MJSAT 5 (4) 280-287

MJSAT

Malaysian Journal of Science and Advanced Technology

journal homepage: https://mjsat.com.my/

AgriCool: A Smart and Affordable Cold Storage Controller for Agricultural Use

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KEYWORDS

IoT
Precision Agriculture
Cold Storage
Cooling System
Post-harvest Loss

ARTICLE HISTORY

Received 6 April 2025
Received in revised form 1 November 2025
Accepted 20 November 2025
Available online 7 December 2025

ABSTRACT

Postharvest losses of fruits and vegetables at the farmer level are a major concern in Bangladesh. With the rising demand for fresh produce, effective cold storage is crucial for minimizing postharvest losses, maintaining product quality, and ensuring better returns. This study aimed to introduce and evaluate AgriCool, an affordable IoT-based cold storage controller designed to address the post-harvest challenges faced by smallholder farmers in Bangladesh. AgriCool integrates IoT-enabled sensors with a standard split air conditioner (AC) to monitor and control temperature and humidity in real time, which is accessible via a mobile application (Android). The system leverages a Wi-Fi-enabled microcontroller, digital temperature sensors, and a relay-driven heater mechanism to maintain optimal storage conditions while preventing ice accumulation on AC fins. AgriCool's simple design with a reliable algorithm, enhanced with a display and Android applications, ensures easy operation and consistent temperature control. Field testing of the system in Bangladesh revealed that AgriCool can sustain stable temperatures ranging from -2 to +15 °C, thereby improving the shelf life of perishable goods. At an estimated cost of USD 290, this affordable cold room controller system could offer substantial benefits to farmers by providing reliable cold storage and flexibility to store fruits and vegetables under better market conditions, thus preventing post-harvest loss and ensuring food security.

1. INTRODUCTION

The growing demand for fresh produce has made efficient cold storage systems a critical requirement, particularly in postharvest management [1]. Fruits and vegetables are among the most perishable commodities, and their quality begins to decline rapidly after harvest [2]. Exposure to high temperatures, such as 35°C for just one hour, can cause deterioration equivalent to 20 h under optimal cold storage conditions. Without timely pre-cooling, produce suffers from moisture loss and weight reduction, which significantly impacts both quality and market value [3]. Appropriate cold storage at low temperatures can extend the shelf life of fruits by preserving their freshness and slowing down microbial activity and ethylene production [4, 5, 6]. Under ideal conditions, fresh produce can last 2–4 weeks, and items such as potatoes, cabbage, and oranges can be stored for even longer [7]. However, prolonged storage without appropriate temperature and humidity control leads to gradual degradation [8]. Inadequate storage infrastructure remains a major challenge in developing regions, where up to 40% of harvested produce is lost, leading to lower farmer income and increased food insecurity [9, 10].

Cold storage not only preserves quality but also provides farmers with the flexibility to delay sales until market prices are more beneficial, enhancing profitability [11]. However, conventional cold storage remains inaccessible in many developing countries, such as Bangladesh. Approximately 80% of Bangladeshi farmers are small-scale or marginal producers and often lack access to affordable cold storage, forcing them to sell crops within a day of harvest to avoid spoilage [12]. High storage charges are consistently cited as a key reason smallholders cannot utilize cold storage, but published studies do not specify the use of imported refrigeration technology as a universal standard in Bangladesh [13, 14]. This highlights the urgent need for decentralized,

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https://doi.org/10.56532/mjsat.v5i4.514
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low-cost, on-farm cold-storage solutions tailored to the realities of rural agriculture.

Cold storage technologies have proven essential in mitigating post-harvest losses and stabilizing agricultural prices in Bangladesh. A study found that the expansion of cold storage capacity has effectively reduced the seasonal price fluctuations of potatoes, which helps stabilize market conditions for both farmers and consumers [15]. However, challenges like high costs, limited infrastructure, and access to cold storage in rural areas persist. Moreover, alternative solutions such as solar-powered and hybrid cold storage systems have shown promise, especially in off-grid areas, as they offer a more sustainable and cost-effective way to tackle these issues [16]. These technologies can reduce dependency on traditional energy sources while also extending the shelf life of perishable crops, which enhances food security.

AgriCool was designed to address this gap by offering a smart, standalone cold-storage solution that integrates multiple functionalities at a much lower cost. Compared with systems such as CoolBot, which was developed by Ron and Kate Khosla for their Huguenot Street Farm in New York [17, 18], AgriCool offers greater accessibility and technical flexibility. CoolBot modifies standard window air conditioners using a microcontroller and temperature probes to override the compressor shut-off, achieving temperatures as low as 2-4°C suitable for walk-in coolers [19, 20, 21]. However, it requires a compatible high-BTU air conditioner (typically 10,000–18,000 BTU) and a well-insulated enclosure (R-25 or higher), which increases the setup costs and complexity.

In contrast, AgriCool is a solar-compatible modular cold-storage unit designed specifically for smallholders. It incorporates thermally insulated chambers using polyurethane foam panels, an energy-efficient direct current (DC) compressor, and a lithium-ion battery system to support off-grid operations. A microcontroller-based IoT system enables the real-time monitoring and control of temperature and humidity via GSM or Wi-Fi, which is accessible through a mobile application. With 5-channel data logging, AgriCool ensures consistent environmental control and provides actionable data to users. The integration of AC cooling with IoT-based environmental control allows for the precise management of internal storage conditions. The intelligent controller of the system automates the compressor cycles and maintains the target temperatures based on crop-specific requirements. This study presents the design, installation, and performance evaluation of the AgriCool cold storage controller, with the aim of offering an affordable and technologically appropriate solution for improving postharvest storage in resource-limited settings.

2. METHODOLOGY

2.1 System Design and Location

The AgriCool controller was designed and developed at the ADI Research Center, Dhaka, Bangladesh, and tested in a cold storage facility located at the Bangladesh Agricultural University (BAU), Bangladesh. The AgriCool IoT controller was designed to control cold storage conditions by remotely monitoring and adjusting the temperature settings. Built with a Wi-Fi-enabled microcontroller, this system allows users to set the target temperatures and monitor the conditions in real time via a dedicated mobile application. The microcontroller communicated data to a real-time database (RTDB), enabling continuous logging for future analysis. The key components include two digital one-wire bus temperature sensors and a low-voltage relay module-controlled customized heater element, which together maintain optimal storage temperatures and prevent ice buildup in the cooling unit (Figure 1). We logged the temperature and humidity data over 2-minute intervals, and we placed five different locations. One sensor monitored the overall storage room temperature, whereas the second detected ice development in the cooling unit, activating the heater when needed, or vice versa. The heater functions as a simulated cold room temperature system designed to mimic the conditions within the cold room and control the AC-cooling unit operation. The controller also has buttons and a display for manually operating the system.

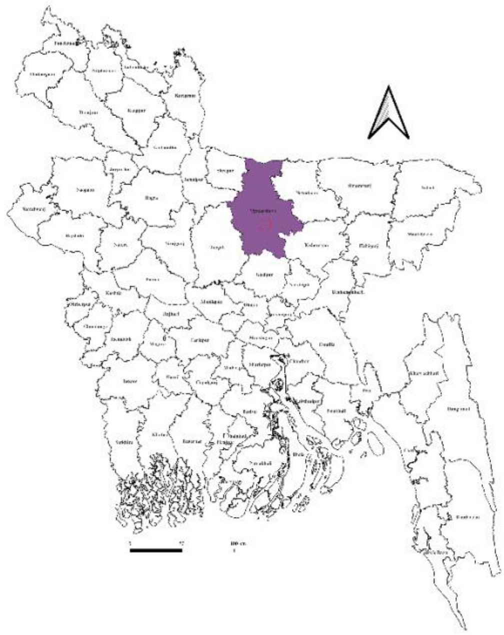

Fig. 1. Study location

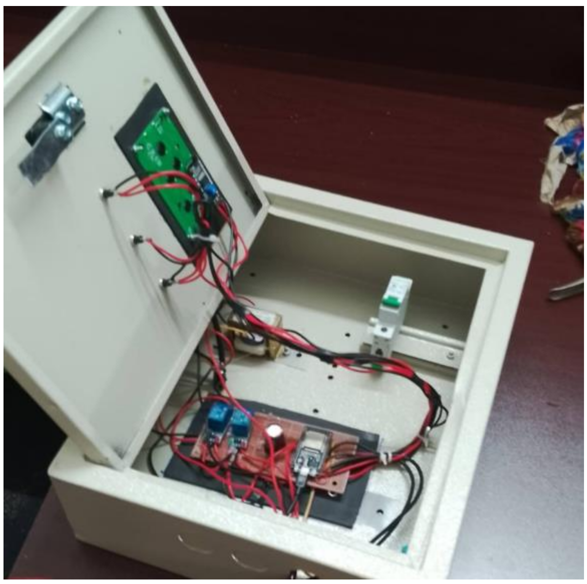

Fig. 2. AgriCool system

The core of the system is a Wi-Fi-enabled microcontroller (Figure 2). which collects all the sensor data, processes it locally, and transmits the information to a server hosting a central database (Figure 3). The data were sent over the Internet in the JavaScript Object Notation (JSON) format, with each reading tagged with a timestamp to ensure precise monitoring. This database acts as a secure repository for real-time data that can be accessed remotely using an Android application.

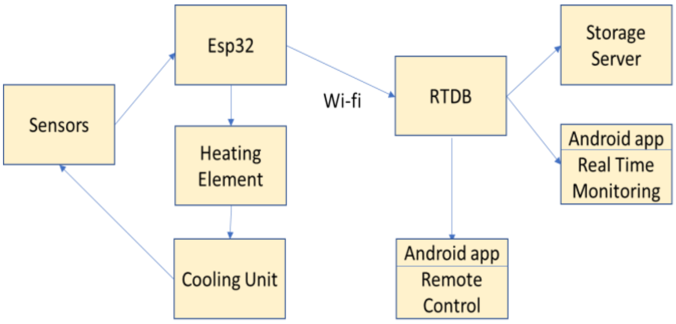

Fig. 3. Flow diagram

2.2 Hardware Setup and Testing

The hardware setup for the AgriCool controller involved the integration of an ESP32 microcontroller, temperature sensors (DS18B20 and DHT 11), relays, and a power supply. The ESP32 controls the cooling by activating the relays connected to the AC unit, thereby maintaining a set temperature. The temperature readings from the DS18B20 sensors were fed into the controller to allow real-time adjustments. A 12V power supply supports both the cooling unit and relays, whereas a separate 5V supply powers the ESP32. During testing, the temperature response and relay activation were monitored under different conditions to ensure stability and performance.

2.2.1 ESP32 Microcontroller

In the AgriCool system, the ESP32 (Figure 4) is a microcontroller with a built-in Wi-Fi functionality. It effectively processes the sensor data, operates the actuators, and provides connections via digital and analog ports.

Fig. 4. ESP32 Microcontroller

The ESP32 operates with a 3.7–5V power supply and includes an internal voltage regulator to ensure stable performance. Its ability to transmit data in JSON format to a Real-Time Database (RTDB) over Wi-Fi is essential for enabling real-time monitoring and data storage, supporting rapid updates, and remote access for effective management [22, 23].

2.2.2 Sensors and actuators and circuit diagram

The IoT-based temperature control system is centered on an ESP32 microcontroller that manages sensor inputs, actuator control, user interactions, and real-time monitoring. The system uses five DHT22 sensors (Figure 6), each providing temperature (±0.5°C accuracy) and humidity (±2–5% accuracy) readings. These sensors were connected to GPIO pins 4, 5, 16, 17, and 18 on the ESP32, with 10kΩ pull-up resistors to ensure stable signal transmission. Additionally, two DS18B20 digital temperature sensors (Figure 5), also with ±0.5°C accuracy, were connected in parallel to GPIO pin 26 using a 4.7kΩ pull-up resistor. All sensors were calibrated prior to deployment by placing them in a controlled environment and adjusting their readings to ensure consistent and accurate measurements.

A 5V relay module (Figure 7) was connected to GPIO pin 33 and controlled the heating element. The relay is activated when the ambient temperature falls below the preset limit, thereby preventing excessively cold storage conditions. Three user control buttons were connected to GPIO pins 34, 32, and 35, enabling the manual adjustment of the temperature setpoints and other parameters. A 4 × 20 LCD display with an I2C interface was used to display the real-time temperature, humidity, and system status, whereas a buzzer connected to GPIO pin 25 provided audible alerts for critical temperature deviations or system faults. A heartbeat LED connected to GPIO pin 19 blinks periodically to indicate that the system is active and functioning.

The power management setup included a 20 W power supply connected to a mini-charge controller that charged a 3.7V 1S 10000mAh Li-ion battery. A voltage regulator ensured that the ESP32 and all peripheral components received a stable power supply, enabling uninterrupted operation. The integration of these component sensors (Figure 5 and 6), actuators (Figure 7), microcontrollers, user interfaces, and power management forms a compact and efficient solution for low-cost IoT-enabled temperature control in small-scale cold storage applications.

Fig. 5. DS18B20

Fig. 6. DHT22

Fig. 7. Relay

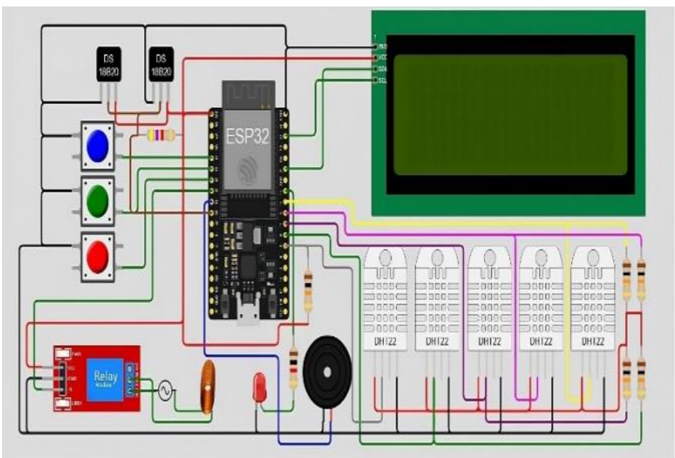

Fig. 8. Circuit diagram

2.3 Programming and Installation

The system was programmed using the Arduino IDE with specific instructions for managing the sensor inputs, sleep modes, and data transmission. The ESP32 wakes up twice daily at pre-programmed intervals, reads the water levels from the sensors, and sends the data to the Real-Time Database (RTDB). The data are sent in JSON format and are accessible through a dedicated Android application [24]. The installation involved securing the sensors in the PVC structure, placing the ESP32 and power supply in weatherproof housing, and ensuring proper connectivity to the Android app via Wi-Fi.

2.4 Android Application

A dedicated Android application was used for the real-time monitoring of the internal temperature of the system. The app receives data from the RTDB and provides notifications to the user whenever a change in the readings is abnormal or does not match the preset settings of the AgriCool System. The user interface allows easy data visualization, including the current cooling unit status and temperature data, enabling efficient management of cold storage (Figure 9).

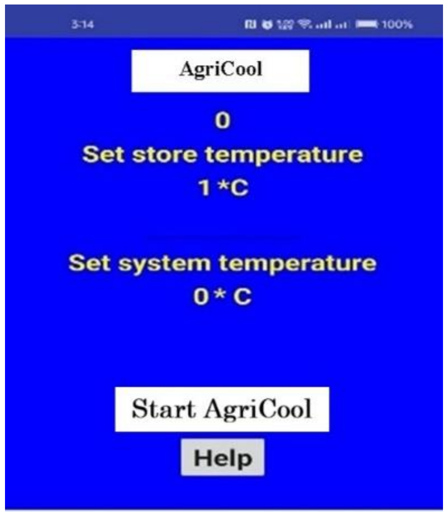

Fig. 9. Screen shot of Android application

2.5 Power consumption calculation

To determine the electrical load and power requirements of the ESP32-based setup, we calculated the power consumption of each component and analyzed the total load. The setup included an ESP32 microcontroller, two relays, five DHT11 sensors, two DS18B20 temperature sensors, and a 10 W temperature load. The ESP32, relays, and sensors operate at 5V, while the temperature load requires 12V. The power consumption P of each component was calculated using [25].

The ESP32, operating at 5V, typically draws 240 mA, leading to a power consumption of 1.2 W. Each relay consumes 70 mA, contributing an additional 0.7 W when both are activated. DHT11 sensors draw around 0.5 mA each, totalling 0.0125 W for five sensors, while the DS18B20 sensors drawing 1.5 mA each, consume 0.015 W. The 10 W temperature load operating at 12V.

3. RESULT AND DISCUSSION

After compiling and uploading the program code to the ESP32 board, each system parameter was systematically tested to evaluate the temperature regulation performance. Figure 11 presents the results of these tests, showing the relationship between the set and actual temperatures for both the fin and room, along with the status of the heater pin, where a value of 1 indicates that the heater is ON and 0 indicates that it is OFF. This heater pin logic serves as a real-time indicator of the thermal response of the system to changes in environmental conditions. For example, with a set fin temperature of 5°C and a set room temperature of 8°C, the actual fin temperature stabilized at 5.3°C and the actual room temperature at 7.3°C, illustrating that the system successfully maintained the target conditions without requiring heater activation (heater pin = 0).

When the room temperature was lowered to 6 and 4°C, the actual room temperature decreased to 6.4 and 4.3°C, respectively. In both instances, the heater pin was switched to 1, signalling the activation of the heater to offset the cooler ambient conditions. This demonstrates that the system responds appropriately by engaging the heating element when the room temperature approaches or falls below a set threshold value. However, in more extreme settings, such as a set room temperature of 0°C, the actual room temperature dropped to -0.7°C while the heater remained inactive (heater pin = 0), indicating a performance limitation in extreme cold conditions where the heating logic may not have been triggered in time or lacked sufficient power to stabilize the environment (Figure 10).

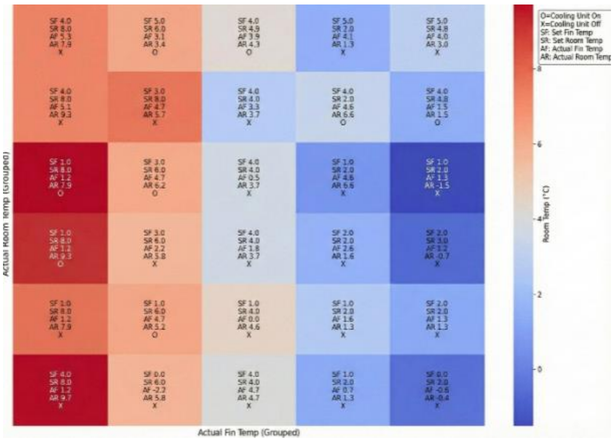

Fig. 10. Performance test of the system

For smallholder farmers, these fluctuations can directly affect their income. When the temperature falls below optimal levels and the quality deteriorates, farmers are forced to sell quickly at lower prices or risk postharvest losses. In addition, inconsistent heating increases energy inefficiency and operational costs. Therefore, understanding and addressing these fluctuations, such as improving the heater control logic or insulating the chamber more effectively, is essential for ensuring that AgriCool delivers reliable, affordable cold storage that protects farmers' harvests and boosts profitability in resource-limited settings [26, 27].

The temperature and humidity data collected between 10:00 AM and 11:58 AM on August 22, 2024, provided a clear picture of the climatic conditions and cooling performance of the AgriCool system. Initially, the environment was warm and humid, with a temperature of 34.0°C and relative humidity of 96%, likely influenced by external heat and high atmospheric moisture levels. Over the observation period, the temperature consistently decreased, reaching as low as 2.17°C by 11:42 AM, indicating substantial cooling within a relatively short timeframe.

Figure 11 highlights this rapid temperature decline, especially between 10:00 AM and 10:30 AM, where the internal temperature fell sharply from 34.0°C to 9.95°C. This dramatic decrease demonstrates the strong thermal responsiveness and cooling efficiency of the system during the initial activation phase, reducing the temperature by over 24°C in just 30 min under typical ambient conditions.

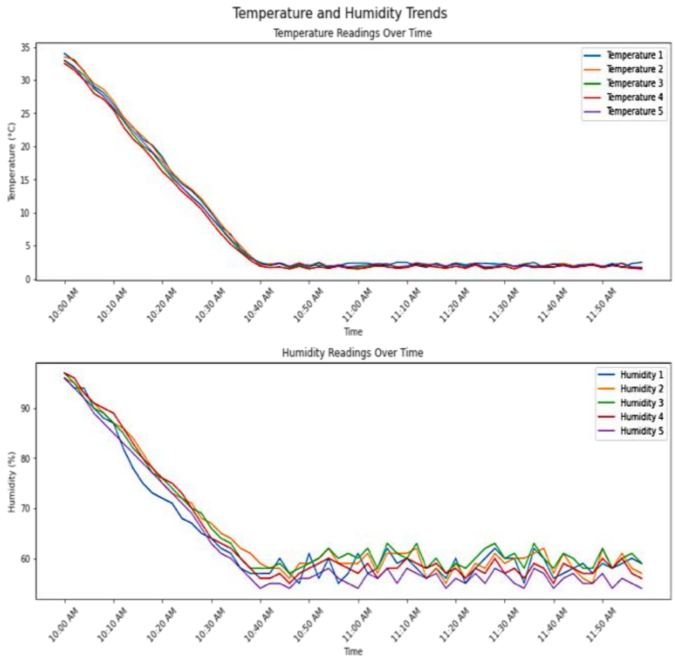

Fig. 11. (a) Temperature and (b) Relative humidity trend over time during test

Following this initial cooling phase, the temperature continued to decline more gradually and stabilized in the range of 1.70°C to 2.49°C during the final 30 min of the observation period. This stabilization indicates that the system successfully maintained a low and consistent internal temperature, fulfilling the target range required for the cold storage of perishable goods in the food industry. The sustained low temperature without frequent fluctuations reflects the controller's ability to balance the cooling demand and compressor cycles, which are critical for energy conservation and ensuring safety.

The relative humidity showed considerable variability throughout the study period. Starting at a peak of 96% at 10:00 AM, the humidity levels gradually decreased and fluctuated between 55%–94%. The overall downward trend in humidity correlated with the temperature drop, suggesting that the cooling action of the system effectively reduced the moisture-holding capacity of the air, which is consistent with thermodynamic expectations. Maintaining relative humidity within this range is essential to prevent both microbial growth (at high humidity) and moisture loss during production (at low humidity). The ability of the system to regulate both temperature and humidity within acceptable limits demonstrates its suitability for the preservation of postharvest quality.

Overall, the data presented in Figure 11 validate the efficiency of the AgriCool system in rapidly achieving and maintaining cold storage conditions while concurrently managing humidity levels. This performance is particularly important for smallholder farmers because it enables the safe storage of fruits and vegetables during peak heat hours, reduces spoilage, and allows flexibility in market timing, ultimately supporting better income and reducing post-harvest losses [28].

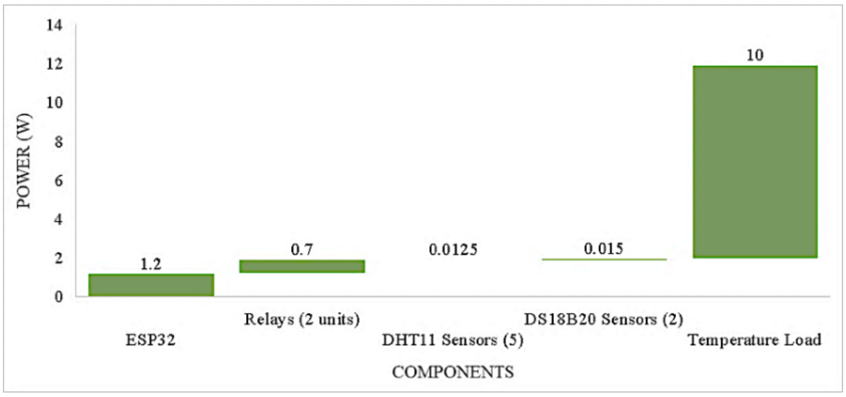

Fig. 12. Power consumption by different components

Table 1. Power Consumption data

Component	Voltage (V)	Current (A)	Power (W)	Percentage of Total Power (%)
ESP32	5	0.24	1.2	10.1
Relays (2 units)	5	0.14	0.7	5.9
DHT11 Sensors (5)	5	0.0025	0.0125	0.1
DS18B20 Sensors (2)	5	0.003	0.015	0.1
Temperature Load	12	0.83	10	83.8
Total			**11.93**	100

Figure 12 and Table 1 clearly demonstrate the efficiency of the AgriCool system, with the temperature control component accounting for the largest share of energy use. This optimized energy distribution highlights the ability of the system to minimize unnecessary power draws, thereby directly contributing to lower operational costs. By maintaining effective temperature regulation while consuming minimal energy, AgriCool ensures cost savings over time, reinforcing its claim of cost-effectiveness. The reduced power requirements not only lower electricity expenses but also make the system viable for users with limited access to reliable power sources, further enhancing affordability for smallholder farmers and resource-constrained settings.

The system's total power consumption was about 11.93 W, with most of that power, around 10 W, going toward temperature control, making up approximately 84% of the total energy usage. The ESP32 and relays each contributed 10.1% and 5.9% respectively, while the sensors used just 0.2% of the power. This breakdown clearly shows that temperature regulation plays a major role in the system's energy consumption. As for cost efficiency, the system's relatively low energy usage combined with the potential to reduce spoilage in perishable goods suggests that users could see a solid return on investment fairly quickly. For comparison, the CoolBot Generation 7 is priced at about $419 USD, while the Generation 6 model costs around $374. A bar graph was also created to visually illustrate the power distribution among the components, clearly showing how much of the energy is devoted to maintaining temperature.

One of the primary advantages of the AgriCool system developed in this study is its cost-effectiveness. Engineered with an emphasis on affordability, the system incorporates low-cost components, thereby making it accessible to a broad spectrum of users, including small-scale farmers and individuals seeking efficient cooling solutions. Below, we delineate the cost components of the system and demonstrate how its economic nature renders it attractive for various future applications. The total estimated cost of the AgriCool system is approximately USD 290 (Table 2), which is relatively affordable given the advanced features it offers. This approach ensures that users receive a robust and reliable system. These prices reflect CoolBot's specialized capability to convert standard air conditioners into efficient cooling systems for walk-in coolers [29, 30].

AgriCol represents a transformative innovation for small-scale farmers in developing regions, where technology affordability often dictates adoption. Rather than depending on costly cooling methods, AgriCol provides an accessible alternative. The system employs technology to monitor storage conditions, specifically temperature and humidity, which are critical for crop freshness. This information is accessible via an application or web interface, enabling remote adjustments by farmers. Although this innovation reduces post-harvest losses, it is not a universal solution. Some farmers may face obstacles like limited electricity or internet access, which could impede the system's efficacy. Nevertheless, for those able to implement it, AgriCol can reduce energy costs and enhance profitability, vital for smallholders with narrow margins. The ability to extend crop preservation likely enhances food security and enables farmers to derive greater value from produce. However, as with any new system, evaluating its scalability and sustainability across farming contexts remains essential.

Table 2. AgriCool system cost

Sl. No	Item Description	Unit Price (USD)	Quantity	Total Price (USD)
1	Electronics Component	125	1	125
2	Fabrication	35	1	35
3	Encloser	30	1	30
4	Wi-Fi Connectivity	50	1	50
5	Cloud Storage and Android app	50	1	50
	Total Price (USD)			290

4. CONCLUSION

The IoT-based cooling system developed in this study offers a practical solution for improving the post-harvest storage of fruits and vegetables in Bangladesh, particularly for smallholder farmers who lack access to conventional cold-storage infrastructure. By automating temperature monitoring and control, the AgriCool system helps reduce post-harvest losses and extends the shelf life of perishable crops, such as tomatoes, green chilies, leafy vegetables and bananas, which are highly sensitive to temperature fluctuations. The system integrates a Wi-Fi-enabled microcontroller and allows real-time environmental monitoring and remote adjustments through a dedicated Android application, thereby enabling users to maintain consistent storage conditions with minimal manual intervention in the storage process. AgriCool's continuous data logging and cloud-based access facilitate informed decision-making for storage management. Although the system demonstrated reliable performance under typical conditions, tests revealed that it may exhibit temperature fluctuations under extremely cold settings, indicating the need for improved heater control or insulation in such scenarios. Despite this, the modular nature of the system allows for potential upgrades, including integration with solar power and battery storage for off-grid use, and scaling to accommodate larger or multiple storage units. These characteristics make AgriCool particularly beneficial for farmer producer groups, community cold rooms, and cooperatives to improve storage efficiency and reduce spoilage without incurring high infrastructure costs.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the AgroMech Development Initiatives (ADI) Foundation and the DBBL-CSR-GraTA funded project, and the "Cold Storage Solution for Reducing Post-Harvest Losses of Fruits and Vegetables in Bangladesh," implemented by the Bangladesh Agricultural University, Mymensingh, Bangladesh. Special thanks are extended to Dutch-Bangla Bank Limited (DBBL) for being the first to finance this initiative as a CSR project and for laying the foundation for innovative post-harvest solutions in the country.

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