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Development of A Smart Food Warmer with Real-Time Temperature and Humidity Monitoring

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ABSTRACT

Conventional food warmers often offer limited environmental control, leading to food overheating, severe dehydration, quality degradation, and excessive energy consumption. Objective: To address these limitations, this study developed and evaluated a portable smart food warmer that automatically regulates internal temperature and relative humidity using an ESP32 microcontroller and a DHT22 sensor. Method: The closed-loop prototype was developed using the Engineering Design Process and integrated a 20×4 liquid crystal display, an incandescent bulb, a circulation fan, a humidifier module, and a manual humidity bypass switch. Results: Experimental evaluations demonstrated that the hysteresis control loop successfully maintained temperature stability within the target 55–60°C range, limiting thermal fluctuations to ± 1.0 – ± 1.5 °C. The selected 300 W incandescent bulb achieved the target holding temperature of 60°C in 1 minute 15 seconds. At the same time, the humidity subsystem successfully regulated the chamber's relative humidity between 50% and 75%, with a moisture recovery time of 4 minutes 10 seconds. Energy consumption across ten tested heating-element wattages was highly comparable, ranging from 0.00567 to 0.00700 kWh per heating cycle, with the 300 W configuration consuming 0.00625 kWh. Conclusion: The findings confirm that integrating embedded systems and automated control can significantly improve food warming performance, offering a practical, reliable, and cost-effective solution that preserves food quality, protects public health, and enhances energy efficiency in real-world applications.

1. Introduction

Food preservation and quality maintenance represent critical considerations in household and commercial culinary environments, primarily driven by the expanding global demand for convenient and reliable food solutions [1,2]. Within this context, hot holding devices, commonly referred to as

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food warmers, serve an essential role by maintaining prepared meals at safe and palatable serving temperatures [3]. Maintaining these safe temperatures is vital for preventing the proliferation of foodborne pathogens while ensuring that food remains ready for consumption for extended periods.

However, conventional food warmers frequently lack automated control, real-time environmental monitoring, and humidity regulation capabilities, resulting in limited environmental stability [3-5]. In the absence of precise regulation, food held in traditional systems is often subjected to continuous heating, which can lead to overheating, excessive dryness, loss of texture, nutritional depletion, and substantial energy inefficiency [2,6]. While food safety guidelines emphasise the need to maintain hot food within a safe serving temperature range of approximately 50–60°C [7-9], managing temperature alone is insufficient to preserve the overall quality of held meals. Humidity also plays a critical role in preserving food texture and preventing dryness [10]. The absence of humidity monitoring in conventional systems further contributes to food quality degradation.

Existing research in food preservation has investigated microcontroller-based systems for temperature control and humidity tracking, but significant limitations persist. Many developed solutions focus exclusively on a single parameter, either temperature or humidity, rather than integrating both mechanisms into a unified, compact solution. Additionally, traditional systems often exhibit poor heating efficiency, limited sensor accuracy, and a critical lack of real-time user feedback, which limits users' awareness of internal storage conditions and reduces overall system reliability [11]. These gaps highlight the need for a more integrated and efficient system that can simultaneously monitor and control temperature and humidity while maintaining energy efficiency and usability.

To address these technical gaps, this study proposes developing a portable smart food warmer with real-time temperature and humidity monitoring. The primary objective is to maintain optimal food preservation conditions through automated control, improve energy efficiency, and enhance user convenience. The system provides a low-cost food-warming solution that integrates temperature and humidity control to reduce food dryness and preserve texture. By utilising an ESP32 microcontroller interfaced with a DHT22 sensor, the work demonstrates the practical application of embedded systems in everyday appliances. Furthermore, the implementation of hysteresis control enhances energy efficiency by minimising unnecessary actuator switching.

1.1 Thermal Regulation and Heating Control Strategies in Hot Holding

Maintaining hot-holding temperatures within the critical range of 50–60°C is vital for preventing the proliferation of foodborne pathogens, such as *Clostridium perfringens* and *Salmonella*, while preserving food palatability [7,9]. Conventional hot holding devices rely on manual on–off switches or continuously powered resistive elements, which often cause severe thermal overshoot, uneven heat distribution, and excessive energy waste [12]. To address these inefficiencies, researchers have implemented automated feedback loops using microcontrollers to govern heating elements [13,14]. In more adaptive environments, Putri [15] implemented a temperature control system using fuzzy logic, demonstrating superior stability compared with standard on–off strategies. Similarly, Jival and Alhassan [16] and Prabowo *et al.*, [17] designed proportional–integral–derivative (PID) control systems to stabilise temperatures and minimise overshoot in heating processes. Additionally, Gao [18] evaluated how heating elements with varying wattages affect thermal stabilisation in insulated chambers.

Despite the high precision offered by fuzzy-logic and PID control algorithms, these advanced methods require significant microcontroller processing power, complex mathematical modelling, and intensive calibration [17,19]. Such complexities increase system development costs and

complicate the design, making them less suitable for low-cost, portable household appliances [12]. The smart food warmer proposed in this study addresses these limitations by utilising a robust hysteresis control strategy operating between 55°C and 60°C. This strategy limits temperature fluctuations to a tight 1.5°C range while preventing rapid relay switching, thereby extending component lifespan. Furthermore, while previous work [18] examines high-power heating configurations, this study contributes empirical verification of heating-element selection. By comparing ten wattages from 25 W to 300 W, the study establishes that a 300 W incandescent bulb achieves the fastest target-temperature recovery of 1 minute 15 seconds without increasing cycle energy consumption (0.00625 kWh), indicating that high-wattage elements managed by hysteresis control optimise both system responsiveness and energy efficiency.

1.2 Relative Humidity Regulation and Moisture Maintenance

Although maintaining safe holding temperatures is critical, thermal regulation alone is insufficient to preserve overall food quality. Unregulated heating causes continuous moisture evaporation, resulting in food dehydration, texture degradation, and nutritional loss [2,10]. To mitigate these effects, studies emphasise the integration of active humidity management in hot holding environments [20]. Hoffmann *et al.*, [21] demonstrated that maintaining proper humidity levels dramatically reduces moisture loss, prevents texture degradation, and extends acceptable holding times. Microcontroller-based environmental monitoring systems have been deployed to adjust humidity using electronic humidifiers [22] dynamically. Related applications, such as the automated crop-drying systems developed by Shoewu *et al.*, [23] and the smart irrigation systems of Correa-Quiroz *et al.*, [24], also demonstrate how sensor-driven relative-humidity control optimises resource consumption and maintains material integrity. However, capacitive humidity sensors, such as the DHT series, often face challenges when exposed to prolonged high-temperature exposure, including response latency and measurement drift [25].

A major limitation of the existing literature is that developed systems typically prioritise temperature control, treat humidity as a secondary, unmonitored variable, or focus on agricultural drying and cold storage rather than hot holding [25,26]. While commercial humidified holding cabinets exist [20], they are engineered for industrial, high-volume operations and lack portability, cost-effectiveness, and design simplicity. The proposed smart food warmer addresses this gap by integrating a dedicated, closed-loop relative-humidity regulation subsystem operating between 50% and 75% relative humidity via an active humidifier module. To limit sensor response delays and system instability documented by Sinha and Mukhopadhyay [25], the system utilises a hysteresis loop operating in parallel with the temperature loop. Crucially, the design introduces a manual control switch that allows users to turn relative-humidity control on or off based on the specific culinary characteristics of the food being held, preventing unnecessary energy and water consumption when holding foods that do not require high moisture levels.

1.3 Integrated Embedded Systems and Real-Time Environmental Monitoring

The modern paradigms of the Internet of Things (IoT) and smart sensing have accelerated the development of integrated food-preservation tracking. Popa *et al.*, [3,27] and Tailor *et al.*, [5] proposed advanced multi-sensor IoT systems for tracking food-quality parameters and transmitting data to remote cloud platforms. Similarly, Riadi and Syaefudin [11] designed an IoT-based microcontroller platform to monitor and control temperature and humidity during food fermentation, facilitating remote administrative tracking. In larger logistics frameworks, Chandra *et*

al., [28] and Ali *et al.*, [29] demonstrated how automated sensor networks in warehouses minimise human error, reduce spoilage, and maintain food safety across supply chains. To ensure the reliability of these environmental controllers, automated calibration systems and robust communication networks have been established to detect system failures in real time [30,31].

Despite these technological advancements, many existing smart monitoring systems are designed for large-scale logistics, warehouses, or industrial processing, and lack compact, localised user-feedback mechanisms appropriate for everyday consumer use [29]. Additionally, systems that rely entirely on cloud connectivity face severe operational limitations in environments with unstable internet access. The proposed smart food warmer addresses these issues by establishing a self-contained, compact hardware architecture driven by an ESP32 microcontroller, integrating local sensing, automated actuation, and immediate visual feedback on a 20×4 LCD interface. This design eliminates the necessity of constant cloud dependency for basic safety and quality functions, ensuring system reliability in resource-constrained or remote settings. By combining localised hysteresis control, parallel temperature and humidity sensing, and high-visibility user displays, the prototype presents a practical, affordable, and accessible approach to smart kitchen technology that translates industrial food-preservation standards into a portable domestic appliance.

2. Methodology

2.1 Engineering Design Framework and System Requirements

This study adopted a structured engineering approach, guided by the Engineering Design Process (EDP), to systematically transition from problem identification to prototype validation. The development phase commenced with translating operational food-holding requirements into technical specifications. The primary design requirement was to maintain hot-held food within a target temperature range of 55–60°C to comply with food safety standards while minimising manual user intervention. These requirements guided the hardware selection, system interfacing, and closed-loop control strategy to ensure stability, safety, and electrical isolation when operating with high-voltage mains electricity.

2.2 Hardware Architecture and Component Selection

The system architecture was designed as an integrated physical–digital platform utilising specialised hardware and software components, illustrated in the block diagram of Fig. 1. The system was structured around an ESP32 microcontroller as the central processing unit. Environmental sensing was conducted using a DHT22 temperature and relative-humidity sensor with a sampling period of 2 seconds. Thermal energy was supplied by an incandescent bulb serving as the heating element. Forced-air convection was driven by a ventilation fan connected in parallel with the heating element to ensure uniform thermal distribution within the mini chamber fan. Relative humidity was regulated via an active air humidifier module. Physical and visual feedback was provided locally via a 20×4 liquid crystal display (LCD) interfaced through an Inter-Integrated Circuit (I²C) communication bus. Control signals from the ESP32 were isolated from the high-power loads using a multi-channel relay module. User-defined control of relative humidity was enabled by a physical manual single-pole single-throw (SPST) switch directly interfaced with a general-purpose input/output (GPIO) pin on the ESP32. The entire platform was programmed, compiled, and uploaded using the Arduino Integrated Development Environment (IDE).

Power is supplied via an AC/DC source, with low-voltage DC regulated for the ESP32 and peripheral components, while mains AC is routed separately to the relay module for safe switching

of high-power loads. The relay module provides electrical isolation, allowing the ESP32 to control the heating and humidity subsystems without direct exposure to high voltage. Table 1 summarises the key hardware and software components and their functions.

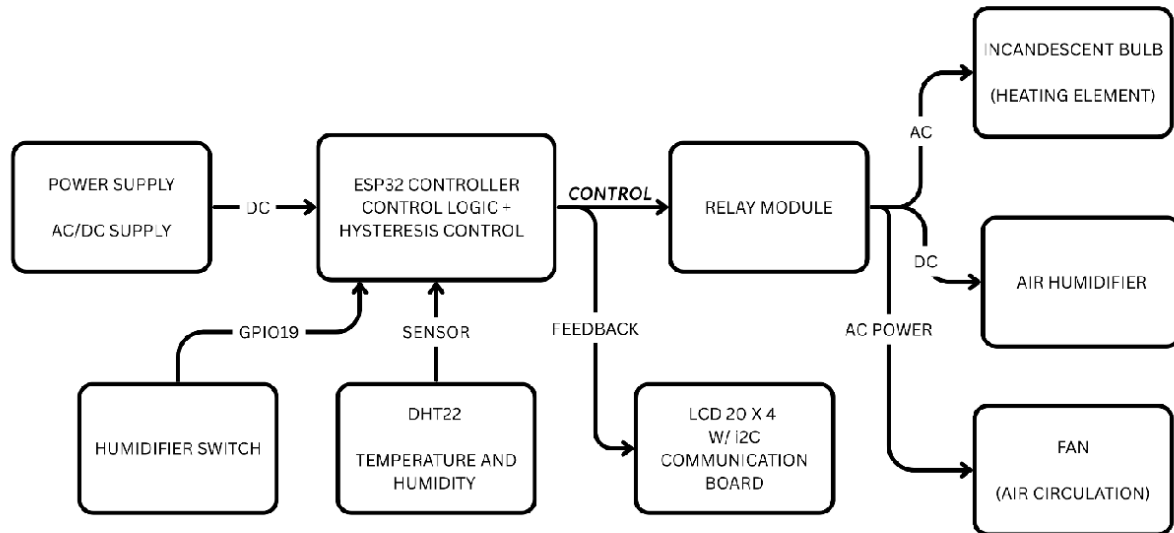


Fig. 1. Block diagram of the smart food warmer system

Table 1

Key hardware and software components of the system

Component	Description / Function
ESP32 Microcontroller	Acts as the main controller, processing sensor data and executing control logic.
DHT22 Sensor	Measures temperature and humidity within the system in real time.
Relay Module	Provides electrical isolation and enables switching of high-power loads (heater, fan, humidifier).
Incandescent Bulb	Functions as the heating element to raise the system temperature.
Ventilation Fan	Circulates air to ensure uniform heat distribution.
LCD (20×4, I ² C)	Displays real-time temperature, humidity, and system status.
Power Supply (240 VAC–5 VDC)	Converts mains AC to low-voltage DC for system operation.
Air Humidifier	Maintains moisture levels to prevent food from drying out.
Arduino IDE	Used for coding, compiling, and uploading firmware to the ESP32.
Canva	Used for designing circuit diagrams and documentation visuals.

2.3 Electrical Integration and Load Isolation

The electrical design integrated high-voltage Alternating Current (AC) and low-voltage Direct Current (DC) domains, ensuring user safety and system stability, as shown in the circuit diagram of Fig. 2. Power was introduced via a 240 V AC mains supply, which was subsequently regulated to a 5 V DC output using an internal power supply unit (PSU) to support the ESP32 and low-power control circuitry. The high-voltage AC mains supply was routed separately to the load-side contacts of the multi-channel relay module. This configuration provided complete galvanic isolation between the ESP32's low-voltage logic circuitry and the high-voltage AC loads, protecting the microcontroller from voltage transients. The electrical circuit was divided into two main actuation lines. First, the incandescent bulb and the ventilation fan were wired in parallel, allowing them to be switched

simultaneously via a single relay channel so that airflow coincided with heating. Second, a separate relay channel was dedicated to switching the active humidifier, enabling independent moisture regulation. A manual switch is incorporated to turn automatic humidity control on or off, allowing user intervention when required.

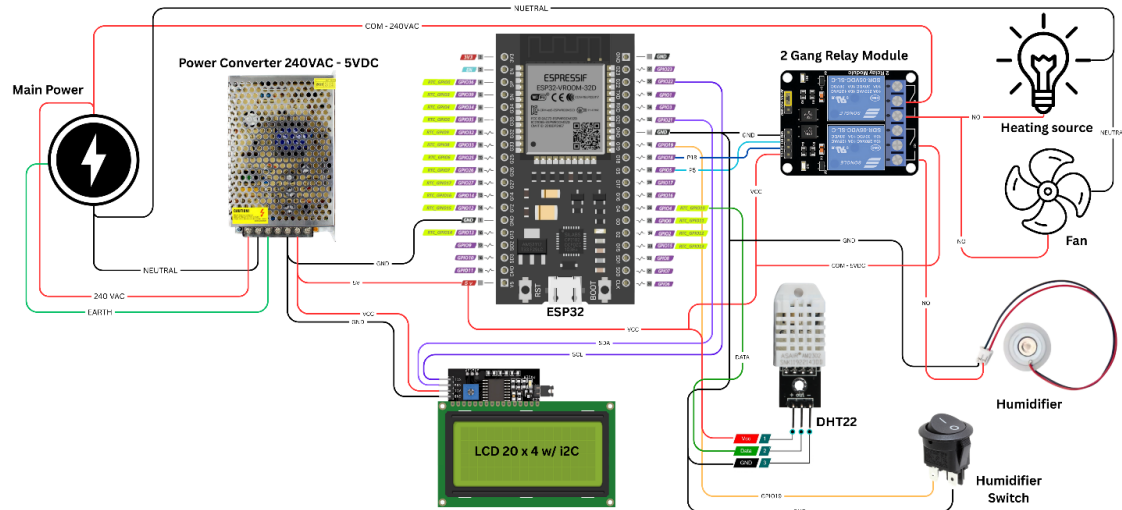


Fig. 2. Circuit diagram of the proposed system

2.4 Closed-Loop Control Strategy and Firmware Logic

The system software was structured to execute a continuous, real-time closed-loop sensing and actuation routine, as shown in the flowchart of Fig. 3. Upon initialisation, the ESP32 executed start-up routines that initialised the DHT22 sensor, established I²C communication with the LCD, and configured the relay module's control pins. Environmental parameters were repeatedly sampled by the DHT22, displayed on the local LCD interface, and processed through parallel hysteresis control loops.

Temperature regulation was governed by a deadband hysteresis control loop operating between predefined thresholds of 55°C and 60°C. The heating subsystem (incandescent bulb and fan) was deactivated immediately when the sensor reading reached or exceeded 60°C. To prevent rapid switching of the relay contacts — which accelerates mechanical wear and decreases component lifespan — the heating subsystem was restricted from reactivating until the monitored temperature dropped to 55°C or below. This created a stable 5-degree deadband, maintaining the target temperature while optimising relay longevity.

Simultaneously, humidity control was managed in parallel when the manual control switch was engaged. When enabled by the user, the ESP32 monitored the relative humidity and triggered the dedicated humidifier relay when it fell below 50%. The humidifier remained active until the relative humidity reached or exceeded 75%, at which point the relay was deactivated. If the manual switch was toggled to the off state, the automatic humidity control loop was bypassed, and the humidifier remained powered off regardless of the internal sensor readings.

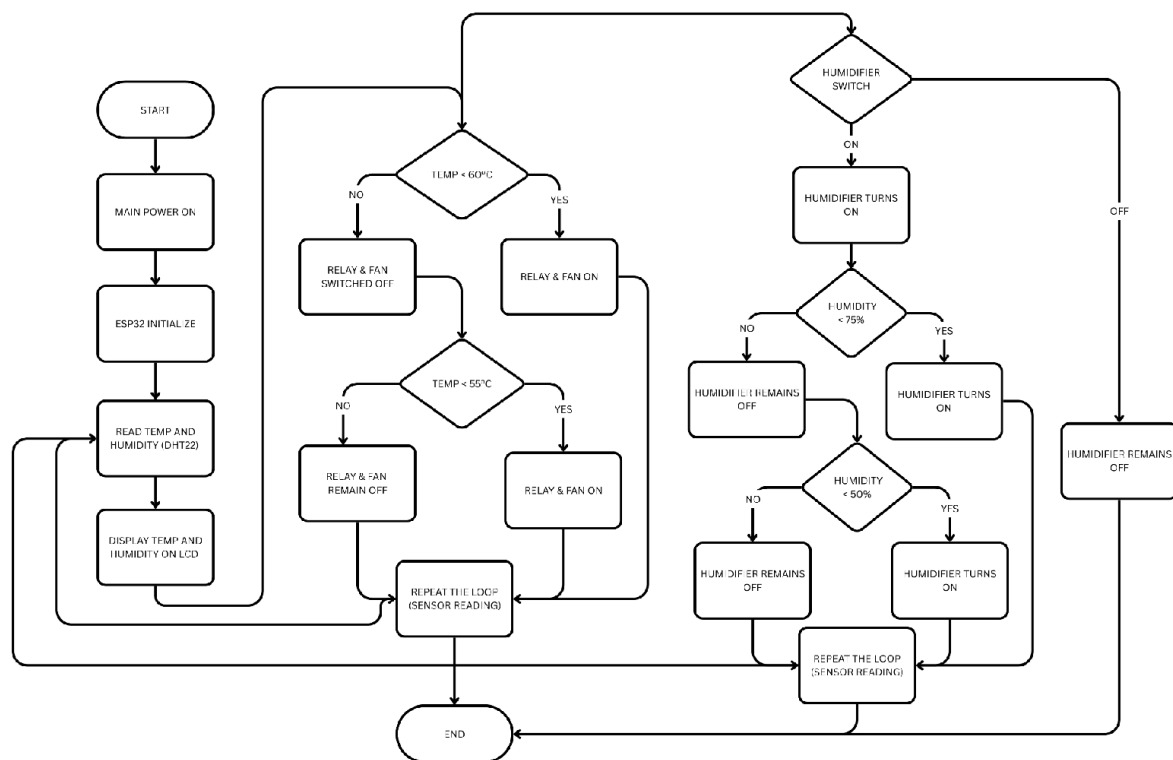


Fig. 3. Flowchart of the developed system

2.5 Experimental Evaluation and Testing Protocols

To evaluate the operational performance, thermal stability, and energy efficiency of the prototype, a series of experimental tests was executed. The physical prototype was assembled sequentially through component preparation, firmware upload, hardware packaging, and system refinement. Testing was divided into three primary experimental phases: heating performance evaluation, relative humidity control evaluation, and energy efficiency analysis.

First, thermal performance was characterised by testing incandescent bulbs at different wattages as the heating element. A total of ten different wattages were tested under identical experimental conditions: 25, 40, 60, 100, 125, 140, 160, 200, 225, and 300 W. The primary metrics measured were the total time required to heat the internal chamber from its starting temperature to the target hot-holding threshold of 60°C, and the temperature recovery rate during cyclical hysteresis operation.

Second, relative-humidity regulation was evaluated by enabling the humidity subsystem and monitoring the time required for the active humidifier to raise the chamber relative humidity from the lower threshold (50% or below) to the upper deactivation threshold (75% or above).

To align with standard testing protocols for commercial kitchen holding cabinets, these performance evaluations broadly follow the thermal-profiling guidance of ASTM F2140-10, "Standard Test Method for Performance of Hot Food Holding Cabinets" [32], and the sanitation requirements of NSF/ANSI 4, "Commercial Cooking, Rethermalization, and Powered Hot Food Holding and Transport Equipment" [33]. These standards establish industry baselines for verifying uniformity of hot-holding temperatures, electrical safety, and moisture retention in commercial food-holding equipment.

2.6 Data Analysis and Energy Calculations

The energy consumption associated with each of the ten tested wattages was calculated to determine the most efficient configuration. For each wattage, the estimated energy used per heating cycle was calculated in kilowatt-hours (kWh) using Eq. (1):

$$\text{Energy Used (kWh)} = (\text{Power in Watts} / 1000) \times \text{Time Taken (hours)} \quad (1)$$

where Power in Watts represents the rated wattage of the incandescent bulb, and Time Taken represents the duration required for that specific bulb to heat the chamber to 60°C. This calculation was used to evaluate the trade-off between higher power draw and reduced heating duration.

3. Results

3.1 System Development and Functional Integration

The physical and digital subsystems of the portable smart food warmer were developed and integrated through a sequential process of hardware assembly, software programming, and system testing. The ESP32 microcontroller successfully established reliable communication interfaces with the DHT22 environmental sensor, the multi-channel relay module, the LCD, the ventilation fan, the heating element, and the active humidifier. Experimental runs demonstrated that the sensor accurately acquired ambient environmental data and that the central microcontroller correctly initiated control signals to switch the relays.

The physical configuration and active operation of the integrated components were documented during testing, as shown in Fig. 4 and Fig. 5. The physical integration successfully supported parallel actuation lines: an incandescent bulb was operated in its active, illuminated heating state to generate thermal energy, while a ventilation fan and an active humidifier were operated inside the closed holding chamber alongside the DHT22 sensor, confirming that the hardware and software integration met the technical and functional requirements of the engineering design framework.



Fig. 4. Incandescent bulb in active state



Fig. 5. Ventilation fan, humidifier, and DHT22 sensor in operation

3.2 Temperature Control and Thermal Performance

The closed-loop thermal regulation subsystem maintained the chamber's internal temperature within the target hot-holding range of 55–60°C using a deadband hysteresis control loop. The heating element was deactivated immediately when the sensor registered temperatures at or above 60°C, and it remained off until the temperature dropped to 55°C or below. This hysteresis logic successfully reduced the frequency of relay switching, which improved system stability. Under standard operating conditions, the temperature control loop limited thermal fluctuations to within $\pm 1.0^{\circ}\text{C}$ of the target range.

The system's heating response was characterised by testing ten different heating-element wattages ranging from 25 W to 300 W, as shown in Fig. 6. The experimental trials showed that heating times decreased significantly as the incandescent bulb's rated wattage increased. Lower-wattage bulbs resulted in slower heating rates, whereas the 300 W bulb achieved the target holding temperature of 60°C in approximately 1 minute and 15 seconds. This fast response enabled the 300 W element to effectively compensate for structural heat loss through the chamber walls, resulting in rapid temperature recovery and enhanced thermal stability during cyclical operation. Under the high-power thermal load of the 300 W element, the hysteresis control loop limited temperature fluctuations to $\pm 1.5^{\circ}\text{C}$, indicating stable operation despite the elevated power output. The selection of the 300 W heating element was based on overall system performance rather than heating speed alone — the higher power output enabled more effective compensation for heat loss within the chamber, resulting in faster temperature recovery and improved stability without introducing unacceptable overshoot.

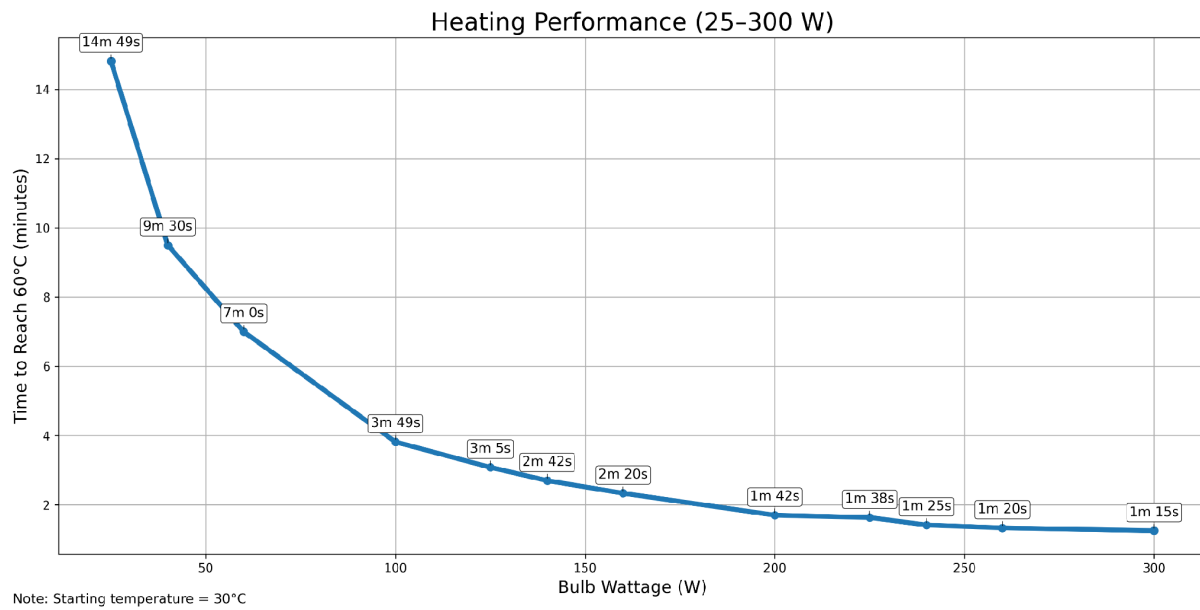


Fig. 6. Heating performance for the 25 W–300 W bulbs tested

3.3 Humidity Control and Moisture Maintenance

The relative humidity within the chamber was regulated between 50% and 75% RH using a parallel hysteresis control loop, as shown in Fig. 7 and Fig. 8. The automated humidifier was activated when the relative humidity fell to 50% or below, and it was deactivated when the relative humidity reached 75% or above. The mechanical transition states of the humidity control loop were monitored and documented: the active, mist-producing state of the humidifier was observed and verified when the relative humidity dropped below the target threshold, and upon reaching the upper deactivation limit of 75% RH, the control signal correctly triggered the relay to place the humidifier in its inactive state.



Fig. 7. Humidity control in the "Active" state (below 75% RH)



Fig. 8. Humidity control in the "Deactive" state (above 75% RH)

The system required approximately 4 minutes 10 seconds to raise the internal relative humidity from the lower threshold of 50% to the upper deactivation limit of 75%, as summarised in Fig. 9. While the rate of humidification was slower than the rate of temperature rise, owing to the high operating temperatures within the holding chamber, the automated control loop maintained the target relative-humidity range, preventing moisture loss and preserving food texture.

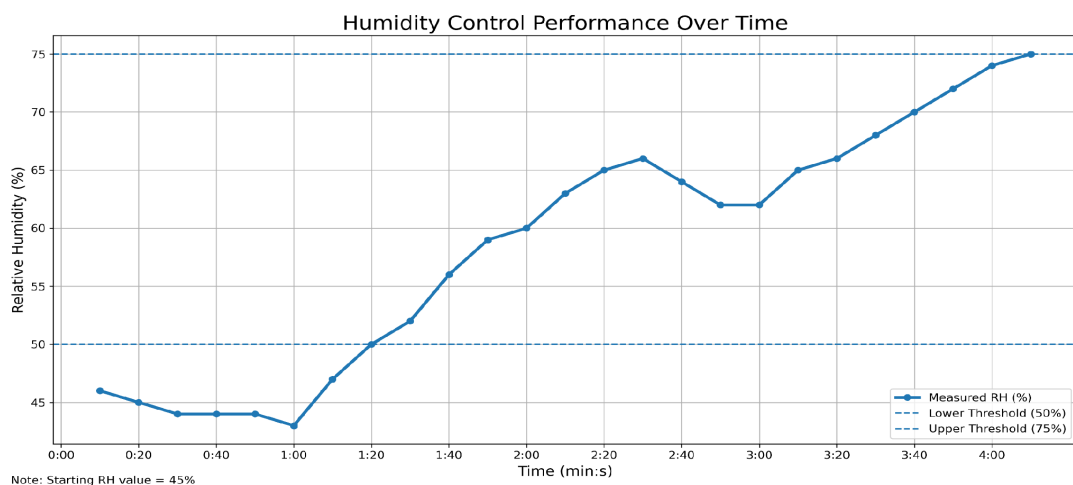


Fig. 9. Humidity control performance

3.4 User Control Interface and System Usability

The physical user interface allowed manual control of the humidity subsystem via a dedicated single-pole, single-throw switch (Fig. 10). Toggling this switch turned on or disabled the automated closed-loop relative-humidity program according to user preference. When the switch was turned off, the microcontroller bypassed the humidity control loop, and the humidifier remained deactivated regardless of the sensor readings. This manual override was confirmed by corresponding feedback on the 20×4 local LCD interface (Fig. 11), which displayed the humidity control status as deactivated while maintaining active temperature monitoring and display.



Fig. 10. Humidity control switch in the "OFF" state



Fig. 11. LCD showing humidity control in the "Off" state

3.5 Energy Consumption Analysis

An energy-efficiency evaluation was conducted to analyse the power consumption of each of the ten tested incandescent-bulb wattages during a single heating cycle. The energy used per cycle was calculated in kWh using Eq. (1), based on the bulb's wattage and the exact time required to heat the chamber to 60°C. The experimental data from these trials are presented in Table 2.

Table 2

Estimated energy consumption for each tested wattage

Wattage	Time Taken	Estimated Energy Used
25 W	14 min 49 s	0.00617 kWh
40 W	9 min 30 s	0.00633 kWh
60 W	7 min 0 s	0.00700 kWh
100 W	3 min 49 s	0.00636 kWh
125 W	3 min 5 s	0.00642 kWh
140 W	2 min 42 s	0.00630 kWh
160 W	2 min 20 s	0.00622 kWh
200 W	1 min 42 s	0.00567 kWh
225 W	1 min 38 s	0.00612 kWh
300 W	1 min 15 s	0.00625 kWh

The energy analysis showed that all ten tested configurations consumed a similar amount of energy, ranging from 0.00567 to 0.00700 kWh per heating cycle. The 200 W configuration consumed the least energy per cycle, at 0.00567 kWh, whereas the 60 W configuration consumed the most, at 0.00700 kWh. Despite having a significantly higher power draw, the 300 W bulb consumed 0.00625 kWh, comparable to the energy consumption of the lower-power elements. This was due to its short heating duration of 1 minute 15 seconds, which offset its high power requirement and confirmed that a higher-wattage element managed by hysteresis control optimises heating speed without increasing energy use.

4. Discussion

4.1 Interpretation of Thermal and Humidity Performance

The experimental evaluation of the portable smart food warmer demonstrates that integrating localised sensing, automated actuation, and parallel hysteresis control successfully addresses the core design objectives of thermal stability, moisture retention, and energy efficiency. The main objective of the study was to maintain food within a safe serving temperature range of 55–60°C while preventing excessive dryness and texture degradation, which are characteristic of conventional, unmonitored food warmers. The thermal control subsystem maintained internal temperatures with minimal fluctuations of $\pm 1.0^{\circ}\text{C}$ under standard operating conditions, and $\pm 1.5^{\circ}\text{C}$ under the high-power thermal load of the selected 300 W incandescent bulb.

Simultaneously, the active relative-humidity regulation subsystem successfully maintained moisture levels between 50% and 75% RH. It required approximately 4 minutes 10 seconds to raise the internal chamber relative humidity from the lower activation threshold to the upper deactivation limit — a humidification rate slower than the temperature recovery rate. This delay is attributed to the high operating temperatures in the holding chamber, which increase the air's moisture-holding capacity and accelerate evaporation, thereby requiring the humidifier to run longer to reach the upper threshold. Providing a manual switch to turn off relative-humidity control also enhances usability by giving users the flexibility to bypass moisture regulation when holding crispy or dry foods, thereby avoiding unnecessary water and power consumption.

4.2 Comparative Analysis of Control Strategies and Actuator Selection

When situated within the broader literature, the performance of the proposed hysteresis control loop agrees with and extends the findings of previous studies. While Putri [15] and Jival and Alhassan

[16] utilised complex fuzzy-logic and PID control algorithms to eliminate thermal fluctuations, their systems required substantial microcontroller processing power and extensive calibration. In contrast, the results of this study demonstrate that a robust hysteresis algorithm operating with a 5-degree deadband (deactivating at 60°C and reactivating at 55°C) provides sufficient thermal stability (within $\pm 1.5^\circ\text{C}$) for household food preservation. This simple control logic effectively prevents rapid relay switching, thereby minimising mechanical wear and extending the operating lifespan of the system components. Recent literature suggests that while PID algorithms offer superior precision, hysteresis control remains a cost-effective and reliable strategy for resource-constrained, portable consumer appliances [12,17].

The integration of parallel relative-humidity monitoring represents a meaningful extension of traditional food-warmer designs. Most existing systems focus exclusively on single-parameter regulation or utilise passive water pans that lack active control. By incorporating an active humidifier governed by a secondary hysteresis loop operating between 50% and 75% RH, the prototype maintains consistent moisture conditions within a compact chamber. This automated approach aligns with the findings of Hoffmann *et al.*, [21], who demonstrated that active humidity management preserves food texture and prevents dehydration. However, integrating capacitive sensors like the DHT22 in high-heat holding environments can expose them to measurement drift and response latency [25]. The prototype manages this limitation by establishing a wide humidity deadband, ensuring stable operation despite sensor limitations.

4.3 Energy Consumption Dynamics and Efficiency Trade-offs

The energy consumption analysis presents an important contribution to the selection of heating elements in compact thermal chambers. Conventional engineering assumptions often dictate that lower-wattage heating elements are inherently more energy-efficient. However, the experimental trials conducted in this study reveal that all ten tested wattages (25–300 W) consumed a comparable range of energy, specifically between 0.00567 and 0.00700 kWh per cycle. The 200 W element achieved the lowest consumption at 0.00567 kWh, whereas the 60 W element consumed the highest at 0.00700 kWh. The selected 300 W element consumed 0.00625 kWh per cycle, highly comparable to the 25 W element (0.00617 kWh).

The physical mechanism behind this result is that the 300 W element achieved the target temperature of 60°C in only 1 minute 15 seconds, compared to the 14 minutes 49 seconds required by the 25 W element. Because energy consumption depends on both power draw and operating time, the short heating time of the high-wattage bulb effectively offsets its higher power requirement. Additionally, the higher thermal output of the 300 W bulb enables faster temperature recovery and more effective compensation for heat loss through the chamber walls. This confirms that selecting a higher-wattage element with hysteresis control optimises system responsiveness without increasing overall energy use — a balanced outcome that supports sustainable kitchen practices by minimising cycle power consumption while preserving food safety and quality, in keeping with energy-efficiency guidance for commercial kitchen equipment [34].

4.4 Project Limitations and Research Constraints

Despite the successful operation and validation of the integrated prototype, several technical and structural limitations must be acknowledged. First, a primary limitation is heat and humidity loss from the holding enclosure to the ambient environment, which contributes to minor temperature and humidity fluctuations inside the chamber. Second, the use of the DHT22 sensor introduces certain

operational constraints due to its relatively slow response time compared to more advanced sensors. Under rapidly changing environmental conditions — such as when the chamber door is opened, or the high-power heater is active — the sensor's response lag can cause brief measurement delays, which in turn delay relay actuation and lead to minor temperature overshoots.

Finally, this project was developed as a student-level prototype under the constraints of a limited budget, limited material availability, and time constraints. These practical factors influenced the overall design, restricted the selection of materials to basic off-the-shelf components, and limited the scale of performance and durability testing. Consequently, further optimisation is required to transition the prototype into a commercial-grade, scalable consumer appliance.

5. Conclusion

This study successfully developed and evaluated a portable smart food warmer that utilises an ESP32 microcontroller to maintain optimal food-preservation conditions. The integrated prototype achieved stable temperature regulation between 55°C and 60°C using hysteresis control, while actively maintaining relative humidity between 50% and 75% to minimise food dryness. By combining dual-parameter regulation within a single compact solution, this work contributes a practical, low-cost application of embedded systems in everyday appliances. This automated approach supports sustainable culinary practices by reducing overall power consumption and minimising post-holding food waste.

5.1 Future Recommendations

Several improvements are proposed to enhance the performance and usability of the smart food warmer system. To address the limitations identified in Section 4.4, future work will focus on replacing the current hysteresis control strategy with a Proportional–Integral–Derivative (PID) algorithm to achieve more precise thermal control and reduce minor temperature fluctuations. In addition, upgrading from the DHT22 sensor to higher-accuracy sensors with faster response times would improve measurement reliability and system responsiveness. The integration of Internet of Things (IoT) capabilities is also recommended to enable remote monitoring and control through mobile or web-based platforms, along with features such as real-time notifications and data logging. Furthermore, the user interface can be enhanced by incorporating a more interactive display, such as a touch-based system with preset modes, to improve convenience and overall user experience.

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