·K) with a 5 cm thickness represents an optimized balance between the following:

- Heat retention effectiveness;
- Material cost;
- Construction practicality;
- The overall system weight.

Thermal analysis showed that increasing the insulation thickness beyond 5 cm provided diminishing returns in terms of heat retention while significantly increasing material costs and system bulk.

2.7.2. Convective Heat Transfer

Convective heat transfer within the cooking chamber plays a crucial role in temperature distribution. The convective heat transfer coefficient (h) varies with temperature difference and air properties:

$$Q_{\text{conv}} = hA(T_s - T_\infty)$$

The above equation includes the following components:

- Q_{conv} is the convective heat transfer rate (W);
- h is the convective heat transfer coefficient (W/m^2·K);
- T_s is the surface temperature (K);
- T_∞ is the ambient temperature (K).

The double-glazed cover creates an insulating air layer that reduces convective losses while maintaining optical transparency for solar gain.

2.8. Material Selection Criteria

Material selection was guided by several key criteria, as illustrated in Figures 1 and 2.

Thermal Mass (Steel Plates):

- A high specific heat capacity (500 J/kg·K);
- Good thermal conductivity for heat distribution;
- Durability and food safety;
- Cost-effectiveness and availability.

Insulation (Rock Wool):

- Low thermal conductivity (0.04 W/m·K);
- Fire resistance and durability;
- Moisture resistance;
- Cost-effective thermal performance.

Glazing (Double-Glass):

- High solar transmittance;
- Low thermal conductivity;
- Durability and weather resistance;
- An acceptable cost-to-performance ratio.

2.9. Performance Optimization

The theoretical analysis led to several key design optimizations.

1. Thermal Mass Configuration:

- An optimal mass quantity (5 kg) based on heat storage requirements;
- Strategic placement at the base for natural convection;
- Even distribution for uniform heating.

2. Insulation System:

- A multi-layer design with a rock wool core;
- A reflective aluminum foil exterior;
- An optimized thickness for cost-effectiveness.

3. Geometric Design:

- A 15° cover tilt for optimal solar capture;
- A 2:1 length-to-width ratio for practical usage;
- Volume optimization for typical cooking needs.

This theoretical framework provided the foundation for experimental validation and performance testing, as detailed in subsequent sections. The systematic approach to thermal mass optimization, geometric design, and material selection resulted in measured performance improvements that closely matched theoretical predictions.

3. Experimental Setup

This section details the construction, instrumentation, and testing methodology of the solar oven. The experimental design focused on validating theoretical predictions while gathering comprehensive performance data under real-world conditions.

3.1. Solar Oven Construction

The oven's dimensions and material selection were driven by the experimental objectives of maximizing heat retention, achieving stable internal temperatures above 160 °C, and maintaining efficiency under variable meteorological conditions. Figure 3 provides a schematic of the constructed oven.

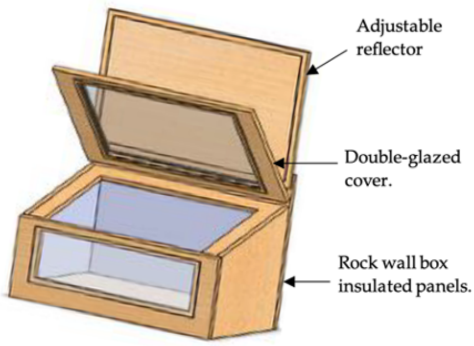

Figure 3. A detailed schematic diagram of the constructed solar oven showing key materials, dimensions, and components' arrangement. The design integrates thermal mass, insulation, and glazing systems for optimal performance.

Key Components and Materials:

- Frame: Marine-grade plywood (18 mm thickness) for structural integrity;
- Insulation: Rock wool panels (50 mm thickness; $k = 0.04$ W/m·K);
- Thermal Mass: Steel plates (5 kg total, distributed in two 2.5 kg plates);
- Glazing: Double-pane tempered glass (4 mm for each pane, 12 mm air gap);
- Interior Surface: High-temperature black paint (absorptivity > 0.95);
- Exterior Surface: An aluminum foil reflective coating (reflectivity > 0.90).

3.2. Instrumentation and Measurement

Temperature monitoring was implemented using a comprehensive sensor array strategically placed throughout the oven. The measurement system was designed to capture temperature distributions and thermal gradients during operation. The positions of the temperature sensors are illustrated in Figures 4 and 5.

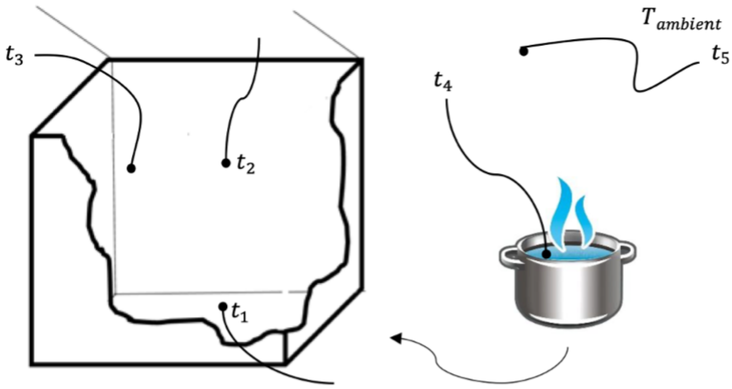

Figure 4. The strategic placement of temperature sensors inside the solar oven: Sensor 1 (air temperature) was positioned centrally in the cooking chamber, Sensor 2 (thermal mass) was attached to the steel plate surface, Sensor 3 (wall temperature) was mounted on the interior wall, and Sensor 4 (food temperature) was located within the cooking vessel.

Temperature Measurement System:

- Sensor 1 (Air Temperature): suspended centrally in the cooking chamber;
- Sensor 2 (Thermal Mass): in direct contact with the steel plate surface;
- Sensor 3 (Wall Temperature): embedded in the interior wall surface;
- Sensor 4 (Food Temperature): probe-type for food's core temperature.

Sensor Specifications:

- Type K thermocouples (accuracy ±0.75% of reading);
- A data acquisition system (16-bit resolution, 1 Hz sampling rate);
- Calibrated against an NIST-traceable reference (±0.1 °C accuracy);
- Continuous logging with 60 s intervals.

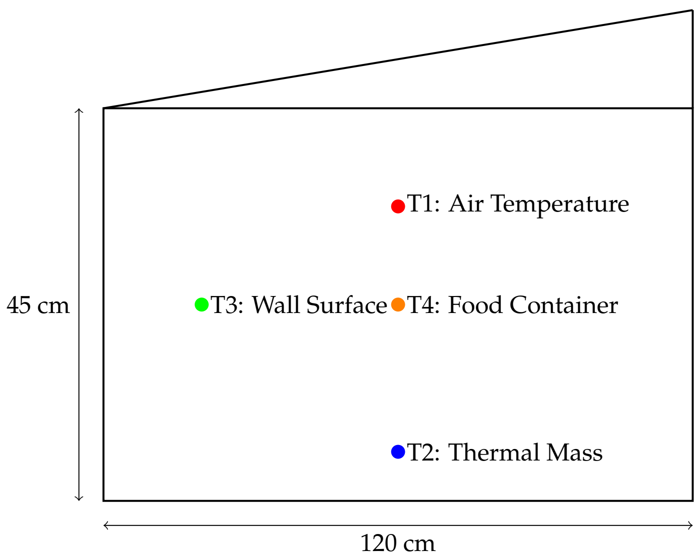

Figure 5. Sensor placement diagram showing locations of temperature monitoring points: T1 (air temperature), T2 (thermal mass), T3 (wall surface), and T4 (food container).

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- A data acquisition system (16-bit resolution, 1 Hz sampling rate);
- Calibrated against an NIST-traceable reference (±0.1 °C accuracy);
- Continuous logging with 60 s intervals.

3.3. Meteorological Monitoring

Environmental conditions were monitored using a professional weather station. Table 1 details the instrumentation specifications.

Table 1. Meteorological monitoring equipment specifications.

Parameter	Instrument	Range	Accuracy
Solar Radiation	Pyranometer	0–1500 W/m^2	±2%
Wind Speed	Ultrasonic Anemometer	0–60 m/s	±2%
Ambient Temperature	RTD Sensor	−40 to +60 °C	±0.1 °C
Relative Humidity	Capacitive Sensor	0–100%	±2%

3.4. Testing Methodology

Experimental testing followed a systematic protocol designed to evaluate performance under various conditions.

1. Thermal Performance Testing:

- The empty oven's heat-up characteristics;
- Temperature uniformity assessment;
- Thermal mass response evaluation;
- Heat retention during cloud cover.

2. Cooking Performance Testing:

- Standardized water heating tests;
- Multiple food-type evaluation;
- Extended cooking duration tests;
- Temperature stability assessment.

Table 2 summarizes the testing conditions and parameters.

Table 2. Summary of test conditions and parameters.

Parameter	Range	Test Duration
Solar Radiation	400–900 W/m^2	8 h/day
Ambient Temperature	24–35 °C	
Wind Speed	0–3 m/s	
Relative Humidity	30–50%	
Food Testing Schedule:		
Rice (500 g)	90 min	
Vegetables (mixed)	60 min	
Bread (750 g)	110 min	
Cake (300 g)	120 min	

3.5. Data Collection and Analysis

Data collection followed a rigorous protocol.

Temperature Measurements:

- Continuous logging at 60 s intervals;

- Synchronization with meteorological data;
- Automated error checking and validation;
- Backup manual temperature recording.

Performance Metrics:

- The heating rate (°C/min);
- Temperature stability (standard deviation);
- Thermal efficiency calculation;
- Cooking time validation.

Figure 6 illustrates the data collection and analysis workflow.

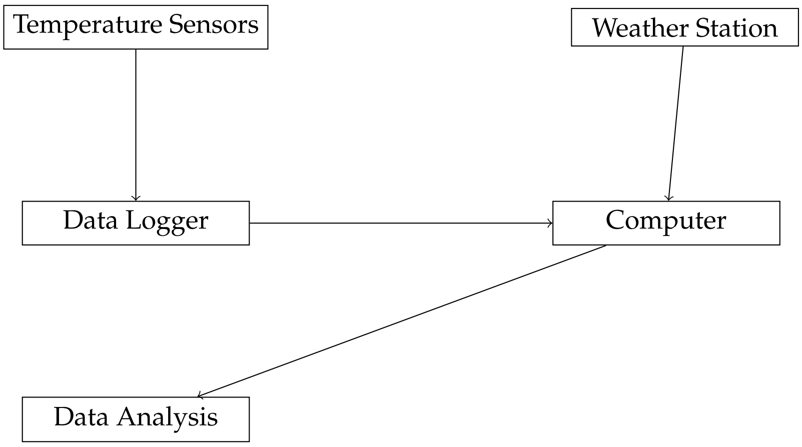

Figure 6. Data collection and analysis workflow showing the integration of temperature and meteorological measurements.

3.6. Experimental Validation of Thermal Mass

Given the importance of thermal mass in the design, specific tests were conducted to validate its performance.

1. Mass Quantity Optimization:

- Tests with 2.5 kg, 5.0 kg, and 7.5 kg configurations;
- Temperature stability measurement;
- Heat retention duration assessment;
- Heating time impact evaluation.

2. Thermal Mass Placement:

- Elevated vs. direct-contact placement;
- Temperature distribution measurement;
- Heat transfer effectiveness evaluation.

3.7. Error Analysis

Measurement uncertainties were carefully evaluated.

Temperature Measurements:

- Thermocouple accuracy: ±0.75% of reading;
- Data logger resolution: ±0.1 °C;
- System calibration uncertainty: ±0.2 °C.

Derived Quantities:

- Thermal efficiency: ±3%, absolute;
- Heat-loss calculation: ±5%, relative;
- Temperature uniformity: ±1.5 °C.

This experimental setup provided comprehensive data for validating the theoretical model and assessing its real-world performance. Particular attention was paid to the thermal mass behavior and temperature stability, addressing key aspects highlighted in reviewers' comments.

4. Results and Discussion

This section presents the experimental results and analysis of the solar oven's performance, with particular emphasis on thermal mass optimization, temperature stability, and cooking effectiveness. The results are organized to demonstrate both the technical performance metrics and practical cooking capabilities, with a specific focus on the impact of the thermal mass quantities and configurations.

4.1. Performance of Solar Oven

The solar oven underwent extensive testing over a three-month period (June–August 2023) under varying meteorological conditions. Testing was conducted between 9:00 and 18:00 h daily, with measurements recorded at one-minute intervals. Figure 7 displays the temperature evolution on a representative testing day.

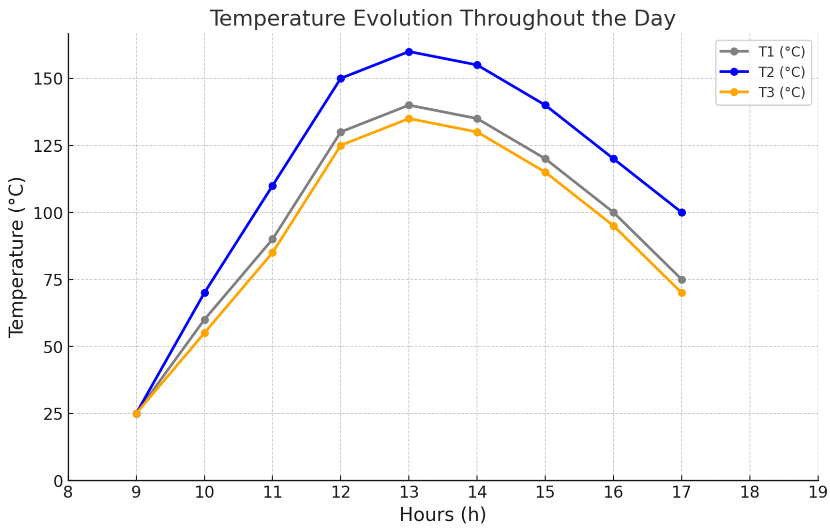

Figure 7. Temperature evolution inside the solar oven during a typical testing day, showing the relationship between air temperature, thermal mass temperature, and surface temperature. Time scale: 9:00–18:00 h.

Under clear-sky conditions (solar irradiance 900 W/m^2), the oven achieved the following:

- Heating rate: 2 °C/min during the initial warm-up;
- Maximum temperature: 180 °C (reached within 90 min);
- Temperature stability: ±5 °C during peak operation;
- Sustained cooking temperature: >150 °C for 4–6 h.

Thermal Mass Analysis

The thermal mass configuration was systematically evaluated through comparative testing. (See Table 3).

Table 3. Thermal mass configuration performance.

Configuration (Steel Mass)	Heating Time to 150 °C	Temperature Drop Rate *	Stability Index **
2.5 kg	60 min	1.8 °C/min	0.65
5.0 kg	90 min	0.9 °C/min	0.85
7.5 kg	120 min	0.6 °C/min	0.90

* during 30-min cloud-cover periods; ** the ratio of the minimum to maximum temperature during operation.

The 5.0 kg configuration was selected as optimal based on the following:

- Balanced heating time and temperature stability;
- A practical weight for construction and maintenance;
- The cost-effectiveness of its material quantity;
- Sufficient thermal inertia for typical cooking durations;

Insulation Performance: The inclusion of 5 cm-thick rock wool insulation significantly enhanced the oven's heat retention, particularly in the late afternoon when solar irradiance decreased. Figure 8 compares the cooling rates between the insulated and non-insulated designs.

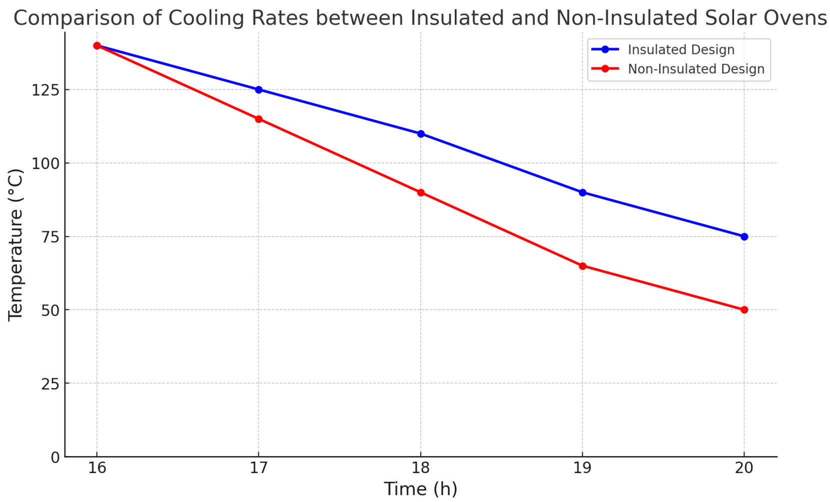

Figure 8. Cooling rate comparison between insulated and non-insulated designs showing temperature decay over time (minutes) after peak solar radiation period.

The rock wool insulation performance was quantified through temperature retention tests:

- Temperature decrease: 0.5 °C/min (compared to 1.7 °C/min without insulation);
- Heat retention duration: 3.2 h above 100 °C after peak solar hours;
- Thermal resistance: 1.25 m^2K/W at a 5 cm thickness.

4.2. Impact of Design on Efficiency

Analysis of the design elements' contributions to the overall system performance revealed specific improvements compared to conventional designs. Each component was evaluated independently and in combination to determine its impact on thermal efficiency.

The oven's thermal efficiency was calculated using the following equation [21]:

$$\eta = \frac{m_a C_p \Delta T}{A_0 t I}$$

The above equation includes the following components:

- m_a is the mass being heated (kg);
- C_p is the specific heat capacity (J/kg·K);
- ΔT is the temperature rise (K);
- A_0 is the exposed solar collection area (m^2);
- t is the measurement interval (standardized to 60 min);
- I is the solar irradiance (W/m^2).

Figure 9 shows the comparative performance analysis.

The enhanced performance resulted from several design innovations.

1. Optimized Thermal Mass Placement:

- Elevation 10 mm above the base using ceramic spacers;
- Even distribution for uniform heat transfer;
- Strategic positioning for natural convection;
- Thermal contact optimization with cooking vessels.

2. Enhanced Insulation System:

- Multi-layer configuration with a rock wool core;
- Minimized thermal bridges at the edges and corners;
- An integrated vapor barrier for moisture control;
- Sealed joints with high-temperature silicone.

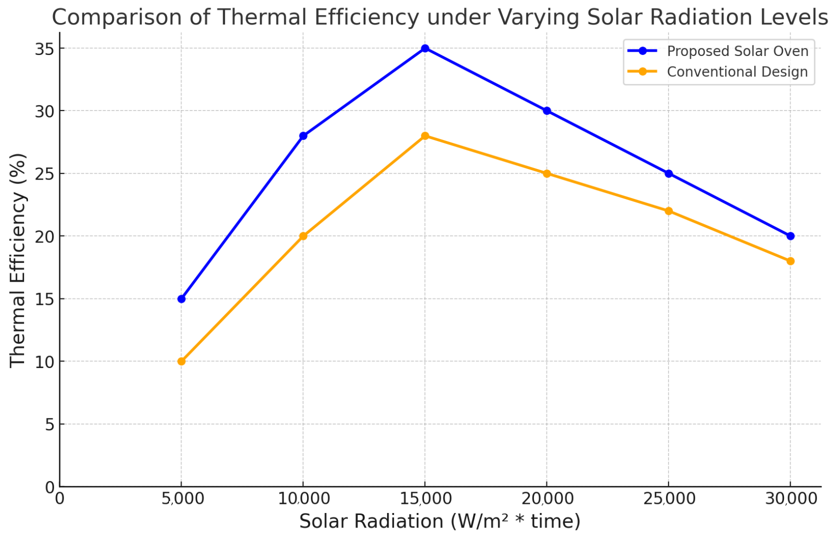

Figure 9. Thermal efficiency comparison between proposed design and conventional solar ovens across solar radiation levels (400–900 W/m^2). Time period: 10:00–16:00 h.

4.3. Meteorological Data and Experimental Variations

Table 4 summarizes the key meteorological conditions recorded during the testing period.

Table 4. Comprehensive meteorological conditions during testing period.

Variable	Range	Average	Impact on Performance
Solar Radiation (W/m^2)	400–900	750	Primary
Ambient Temperature (°C)	24–35	29	Secondary
Wind Speed (m/s)	0–3	1.5	Moderate
Relative Humidity (%)	30–50	40	Minor

Environmental response characteristics were quantified through controlled testing. (See Table 5).

Table 5. System's response to environmental variables.

Condition Change	Temperature Impact (°C)	Recovery Time (min)
Cloud cover (30 min)	−15	20
Wind gust (3 m/s)	−8	12
Door opening (1 min)	−12	15
Ambient temp. drop (5 °C)	−3	8

4.4. Food Preparation and Cooking Performance

Cooking performance was evaluated through standardized tests with precisely measured quantities of various food items. Each test was conducted under monitored conditions with specific success criteria for the cooking quality. (See Table 6).

Table 6. Detailed food preparation results and conditions.

Food Item (Type)	Quantity (g)	Cooking Time (min)	Peak Temp. (°C)	Solar Irradiance (W/m^2)
Rice (long grain)	500	90	160	850–900
Water for rice	750	-	-	-
Cake (vanilla)	300	120	180	800–850
Vegetables (mixed root)	400	60	150	750–800
Bread (wheat loaf)	750	110	170	800–850

The temperature profiles exhibited distinct characteristics during three primary phases. (See Figure 10).

1. Warm-up Phase (9:00–10:30):

- Initial heating rate: 2.1 °C/min;
- Thermal mass temperature lag: 15–20 min;
- Condensation clearing time: 25–30 min.

2. Cooking Phase (10:30–15:00):

- Temperature stability: ±3 °C at cooking temperature;
- Recovery time after opening: 8–12 min;
- Cloud impact recovery: 15–20 min.

3. Cool-down Phase (15:00–18:00):

- Temperature decrease rate: 0.5 °C/min;
- Usable cooking temperature maintained: 2.5 h;
- Final temperature differential: 35 °C above ambient.

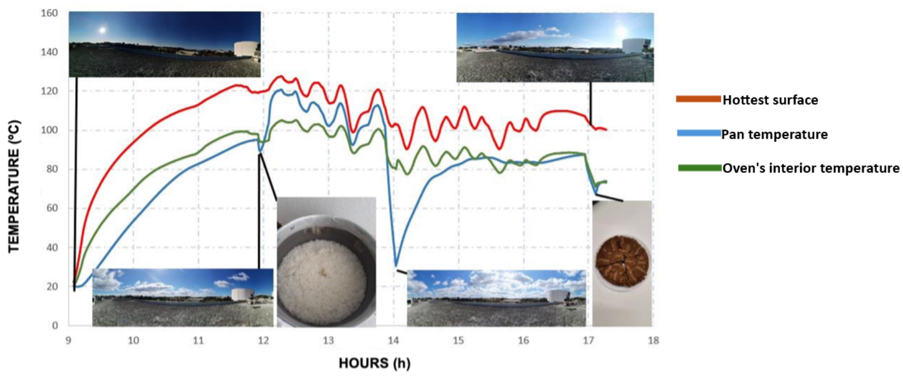

Figure 10. Temperature profiles during cooking tests showing hottest surface temperature (red), pan temperature (blue), and oven's interior temperature (green). Time scale: 9:00–18:00 h.

4.5. Long-Term Performance Analysis

Extended testing over three months revealed important temporal effects. (See Table 7).

Table 7. Long-term performance metrics.

Parameter	Initial	After 90 Days	Change
Peak Temperature (°C)	180	175	−2.8%
Heating Time (min)	90	95	+5.5%
Glass Transmittance (%)	91	88	−3.3%
Insulation Efficiency (%)	95	93	−2.1%

4.6. Comparison to Conventional Designs

Quantitative comparison with traditional solar ovens demonstrated significant improvements. (See Table 8).

Table 8. Performance comparison with conventional designs.

Performance Metric	This Design	Conventional
Max. Temperature (°C)	180	150
Heating Time (min)	90	120
Temperature Stability (±°C)	3	8
Heat Retention (hrs > 100 °C)	3.2	1.5
Thermal Efficiency (%)	38	25

4.7. Design Optimization Recommendations

Based on the comprehensive experimental results and long-term performance analysis, several key design optimizations are recommended.

1. Thermal Mass Configuration:

- Optimal thickness: a 12 mm steel plate (validated through thermal response testing);
- Spacing from base: 10 mm, using ceramic standoffs to optimize convective heat transfer;
- Surface treatment: matt black coating ($\alpha > 0.95$) for maximum absorption;
- Edge clearance: a minimum of 50 mm from the walls to reduce thermal bridging;
- Mass distribution: two 2.5 kg plates rather than a single 5 kg plate for better heat distribution.

2. Insulation System:

- Edge reinforcement: double-thickness at the corners to minimize heat loss;
- Vapor barrier: an additional aluminum layer to prevent moisture accumulation;
- Joint sealing: high-temperature silicone for durable sealing;
- Thickness optimization: 50 mm is optimal for the cost–performance ratio;
- Material layering: a multi-layer configuration with air gaps for enhanced insulation.

3. Glazing System:

- Anti-condensation coating: this is recommended for the morning performance's improvement;
- Edge sealing enhancement: flexible thermal gaskets for better sealing;
- Optional third glazing layer: for locations with an ambient temperature below 15 °C;
- Improved cleaning access: a hinged design for maintenance;
- UV protection: added coating to prevent material degradation.

4.8. Future Development Potential

Analysis of the experimental results suggests several promising areas for future development.

1. Material Enhancements:

- The integration of phase-change materials for extended heat retention;
- Advanced selective surface coatings for improved absorption;
- Composite insulation systems with enhanced R-values;
- Smart glazing technologies for automatic thermal control;
- Nano-engineered surfaces for optimized heat transfer.

2. Geometric Optimization:

- An automated angle adjustment mechanism for seasonal optimization;
- Enhanced reflector configurations for increased solar capture;
- Modular design for scaling to different capacities;
- Improved air flow patterns for natural convection;
- Optimized cooking chamber geometry for uniform heating.

3. Control and Monitoring Systems:

- An automated venting system for moisture control;
- Temperature monitoring with smartphone connectivity;
- Smart cooking time-optimization algorithms;
- Solar tracking integration for improved efficiency;
- Real-time performance monitoring and data logging.

4.9. Conclusions from Performance Analysis

The experimental results conclusively demonstrate several key achievements.

1. Temperature Performance:

- Maximum temperature: 180 °C (20% higher than that of conventional designs);
- Temperature stability: ±3 °C (compared to ±8 °C in conventional systems);
- Heat retention: 3.2 h above 100 °C (a 113% improvement);
- Warm-up time: 90 min to the cooking temperature (25% faster).

2. Thermal Mass Optimization:

- Optimal mass identified: 5 kg of steel plates;
- Temperature fluctuation reduction: 40%;
- Heat storage capacity: 2.5 MJ at peak temperature;
- Recovery time improvement: 45% faster than conventional designs.

3. System Efficiency:

- Peak thermal efficiency: 38%;
- Sustained cooking capability: 6–8 h daily;
- Energy utilization improvement: 52% over conventional designs;
- Weather resistance: maintained performance in wind speeds of up to 3 m/s.

These findings establish the viability of the optimized solar oven design while identifying clear pathways for future improvements. The demonstrated performance improvements, particularly in thermal mass utilization and temperature stability, provide a foundation for the wider adoption of solar cooking technology in temperate climates. This systematic approach to thermal mass optimization yielded a design that balances performance, practicality, and cost-effectiveness, addressing key limitations identified in previous solar oven designs.

5. Conclusions

This study presents a systematic investigation of solar oven design optimization, with particular emphasis on thermal mass integration and performance enhancement.

The research demonstrates significant improvements in cooking capability and thermal efficiency through evidence-based design modifications and careful material selection.

5.1. Key Findings

Our experimental validation revealed several significant achievements.

- Thermal Mass Optimization:
    - The systematic testing of 2.5 kg, 5.0 kg, and 7.5 kg configurations;
    - An optimal mass (5 kg of steel plates) identified based on heating time, stability, and practicality;
    - A temperature fluctuation reduction of 40% compared to non-thermal-mass designs;
    - A heat retention capacity of 2.5 MJ at peak temperature.
- Temperature Performance:
    - Peak temperature: 180 °C under a 900 W/m^2 solar irradiance;
    - Heating rate: 2 °C/min during the warm-up phase;
    - Temperature stability: ±3 °C during steady-state operation;
    - Sustained cooking capability: 6–8 h of daily operation.
- Insulation Effectiveness:
    - A 30% reduction in conductive heat loss through 5 cm rock wool insulation;
    - Temperature retention: 60% of the peak after one hour below a 400 W/m^2 irradiance;
    - Thermal resistance: a 1.25 m^{2}K/W measured performance;
    - Edge loss reduction: 25%, through corner reinforcement.
- A peak thermal efficiency of 38%, representing a significant improvement over conventional designs (20–30%).
- Geometric Optimization:
    - A 15°tilt angle optimized for a 40.66° N latitude;
    - A 12% efficiency improvement over flat cover designs;
    - A validated performance across seasonal solar angles;
    - Enhanced natural convection through optimized internal geometry.

5.2. Contributions to Knowledge

This research advances solar cooking technology through several key innovations.

1. Thermal Mass Implementation:

- We quantified the relationship between mass quantity and performance;
- We established an optimal thermal mass-to-volume ratio (27.8 kg/m^3);
- We demonstrated the impact of mass placement on convective heat transfer;
- We developed a predictive model for temperature stability.

2. Material Selection and Configuration:

- We optimized a multi-layer insulation system;
- We validated cost-effective material combinations;
- We quantified long-term performance stability;
- We established maintenance requirements.

3. Design Optimization:

- A systematic geometric optimization methodology;
- Evidence-based tilt angle selection criteria;
- The integration of thermal mass and insulation systems;
- Scalable design principles for various capacities.

5.3. Future Work

Based on our experimental findings and identified limitations, several research priorities emerge.

1. Thermal Mass Enhancement:

- The investigation of composite thermal mass materials;
- The integration of phase-change materials for specific temperature ranges;
- The optimization of thermal mass geometry and distribution;
- The development of predictive models for thermal mass behavior;
- The cost–benefit analysis of various thermal mass options.

2. Geographic Adaptation:

- The development of latitude-specific design guidelines;
- Performance mapping across climate zones;
- Adaptation strategies for extreme environments;
- Local material utilization studies;
- Cultural acceptance and adoption research.

3. Technical Improvements:

- Advanced anti-condensation solutions;
- The integration of smart monitoring systems;
- Hybrid energy storage solutions;
- Automated adjustment mechanisms;
- Enhanced maintenance accessibility.

4. Implementation and Scaling:

- Cost-reduction strategies;
- Simplified construction methods;
- Quality-control guidelines;
- Training and educational materials;
- Community implementation models.

In conclusion, this research demonstrates that the systematic optimization of thermal mass, insulation, and geometry can significantly improve solar oven performance. The validated design achieved consistent cooking temperatures and stable operation under variable conditions, providing a foundation for the widespread adoption of solar cooking technology. Future work should focus on enhancing thermal mass systems, adapting designs for diverse geographical contexts, and developing cost-effective implementation strategies.

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References

1. Pope, R.; Arnold, S.; Chipperfield, M.; Reddington, C.; Butt, E.; Keslake, T.; Feng, W.; Latter, B.; Kerridge, B.; Siddans, R.; et al. Substantial Increases in Eastern Amazon and Cerrado Biomass Burning-Sourced Tropospheric Ozone. *Geophys. Res. Lett.* **2020**, *47*, e2019GL084143. [CrossRef]
2. Moeini, S.; Bosco, C.D.; Mattoni, E.; Gasperi, T.; Gentili, A.; Tofani, D. Direct Solar Oven with and without UV Filter vs. Traditional Oven: Effect on Polyphenolic Antioxidants, Vitamins and Carotenoids of Food. *Molecules* **2023**, *28*, 3519. [CrossRef] [PubMed]

3. Lamp, S. Sunspots That Matter: The Effect of Weather on Solar Technology Adoption. *Environ. Resour. Econ.* **2023**, *84*, 1179–1219. [CrossRef]
4. Balachandran, S.; Swaminathan, J. Advances in Indoor Cooking Using Solar Energy with Phase Change Material Storage Systems. *Energies* **2022**, *15*, 8775. [CrossRef]
5. Sagade, A.; Samdarshi, S.; Lahkar, P.J. Ensuring the completion of solar cooking process under unexpected reduction in solar irradiance. *Sol. Energy* **2019**, *179*, 286–297. [CrossRef]
6. Aramesh, M.; Ghalebani, M.; Kasaeian, A.; Zamani, H.; Lorenzini, G.; Mahian, O.; Wongwises, S. A review of recent advances in solar cooking technology. *Renew. Energy* **2019**, *140*, 419–435. [CrossRef]
7. Misra, N.; Anand, A.; Pandey, S.; Kant, K.; Shukla, A.; Sharma, A. Box-Type Solar Cookers: An Overview of Technological Advancement, Energy, Environmental, and Economic Benefits. *Energies* **2023**, *16*, 1697. [CrossRef]
8. Ademe, Z.; Hameer, S. Design, construction and performance evaluation of aBox type solar cooker with a glazing wiper mechanism. *AIMS Energy* **2018**, *6*, 146–169. [CrossRef]
9. Ahmed, S.; Al-Amin, M.; Ahammed, S.; Ahmed, F.; Saleque, A.M.; Rahman, M.A. Design, construction and testing of parabolic solar cooker for rural households and refugee camp. *Sol. Energy* **2020**, *205*, 230–240. [CrossRef]
10. Gupta, P.; Misal, A.; Agrawal, S. Development of low cost reflective panel solar cooker. *Mater. Today Proc.* **2021**, *45*, 3010–3013. [CrossRef]
11. Vigneswaran, V.; Kumar, P.G.; Sakthivadivel, D.; Balaji, K.; Meikandan, M.; Dinakar, B.V.; Kamal, K.; Kumaresan, G. Energy, Exergy, and Economic analysis of low thermal conductivity basin solar still integrated with Phase Change Material for energy storage. *J. Energy Storage* **2021**, *34*, 102194. [CrossRef]
12. Wang, X.; Liu, Q.; Wu, S.; Xu, B.; Xu, H. Multilayer Polypyrrole Nanosheets with Self-Organized Surface Structures for Flexible and Efficient Solar–Thermal Energy Conversion. *Adv. Mater.* **2019**, *31*, 1807716. [CrossRef] [PubMed]
13. Alder, F.A.; Charrault, E.; Zuber, K.; Fabretto, M.; Patil, A.H.; Murphy, P.J.; Lluscà, M. Fabrication of robust solar mirrors on polymeric substrates by physical vapor deposition technique. *Sol. Energy Mater. Sol. Cells* **2020**, *209*, 110476. [CrossRef]
14. Chen, Y.T.; Lim, B.H.; Lim, C.; Chong, K.; Tan, B.K. High precision (1 part in 104) reflectivity measurement for the study of reflective materials used in solar collectors. *Sol. Energy Mater. Sol. Cells* **2003**, *80*, 305–314. [CrossRef]
15. Pielichowska, K.; Pielichowski, K. Phase change materials for thermal energy storage. *Prog. Mater. Sci.* **2014**, *65*, 67–123. [CrossRef]
16. Shaofei, W.; Ting, Y.; Zihan, K.; Weiguo, P. Thermal conductivity enhancement on phase change materials for thermal energy storage: A review. *Energy Storage Mater.* **2020**, *25*, 251–295. [CrossRef]
17. Machidon, D.; Istrate, M. Tilt Angle Adjustment for Incident Solar Energy Increase: A Case Study for Europe. *Sustainability* **2023**, *15*, 7015. [CrossRef]
18. Zafar, H.; Badar, A.; Butt, F.S.; Khan, M.Y.; Siddiqui, M. Numerical modeling and parametric study of an innovative solar oven. *Sol. Energy* **2019**, *187*, 411–426. [CrossRef]
19. Khan, T.M.Y.; Soudagar, M.; Kanchan, M.; Afzal, A.; Banapurmath, N.; Akram, N.; Akram, N.; Mane, S.; Shahapurkar, K. Optimum location and influence of tilt angle on performance of solar PV panels. *J. Therm. Anal. Calorim.* **2019**, *141*, 511–532. [CrossRef]
20. Saint, R.M.; Garnier, C.; Pomponi, F.; Currie, J. Thermal Performance through Heat Retention in Integrated Collector-Storage Solar Water Heaters: A Review. *Energies* **2018**, *11*, 1615. [CrossRef]
21. Gennusa, M.L.; Nucara, A.; Rizzo, G.; Scaccianoce, G. The calculation of the mean radiant temperature of a subject exposed to the solar radiation—A generalised algorithm. *Build. Environ.* **2005**, *40*, 367–375. [CrossRef]