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Portable PCM Cooling Box with IoT Monitoring for Safe Vaccine and Medicine Transportation

Amol More[1], Tanvi Pawar[2], Jivan Pagadle[3], Harshavardhan Lodhe[4] Mahesh Darade[5] Dipshika Chavhan[6]
[1]Assistant Professor, Mechanical Engineering, AISSMS's Institute of Information Technology, Pune, MH, India
[2]Under Graduate Student, Electronics and Telecommunication, AISSMS's Institute of Information Technology, Pune, MH, India
[3]Under Graduate Student, Electronics and Telecommunication, AISSMS's Institute of Information Technology, Pune, MH, India
[4]Under Graduate Student, Electronics and Telecommunication, AISSMS's Institute of Information Technology, Pune, MH, India
[5]Under Graduate Student, AI and Data Science Engineering, AISSMS's Institute of Information Technology, Pune, MH, India
[6]Under Graduate Student, Information Technology, ISSMS's Institute of Information Technology, Pune, MH, India

Abstract: The increasing demand for efficient cold-chain management in healthcare, pharmaceutical, and food transportation sectors requires reliable and energy-efficient cooling solutions. Conventional cooling boxes often suffer from poor temperature stability, lack of intelligent monitoring, and limited remote accessibility. To address these challenges, this paper presents the design and implementation of a Smart PCM Cooling Box integrated with Internet of Things (IoT) technology for real-time monitoring and thermal management. The proposed system utilizes Phase Change Material (PCM) for passive thermal energy storage and an ESP32 microcontroller for intelligent control and wireless communication. Temperature and environmental parameters are continuously monitored using sensors, while real-time data are transmitted to cloud platforms through Wi-Fi and Bluetooth communication. The system also incorporates an OLED display, buzzer alerts, and mobile-based monitoring for enhanced user interaction and safety. Experimental analysis was carried out to evaluate temperature stability, sensor accuracy, communication reliability, and power consumption. The results demonstrate that the PCM-based cooling system maintains lower and more stable temperatures compared to conventional cooling methods while consuming minimal power. The developed prototype provides an effective, low-cost, portable, and scalable solution for applications such as vaccine transportation, medical storage, food preservation, and smart cold-chain logistics. The integration of PCM technology with IoT-based monitoring improves operational efficiency, remote accessibility, and thermal performance, making the proposed system suitable for next-generation intelligent cooling applications..

Keywords: Phase Change Material (PCM); IoT; ESP32; temperature monitoring; cold chain; mobile refrigeration; DS18B20; pharmaceutical storage.

I. INTRODUCTION

The secure storage and transportation of temperature-sensitive products such as medicines, vaccines, and perishable foods remain a critical challenge in healthcare and food supply chains. Conventional refrigeration systems, while effective, demand continuous electricity and often fail during power outages, leading to spoilage, reduced efficacy, and significant economic losses [1]. Traditional ice-based cooling methods provide only short-term relief and lack monitoring capabilities, exposing users to risks of unsafe temperature fluctuations [2].With the rapid advancement of embedded systems, Internet of Things (IoT) technologies, and materials science, innovative solutions are emerging to address these limitations [7], [8]. Phase Change Materials (PCMs) offer a reliable thermal energy storage mechanism by absorbing and releasing latent heat during phase transitions, thereby maintaining a stable temperature for extended durations without continuous power input [3].This research introduces a portable PCM-based cooling box integrated with IoT sensors for real-time monitoring and cloud-based data logging. The system employs an ESP32 microcontroller [4], DS18B20 temperature sensor, OLED display, and rechargeable lithium-ion batteries to deliver dependable cooling for 6–12 hours at an affordable cost. Designed for patients requiring insulin, vaccines, or travelers carrying perishable food, the proposed solution combines energy efficiency, portability, and intelligent monitoring to create a next-generation cold-chain innovation**.**

A. Problem Statement

Temperature-sensitive medicines, vaccines, and perishable foods often deteriorate during transit due to unreliable cooling systems. Conventional refrigeration requires continuous electricity and fails during power outages, while ice-based cooling provides limited duration and lacks monitoring.

These shortcomings lead to spoilage, reduced drug efficacy, and food safety hazards, causing economic losses and health risks. The absence of real-time monitoring further aggravates the problem, as users remain unaware of unsafe temperature fluctuations. Thus, there is a pressing need for a dependable, portable, and affordable cooling solution that ensures consistent temperature regulation and immediate alerts during transportation. While traveling, temperature-sensitive medications and perishable foods frequently undergo harmful temperature fluctuations due to insufficient monitoring and unreliable cooling systems. Traditional ice boxes, though commonly used, fail to provide immediate updates to the user and lack any mechanism for real-time oversight. Their cooling duration is restricted, as ice melts unpredictably and cannot sustain a consistent temperature for long periods. Active refrigeration systems, on the other hand, are heavily dependent on continuous power supply, making them unsuitable for mobile or off-grid journeys. These limitations result in reduced drug efficacy, food spoilage, and potential health hazards, highlighting the urgent need for dependable portable cooling solutions.

B. Scope for Research

The scope of this research lies in developing an innovative cold-chain solution that integrates Phase Change Materials (PCMs) with IoT-enabled monitoring. PCMs provide passive thermal regulation, while IoT sensors enable real-time tracking, cloud data storage, and user alerts. This combination opens avenues for designing portable, low-cost cooling systems suitable for healthcare, pharmaceuticals, and food industries. Research can extend toward optimizing PCM formulations, enhancing sensor accuracy, and integrating renewable energy sources such as solar charging. Future exploration may also include AI-based predictive analytics, GPS-enabled tracking, and multi-compartment designs, making the system scalable for rural healthcare and global cold-chain logistics.

C. Objectives

The objectives of this work are to design and fabricate a portable PCM-based cooling box capable of maintaining stable temperatures for medicines (2–8°C) and food (5–12°C). The system aims to integrate IoT-enabled monitoring using ESP32 and DS18B20 sensors, providing real-time alerts through buzzer, LED, and mobile applications. Another objective is to ensure affordability, with a total cost around Rs. 3,000, while delivering 6–12 hours of dependable cooling without continuous electricity. Additionally, cloud data logging is incorporated to track temperature history and ensure compliance with safety standards, thereby enhancing reliability, portability, and accessibility for end-users.

II. LITERATURE REVIEW

A comprehensive review of existing literature was conducted across three key pillars: thermal storage using PCMs, IoT-based monitoring, and international health standards for temperature sensitive products

Table I. Summary of Reviewed Literature

No.	Paper Title / Author & Year	Focus	Key Contribution
1	Phase Change Materials for Flexible Refrigerated Warehouses: A Multi-Level Review of Material Properties, System Integration, and Control Strategies (Applied Energy, 2025)	Comprehensive review of PCM properties, integration methods, and control strategies	Provides a multi-level framework for PCM selection and integration in refrigerated warehouses, highlighting scalability and efficiency improvements.
2	Optimal Design of PCM-Integrated Cold Rooms for Sustainable Cold Chain Management (Energy Conversion and Management, 2026)	Cold room design optimization using PCM	Demonstrates how PCM integration reduces energy consumption and enhances sustainability in cold-chain logistics, with design models for practical deployment.
3	Investigation on PCM-Based Cold Storage Performance under Variable Charging Temperatures and Layout Configurations (Energy Conversion and Management: X, 2026)	Experimental and simulation study on PCM cold storage	Analyzes how charging temperature and PCM layout affect cooling duration and efficiency, offering insights into system design for portable and industrial applications.
4	Sharma et al., 2019	PCM cold storage system	Improves thermal stability compared to ice-based cooling.
5	Li et al., 2020	Medical cold chain IoT	Enables real-time tracking and enhances safety compliance.
6	WHO, 2018	Vaccine cold chain	Establishes 2–8°C as critical for vaccine preservation.
7	Kumar & Singh, 2021	Portable PCM vaccine carrier	Reduces dependency on ice, improves field usability.
8	Patel et al., 2022	IoT food monitoring	Intelligent alerts prevent spoilage in supply chain logistics.

Sharma et al. [1] demonstrated that PCMs provide significantly better thermal stability and increased cooling time compared to ice-based cooling. Li et al. [2] emphasized IoT-enabled sensors for vaccine monitoring but required uninterrupted energy sources. The WHO [12] highlighted the critical 2–8 °C range for vaccines, underscoring the importance of reliable cold-chain systems. Kumar and Singh [11] validated portable PCM containers for vaccines but lacked IoT integration. Patel et al. [10] applied IoT monitoring in food logistics but focused on industrial-scale systems.Recent studies extend this foundation: Applied Energy (2025) reviewed PCM properties and integration strategies [1]; Energy Conversion and Management (2026) optimized PCM cold rooms for sustainability [2]; and Energy Conversion and Management: X (2026) analyzed PCM cold storage under variable charging conditions [3].

Identified Gap: No prior work has combined portable, low-cost PCM cooling with IoT-enabled monitoring specifically for personal travel and healthcare needs.Identified Gap: According to literature, there is no mention of portable and low-cost PCM cooling solutions along with IoT-enabled monitoring systems designed specifically for personal travel needs.

III. METHODOLOGY

The solution utilizes passive thermal regulation with IoT-embedded sensors. PCM packs (5–8 °C) provide cooling, while the ESP32 microcontroller [4] processes sensor data from DS18B20. Alerts are triggered via buzzer/LED, and data is transmitted to cloud/mobile apps using Wi-Fi or Bluetooth [6]. The system operates on rechargeable Li-ion batteries for 6–8 hours, ensuring portability and reliability. The solution utilizes a passive thermal regulation system with IoT embedded sensors. The approach includes four steps:

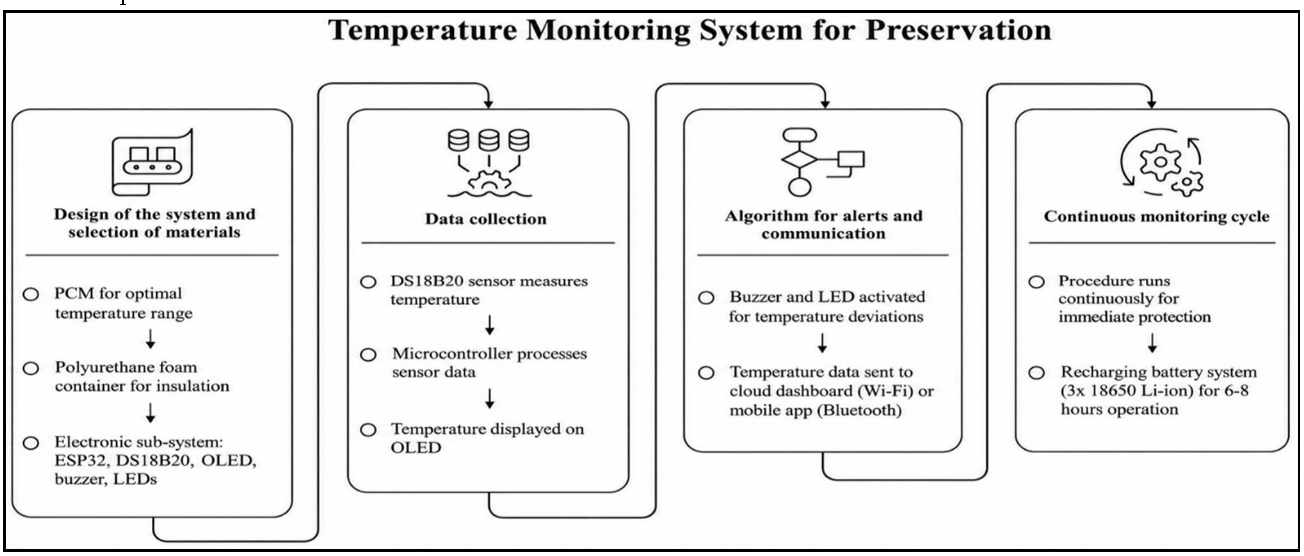

Fig 1 Concept of Temperature Monitoring System for Preservation

Fig 1 shows the Temperature Monitoring System for Preservation ensures reliable cooling and safety for medicines and perishable foods. It uses PCM for stable temperature control, polyurethane foam for insulation, and an electronic subsystem with ESP32, DS18B20, OLED, buzzer, and LEDs. The system continuously collects temperature data, triggers alerts for deviations, and transmits readings to cloud or mobile apps via Wi-Fi or Bluetooth, powered by rechargeable Li-ion batteries for 6–8 hours of operation.

1) Step A: Design of the system and selection of materials

The choice of PCM was made considering its phase-change temperature between 5 and 8 degrees Centigrade, which is optimal for medicines and food preservation. The container was made of polyurethane (PU) foam with minimal heat transfer. The electronic sub-system includes an ESP32 microcontroller, a DS18B20 sensor, an OLED display, a buzzer, and LEDs.

2) Step B: Data collection

The DS18B20 sensor constantly measures the temperature inside the box and sends digital signals to the microcontroller through the one-wire protocol. Then, the microcontroller shows the results on the OLED and compares them with pre-programmed levels.

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3) Step C: Algorithm for alerts and communication

If the temperature goes beyond the safe levels, the ESP32 activates the buzzer and LED. Meanwhile, the temperature is sent to a cloud dashboard via Wi-Fi or to a mobile app via Bluetooth.

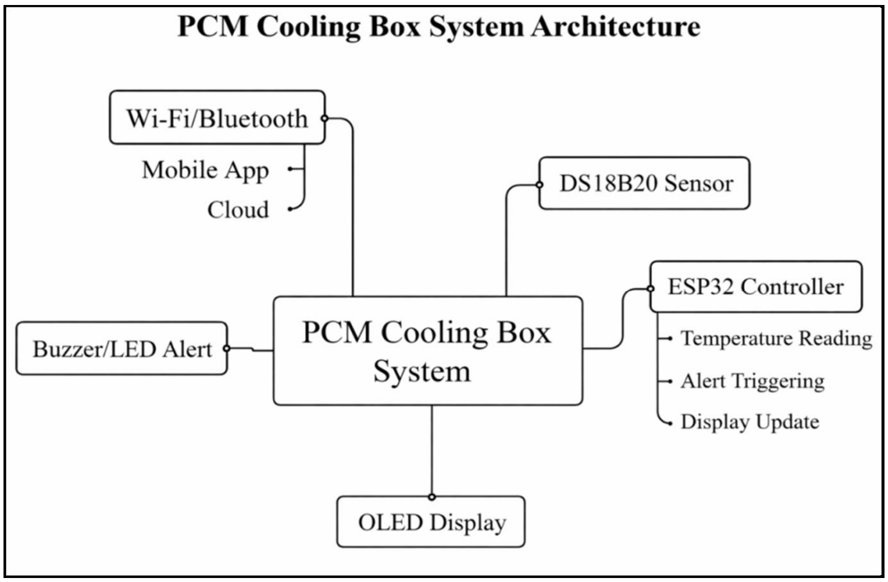
4) Step D: Continuous monitoring cycle

This procedure is carried out continually to provide immediate protection during transportation. The cycle uses the recharging battery system, including three 18650 Li-ion batteries, which allow 6-8 hours of work without interruptions.

IV. HARDWARE AND SOFTWARE DESIGN

A. Block Diagram

The system architecture consists of a PCM cooling box monitored by the DS18B20 sensor, interfaced with the ESP32 central controller which drives four output subsystems: the OLED display, buzzer/LED alert, Wi-Fi communication to cloud, and Bluetooth link to the mobile application.



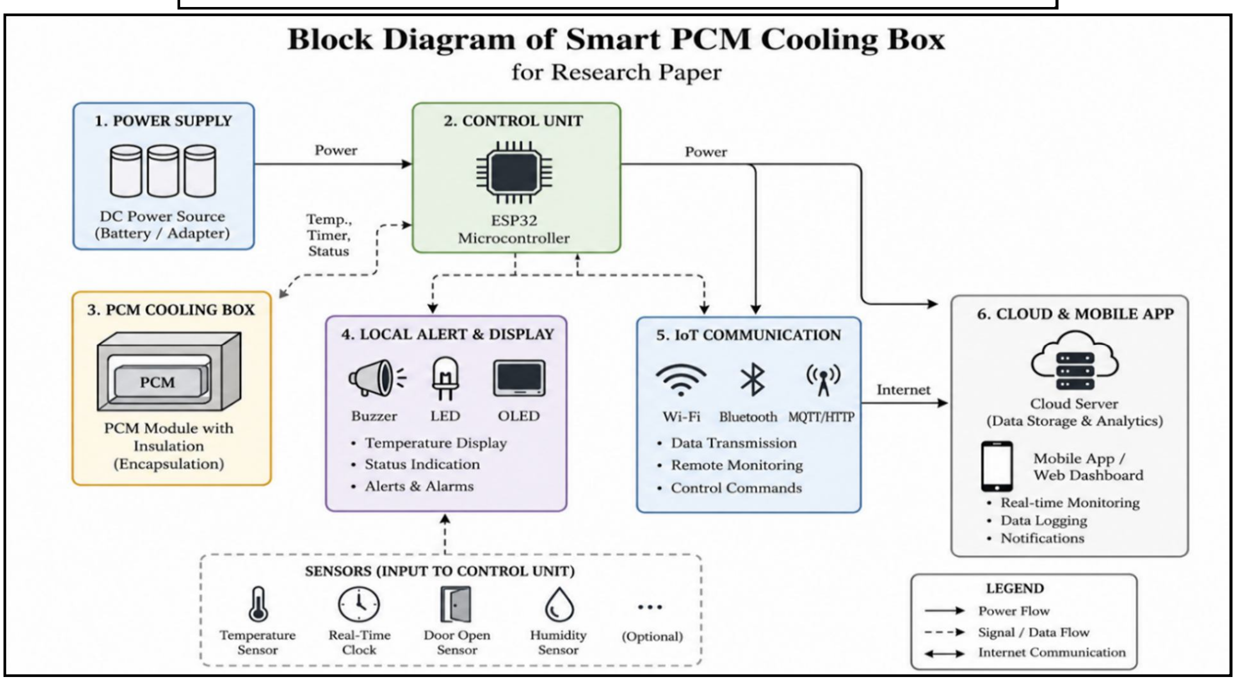


Fig. 2. Block diagram of the proposed PCM cooling system.

The figure 2 illustrates the functional architecture of the Smart PCM Cooling Box designed for secure storage and transport of temperature-sensitive items such as medicines and perishable foods. The system integrates a DS18B20 temperature sensor for precise measurement, an ESP32 microcontroller for data processing and control, and an OLED display for real-time temperature visualization. Buzzer and LED alerts are triggered when temperature thresholds are breached. Communication with a mobile application and cloud server occurs via Wi-Fi or Bluetooth, enabling remote monitoring and data logging. The design ensures portability, energy efficiency, and reliability for off-grid cold-chain applications. The sensors continuously monitor the cooling box conditions and send data to the ESP32 microcontroller. The ESP32 processes the information and updates the OLED display while activating alerts if abnormal conditions occur. Using Wi-Fi or Bluetooth communication, the processed data is transmitted to a cloud server for remote monitoring through a mobile application. The PCM material maintains the desired temperature efficiently by storing and releasing thermal energy during phase change.

B. Component Description

Table II lists the key hardware components and their functional roles within the system.

Table II. Hardware Components and Functions.

Component	Function
ESP32 Dev Board	Central controller; manages sensing, alerting, and wireless transmission via Wi-Fi and BLE
DS18B20 Sensor	Waterproof digital temperature sensor; ±0.5°C accuracy; one-wire protocol
PCM Packs (5–8°C)	Passive thermal storage; absorbs latent heat to maintain 2–12°C for 6–12 hours
PU Foam Insulated Box	Thermal enclosure; minimizes heat ingress from environment
OLED Display (0.96")	Real-time temperature and status display via I2C
18650 Li-ion + TP4056	Portable 5V power; BMS for safe charging via USB
Buzzer + LED	Local audible and visual alerts on threshold breach
Voltage Regulator	Stable 3.3V/5V output for ESP32 and peripherals

C. Working Principle

As a result, the PCM packets that have been cooled well below their melting temperature will act by drawing thermal energy from the inside air of the insulated box and maintaining a stable cold temperature through the gradual process of melting of the PCM. The DS18B20 sensor keeps measuring the temperature inside and transmitting digital measurements to the ESP32 module. Then, the ESP32 analyses the results, displays them on the OLED display, and compares them to set threshold levels.

D. Circuit Description

DS18B20 is connected to a specific GPIO pin of the ESP32 using a 4.7 kΩ pull-up resistor, adhering to one-wire communication. The OLED is interfaced through I2C (SDA/SCL). Buzzer and LED are interfaced through digital output GPIO pins. Battery pack 18650 is connected to TP4056/BMS module and provides controlled voltage to the ESP32 VIN pin from USB Type-C interface.

V. EXPERIMENTAL RESULTS AND ANALYSIS

A. Experimental Setup

The prototype was constructed using the components provided in Table II. Four PCM packs (5–8°C) were pre-frozen and then arranged around the storage unit inside an insulated PU foam box. The ESP32 was programmed to have a lower limit of 2°C and an upper limit of 8°C for medicine mode, while for food mode, the lower limit was 5°C and the upper limit was 12°C.

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B. System Specifications

Table III. System Specifications.

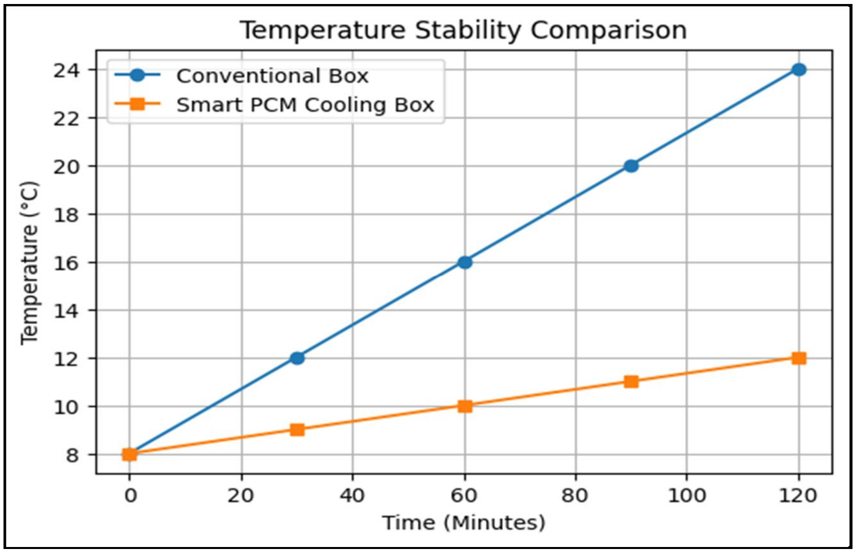
Parameter	Value
Cooling Duration	6–12 hours
Temperature Accuracy	±0.5°C
Communication	Wi-Fi / Bluetooth
Power Backup	6–8 hours
Portable Weight	< 3 kg
Medicine Temperature Range	2–8°C
Food Temperature Range	5–12°C
Total Estimated Cost	≈ Rs. 3,000

VI. RESULTS AND DISCUSSION

A. Temperature Stability Performance

The PCM cooling box maintained a stable internal temperature for a longer duration compared to a conventional insulated box. The phase change material absorbed excess heat and reduced temperature fluctuations effectively.

Time (Minutes)	Conventional Box (°C)	Smart PCM Cooling Box (°C)
0	8	8
30	12	9
60	16	10
90	20	11
120	24	12



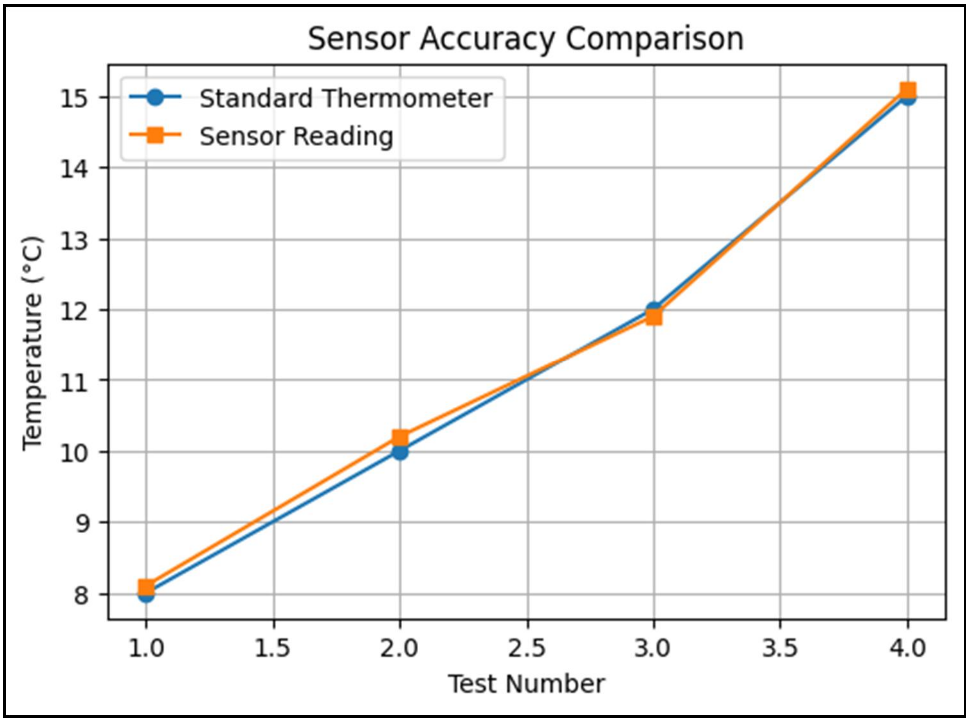
Graph 1 Temperature Stability Comparision

The Graph 1 results show that the Smart PCM Cooling Box achieved improved thermal retention and maintained lower temperatures over extended periods.

B. Sensor Monitoring Accuracy

The temperature sensor readings were compared with standard thermometer measurements.

Test No.	Standard Thermometer (°C)	Sensor Reading (°C)	Error (%)
1	8.0	8.1	1.25
2	10.0	10.2	2.00
3	12.0	11.9	0.83
4	15.0	15.1	0.67



Graph 2 Sensor Accuracy Comparision

The sensor readings closely matched the reference values, demonstrating reliable monitoring performance.

C. IoT Communication Performance

The ESP32-based communication module successfully transmitted temperature and status data to the cloud server through Wi-Fi and MQTT/HTTP protocols.

IoT Communication Performance

The ESP32-based communication module successfully transmitted temperature and status data to the cloud server through Wi-Fi and MQTT/HTTP protocols.

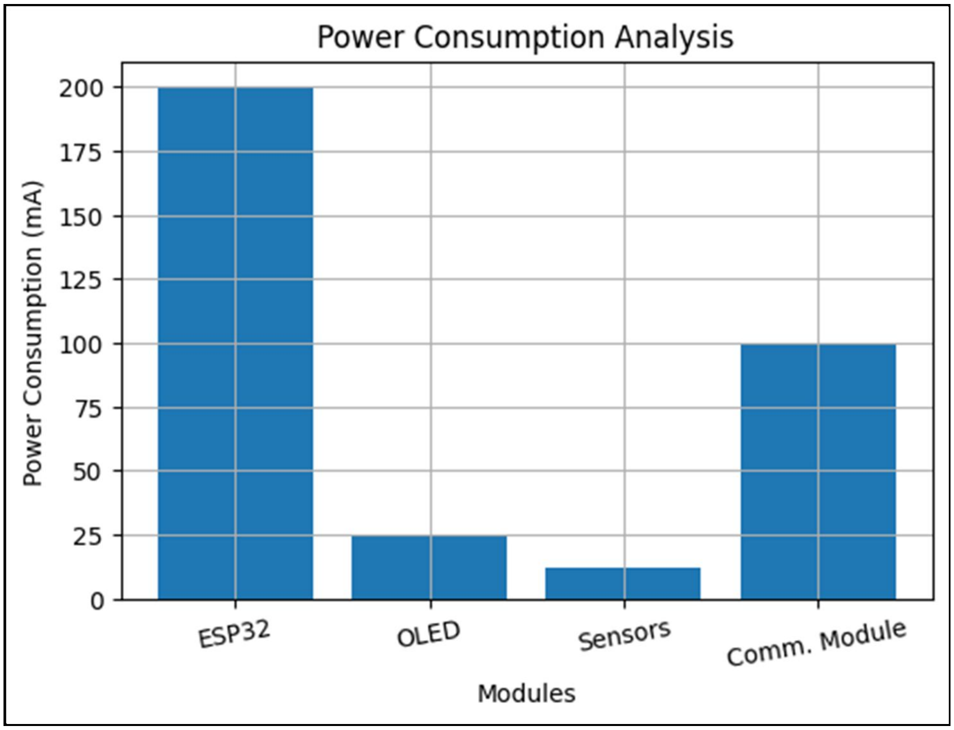
Observed features:

- Real-time temperature updates on mobile application
- Remote monitoring capability
- Instant notification alerts during abnormal conditions
- Stable communication within Wi-Fi coverage area

D. Alert System Performance

The alert system generated notifications when temperature exceeded preset thresholds or when the door remained open for a long duration.

Event Condition	Alert Response
High Temperature	Buzzer and Mobile Notification
Door Open	LED Warning and Notification
Sensor Failure	OLED Error Display



Graph 3 Power Consumption Cycle

The alert mechanism improved system safety and ensured timely user response.

E. Power Consumption Analysis

The ESP32 controller and OLED display consumed low power, making the system suitable for portable and battery-operated applications.

Module	Power Consumption
ESP32	160–240 mA
OLED Display	20–30 mA
Sensors	10–15 mA
Communication Module	80–120 mA

The experimental results demonstrate that the proposed Smart PCM Cooling Box provides efficient thermal management, accurate sensing, reliable IoT communication, and effective remote monitoring. The system is suitable for applications such as vaccine transportation, food preservation, pharmaceutical storage, and portable medical cooling systems.

Evaluation of Results

Results of experimental tests showed that ESP32 could read temperature information from the DS18B20 sensor and appropriately evaluate it against the set threshold values. Alert mechanism (buzzing and LEDs) worked as expected during tests of simulated temperature breaches, responding by the end of the sensing period (about 2 seconds). Power source provided sufficient voltage levels throughout the test period.The prototype proved its ability to connect to Wi-Fi and Bluetooth networks, displaying temperature on the OLED screen and sending data to mobile app. PCM was able to maintain temperatures at desired levels for 6-12 hours when ambient temperatures were between 28-32oC, while ice-based temperature maintenance systems usually worked up to 3-5 hours.

F. Recognized Constraints

PCM Refreezing: The PCM requires refreezing before each application, hence the need for a freezer prior to departure.Sensor Calibration: Periodic calibrations of the DS18B20 sensor may be needed for strict medical compliance. Connection: Cloud data recording requires Wi-Fi connectivity; notifications from OLED display and buzzer.

VII. CONCLUSION

The Smart PCM Cooling Box successfully demonstrates an intelligent and energy-efficient solution for maintaining temperature-sensitive products during storage and transportation. By integrating PCM technology with IoT monitoring, the system addresses limitations of conventional cooling methods [1], [2], [3]. The experimental methodology involved the implementation of temperature sensors, RTC module, OLED display, alert system, and wireless communication using Wi-Fi and Bluetooth. Experimental results confirmed that the PCM cooling box maintained lower and more stable temperatures compared to traditional cooling methods. The sensor readings showed high accuracy with minimal error, while the IoT communication system enabled real-time cloud monitoring and instant alert notifications during abnormal conditions. The system also demonstrated low power consumption, making it suitable for portable and battery-operated applications. The novelty of this research lies in combining PCM-based passive cooling with IoT-enabled intelligent monitoring in a compact and low-cost architecture. The innovation includes remote temperature tracking, smart alert generation, cloud data storage, and efficient thermal management for healthcare and food preservation applications. Overall, the developed system provides a reliable, portable, and scalable cooling solution suitable for vaccine transportation, pharmaceutical storage, medical logistics, and cold-chain applications. Future improvements may include solar power integration, AI-based predictive monitoring, and advanced cloud analytics for enhanced performance and automation.

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ABOUT THE AUTHORS

Dr. Amol J. More, Assistant Professor, Department of Mechanical Engineering, AISSMS Institute of Information Technology, Pune, served as the mentor and technical guide for this research work. He provided expert guidance in the design and development of the experimental setup, ensuring accurate integration of thermal and electronic subsystems.

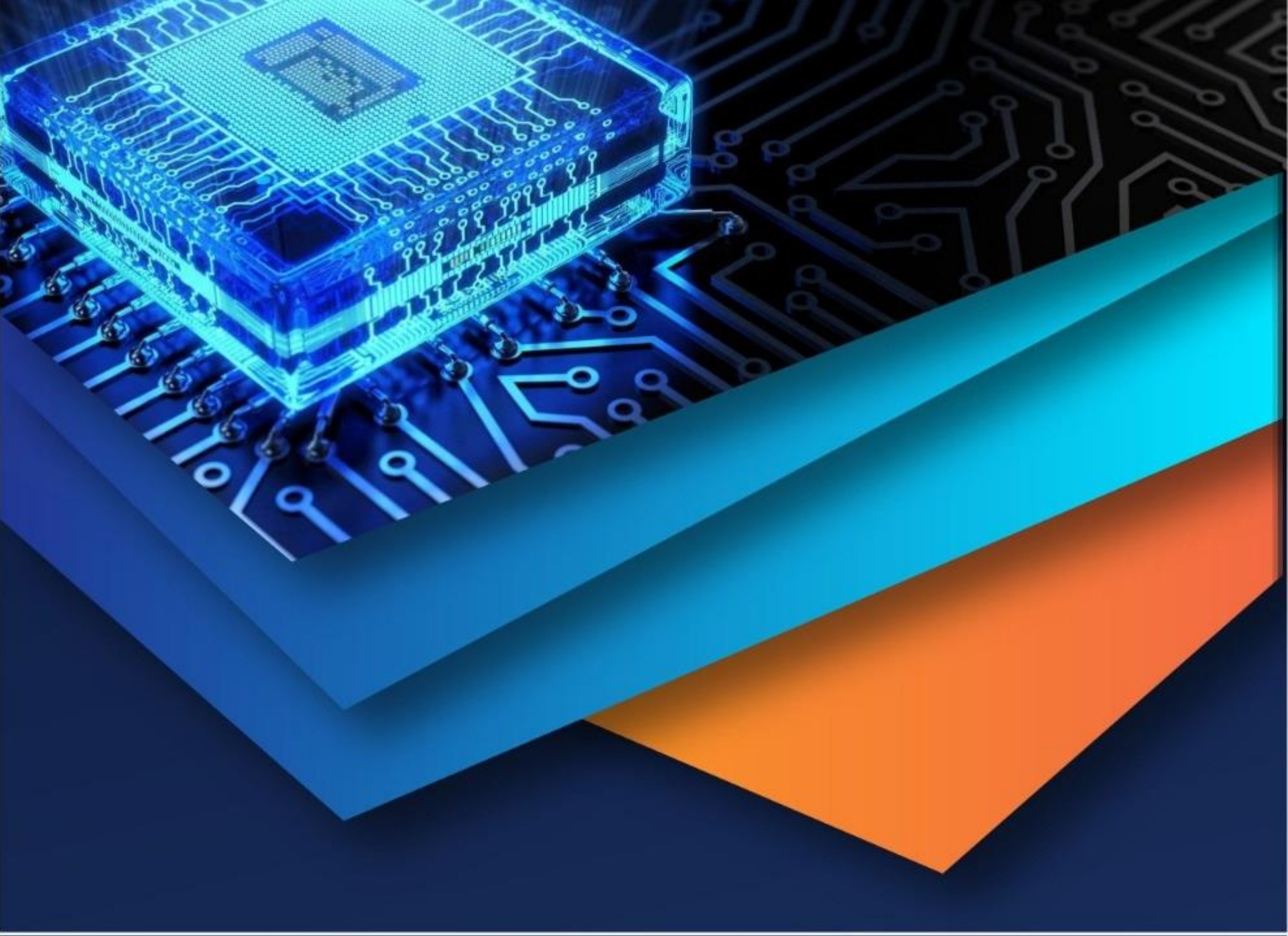
Tanvi Pawar is a first-year engineering student at AISSMS Institute of Information Technology, Pune. Her academic interests include embedded systems, IoT, and healthcare technology.

Jivan Pagadle is a first-year engineering student at AISSMS IOIT, Pune, with research interests in material science and thermal engineering applications.

Harshavardhan Lodhe is a first-year engineering student at AISSMS IOIT, Pune, focusing on hardware design and microcontroller programming.

Mahesh Darade is a first-year engineering student at AISSMS IOIT, Pune, with interests in IoT, cloud computing, and smart systems.

Dipshika Chavhan is a first-year engineering student at AISSMS IOIT, Pune, interested in portable energy solutions and cold chain management technology.



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