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SMART FOOD SPOILAGE PREVENTION SYSTEM USING AUTOMATED COLD STORAGE AND REAL-TIME MONITORING

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***Abstract*—Food spoilage poses a serious threat to today's global food supply chain. Food spoilage has detrimental effects on an organization finances, product quality, and public safety. Food spoilage occurs due to temperature fluctuations, high humidity, and excessive accumulation of spoilage-inducing gases in food storage environments. All of these conditions accelerate the growth of harmful bacteria, leading to the spoilage of food products. This study presents the Smart Cold Storage System for Food Spoilage Prevention, which provides real-time monitoring and automated control of critical storage conditions to keep food as fresh and tasty as possible. The Smart Cold Storage System is comprised of a micro-controller-based control unit, temperature, gas, and IR sensors that constantly monitor the internal condition of food product storage. When the conditions of the stored food products exceed predefined limits, the system will automatically activate its cooling equipment and provide an immediate notification via an Internet of Things (IoT) module. A keypad allows the user to configure the unit, while an LCD provides a viewable display of the unit's current condition. By implementing the Smart Cold Storage System for Food Spoilage Prevention, food waste will be reduced, public safety enhanced, and sustainable management of cold chain systems will be maintained.**

***Index Terms*—Smart Crutch, Internet of Things (IoT), Axillary Crutch, Fall Detection, GPS Tracking, Load Sensor, Rehabilitation Monitoring, Assistive Technology.**

I. Introduction

Food spoilage is a very serious problem in the world food supply chain that causes losses of economic values, degrading food quality and raising threats to the health of the population. Recent reports highlight the increasing demand for smarter food systems which have the integration of the modern technologies to advance food quality monitoring and safety management [1]. Storage environments should be controlled effectively because an inappropriate temperature, excessive humidity, and the accumulation of gases are important factors that increase the rate of microbial growth and food degradation. To overcome these issues, cold supply chain management has been named as one of the main solutions to preserve the perishable food products and reduce the losses after harvesting with the help of technologies and structure [2]. Poor storage environments not only cause spoilage but also enhance food borne diseases because of poor handling of the products and products that are still fresh, this is due to the fact that there have been advancements on micro cold storage systems that have improved production of fresh food and fruits due to sensor-based monitoring systems and automatic control solutions [4]. Also, the adoption of food safety management systems like HACCP draws attention to the ongoing monitoring and preventive controls in the food storage and handling processes [5]. These changes highlight the importance of automated, intelligent cold storage systems to prevent food spoilage effectively.

A. Objectives

- To develop and design an axillary crutch that is lightweight, foldable, and uses the IoT technology to increase mobility support.
- To design and develop a smart cold storage system to ensure effective food spoilage prevention.
- To continuously record vital storage conditions including temperature, gas concentration, and movement employing inbuilt sensors.
- To introduce automated control systems that ensure the best storage conditions through switching on cooling systems when the threshold levels are met.
- To facilitate remote monitoring and instant alert notification with help of Internet of Things (IoT) technology.
- To minimize food wastage and increase food safety through cold storage conditions which are stable and controlled.

B. Contribution of the Work

- Design of a smart microcontroller-based cold storage system to prevent real time food spoilage.
- Combination of temperature sensors, gas sensors and IR sensors to provide a complete monitoring of food storage conditions.
- Installation of an alert system which uses IoT to notify of abnormal storage conditions promptly.
- Inclusion of a user-friendly interface with a keypad as a configuration and an LCD to display a real time system status.
- Exhibition of an economical and energy-efficient system that enables sustainable cold-chain management and better-quality control of foods.

The remaining portion of the document is divided into significant sections, which are described as follows: Section II examines the current research efforts in Smart Food Spoilage Prevention System used by different authors. Section III explains the workflow of the suggested approach in Proposed Methodology. Section IV presents the findings analysis and performance data. Section V presents the conclusion.

II. LITERATURE SURVEY

Jung et al. (2022) designed a smart packaging system based on the use of laser-induced graphene (LIG) that was produced on paper using laser-induced graphene (LIG). Their research showed that low-priced, flexible electronic sensors that can detect food spoilage gases in real-time were successfully integrated so that quality monitoring in storage can be continuous. The paper-based LIG has a mechanical flexibility, light weight and can be used with scaled production. Notably, the suggested platform will resolve environmental issues associated with the traditional electronic sensors based on plastic by ensuring sustainability and disposability. This article sheds light on the practicability of environmentally friendly clever packaging designs that will merge real-time sensing operational features with less environmental effects.

Khalid et al. (2024) have provided an extensive overview of the key causes of tomato spoilage, including the development of microorganisms, enzyme activities, and environmental influences, including temperature and humidity during storage and transportation. The paper has critically evaluated the weaknesses of the traditional packaging systems that include poor gas and moisture barriers properties and lack of real-time monitoring of quality. The authors also emphasized the role of these weaknesses in the losses incurred after harvesting fresh produce. Their results highlight the fact that there is a high demand for sophisticated packaging methods, especially active and intelligent packaging methods, to improve shelf life, ensure quality and decrease food waste.

The article by Khan et al. (2024) covered recent material and technological advances in smart food monitoring systems and especially responsive materials, biosensors, and on-site diagnostic instruments. They have made the integration of chemical, biological, and physical sensing processes in food packaging in their study to detect markers of food spoilage and food contaminants in real-time. The authors identified the progress of miniaturized sensors, signal transduction, and data interpretation that make it possible to monitor the food supply network at in-situ locations. Furthermore, the review has highlighted the increased role of wireless communication and data-processing capabilities in smart packaging. The paper serves well in the design of multifunctional intelligent packaging systems that can be used to improve food safety and quality assurance.

Kumar et al. (2022) explored the implementation of cold plasma as a non-thermal process to decontaminate food materials by the use of cold plasma in inactivating food-borne pathogens, toxins, and allergens. They showed that cold plasma treatment proved to be very useful in minimizing microbial contamination and maintaining nutritional and sensory qualities of food products. Compared to the traditional thermal processing, cold plasma is also performed at low temperatures and reduces the negative impact on the food structure and freshness. Issues that play a major role in treatment efficiency which include plasma source, exposure time and food matrix were also discussed by the authors. All in all, the present research makes cold plasma a promising complementary technology to intelligent packaging systems in order to enhance food safety and shelf life.

Ma et al. (2022) have been an elaborate review of intelligent packaging indicators, such as pH-sensitive dyes, gas-sensitive indicators, and time-temperature indicators, which were used to detect food spoilage. Their contribution saw the importance of visual indicators, being simple and consumer-friendly in that they can be used to quickly test the freshness of food without any special tools. The authors addressed the workability, work mechanism, and usage contexts of the diverse pointers of dissimilar foods items. Nevertheless, there were also problems like insensitivity, reproducibility in color, accuracy in reactions, and mass production that were pointed out. The paper highlights the necessity of a more advanced optimization that would enhance reliability and business feasibility of intelligent packaging indicators.

TABLE I COMPARISON TABLE FOR LITERATURE SURVEY

Ref.No	Study Focus	Technology Approach	Application	Major Advantages
11	Biodegradable active packaging films	Nano, microcapsule incorporation in biopolymer films	General food packaging	Improved mechanical strength, controlled release of active agents, enhanced antimicrobial and antioxidant properties
12	Post-harvest loss reduction	Improved handling, storage, and supply-chain strategies	Sweet corn	Extended shelf life, reduced food waste, improved food security
13	Biological preservation methods	Bacteriophage delivery systems	Meat, dairy, fresh produce	High specificity against pathogens, minimal impact on

				food quality, eco-friendly
14	Shelf-life and quality evaluation	Cold storage and biochemical profiling	Edible flowers	Preservation of sensory attributes and bioactive compounds, quality assessment
15	Digital and advanced processing integration	Artificial intelligence and advanced food processing technologies	Food safety and quality management systems	Real-time monitoring, predictive quality control, enhanced decision-making

A comparative summary of recent research concentrating on advanced food packaging, preservation, and safety technologies is provided in Table 1. Among the chosen literature, various approaches, such as biodegradable active films containing nano/microcapsules, biocontrol based on bacteriophages, better post-harvest practices, and cold storage methods to maintain quality, are identified. Moreover, new strategies that combine artificial intelligence and modern technologies of food processing are demonstrated to assist in real-time performance and predictive quality control. Although these methods show considerable potential in the extension of shelf life, improvement of food safety, and minimization of food waste, issues of scalability, cost, regulatory approval, and acceptance by consumers persist, which signifies that integrated and sustainable solutions are needed.

III. PROPOSED METHODOLOGY

The proposed approach is to create a Smart Cold Storage System that continuously monitors and controls food storage conditions. The Smart Cold Storage System will use a microcontroller as a central control unit, integrating temperature, gas, and infrared (IR) sensors to monitor the storage environment in real time. The sensors will continuously collect and evaluate data against predefined threshold values to determine whether the conditions for food storage are acceptable. Once the temperature or gas level exceeds the permissible limits, the microcontroller will automatically activate a relay module, which will switch on a cooling mechanism to restore the storage to acceptable levels. At the same time, an Internet of Things (IoT) module will transmit real-time data and alert notifications to users via a mobile and/or web-based user interface. A keypad will also be provided to allow the user to set threshold values, and an LCD will display the system's current status in real time. The overall objective of this automated and intelligent approach is to provide earlier detection of food spoilage, more effectively manage the environment, and improve cold-chain management.

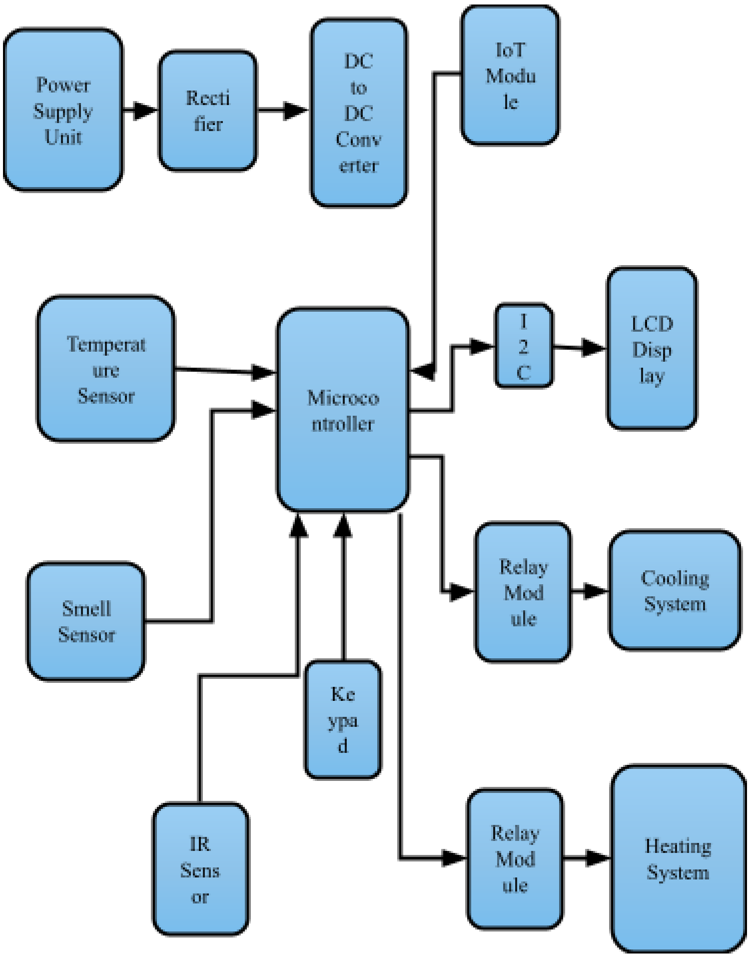

Fig.1.Proposed Overall Block Diagram

A. Sensor-Based Data Acquisition System

A Sensor-Based Data Acquisition System that continuously receives updated data related to different environmental parameters within the cold storage unit is one of its key components in the proposed smart cold storage model. The Integrated system of Temperature sensor (LM35), Gas sensor, Infra-Red (IR) Sensor which detects the parameters responsible for food spoilage. Moreover, the IR sensor is used in tracking any movement or changes of items being stored. The sensed data is reached by the microcontroller for further analysis. This data acquisition system allows the user to monitor any time causing early detection of unsuitable conditions and prevents food spoilage and maintains storage quality.

TABLE II Mathematical Models for Sensor Data Acquisition

S. No	Parameter	Formula	Description
1	Temperature Conversion	$T(^{\circ}C) = \frac{V_{out} - V_{offset}}{S}$	Converts sensor voltage output into temperature value
2	Gas Sensor Ratio	$\frac{R_s}{R_0}$	Indicates concentration of spoilage gases based on resistance ratio

3	Sensor Resistance	$R_s = R_L\left(\frac{V_c - V_{out}}{V_{out}}\right)$	Calculates sensor resistance from output voltage
4	Threshold Condition	$T > T_{max}\ or\ Gas >$	Determines abnormal condition for spoilage detection
5	Sampling Frequency	$f_s = \frac{1}{T_s}$	Defines how frequently sensor data is collected

Table 2 above provides mathematical models for the important parameters to be used in Sensor-Based Data Acquisition System for Food Storage monitoring. It is crucial to use the temperature conversion program in order to convert the sensor voltage into precise temperature readings for environmental control. Gas sensor ratio using resistance change as an indicator of gas concentration makes it easier to determine spoilage. There are sensor resistance calculations using circuit parameters that enables accurate levels of gas measurement. The threshold condition equation determines whether the environment exceeds safe limits, triggering alerts or control actions. Finally, the sampling frequency defines how often data is collected, ensuring continuous and real-time monitoring. Together, these equations enable accurate sensing, timely decision-making, and effective prevention of food spoilage.

B. Arduino Uno Microcontroller-Based Processing and Decision Making

One of the most important challenges our global community is facing is climate change. All of this demonstrates a changing climate: It getting hotter, icebergs are melting and monstrous weather events keep happening. If we do not act soon to lower greenhouse gas emissions, the catastrophic outcomes could be entirely unpredictable, according to scientists. All three have a duty to fulfil in this crisis. Conventional sources of energy such as coal and gas have negative environmental impacts whereas renewable energy resources like wind, solar power have cleaner environment benefits. In doing so, we will be working together to help alleviate the consequences of climate change with these new forms of technology and choices.

Fig.2. Arduino Uno Microcontroller

If there is anything that can lay claim to being a pressing issue of our world today, it is climate change. A lot of the changes associated with a changing climate, such as higher temperatures, melting ice caps and extreme weather events, are well-publicized. If we fail to curb greenhouse gas emissions today, the ramifications could be cataclysmic, scientists warn. This crisis is something that can only be solved by governments, businesses and all of us as individuals. Wind and solar power are quickly renewable sources that can replace harmful fossil fuels. In consequence, through utilizing these advancements innovation and having supportable choices, we can limit the results of environmental change.

TABLE III ARDUINO UNO SPECIFICATIONS

S. No	Specification	Details
1	Microcontroller	ATmega328P
2	Operating Voltage	5V
3	Input Voltage (Recommended)	7V – 12V
4	Input Voltage (Limits)	6V – 20V
5	Digital I/O Pins	14 (of which 6 provide PWM output)
6	Analog Input Pins	6
7	Flash Memory	32 KB (0.5 KB used by bootloader)
8	SRAM	2 KB
9	EEPROM	1 KB
10	Clock Speed	16 MHz
11	USB Interface	USB Type-B
12	Communication	UART, SPI, I2C
13	DC Current per I/O Pin	20 Ma
14	DC Current for 3.3V Pin	50 Ma
15	Power Consumption	Low power consumption suitable for embedded systems

One of the most urgent problems of our world today is climate change. The changing climate is manifested by rising temperatures, melting ice caps, and more occurrence of extreme weather events just to mention but a few. Scientists caution that the effects of not acting now to mitigate greenhouse gas emission can be disastrous. This is a crisis that should be addressed by governments, businesses, and individuals. Wind and solar power are renewable energy sources that can be used as an alternative to fossil fuels. Through the adoption of these technologies and environmentally friendly decisions, we can contribute to the reduction of the effects of climate change.

C. Automated Cooling and Control Mechanism

Automated Cooling and Control Mechanism is the mechanism that controls the optimal storage conditions within the cold storage system by controlling the temperature and environmental conditions within the cold storage system. The microcontroller in this module is constantly fed with processed sensor data that is used to decide whether the existing conditions fall above predetermined threshold values. In case of an increase in temperature or gases concentration above safe levels, the microcontroller transmits a control signal to the relay module. The relay is a switch that will automatically turn on the cooling system, e.g. a refrigeration unit or a fan, to cool down the temperature and provide a safe environment again. Similarly, if required, a heating element can also be controlled to maintain balance. When the surroundings resume normal conditions, the system will automatically deactivate the cooling system to save on energy. This automation will guarantee an efficient operation, a minimized manual intervention, and assists in avoiding food spoilage.

$$Q = mc\Delta T \qquad (1)$$

The equation $Q = mc\Delta T$ represents the amount of heat that must be removed from the storage environment to reduce the temperature. Here, m denotes the mass of the stored food, $c$is the specific heat capacity, and ΔT is the change in temperature. This equation helps in estimating how much thermal energy needs to be extracted to maintain safe storage conditions.

$$P = \frac{Q}{t} \qquad (2)$$

The equation $P = \frac{Q}{t}$ defines the cooling power required by the system, where Q is the heat removed and $t$is the time taken. It indicates how quickly the cooling system must operate. Together, these equations help in designing an efficient cooling mechanism for preventing food spoilage.

D. IoT-Based Real-Time Monitoring and Alert System

The IoT-Based Real-Time Monitoring and Alert System will allow one to monitor the cold storage environment in real time even when at other locations by having an internet connection. The module will connect the Arduino Uno to an IoT communication module (say Wi-Fi) and the sensor data will be transmitted in real-time to a cloud service or mobile app to display temperature, gas levels, and system status. The data gathered is continuously updated and the user can check on storage conditions any time. In the case where the system picks up on abnormal situations, i.e. temperature is greater than the set point or there is evidence of spoilage gases, then instant alert messages are provided to the user via mobile alerts, SMS, or web dashboards. This aspect guarantees fast reaction and preemptive measures even in case of absence. In general, the IoT integration facilitates better intelligence of the system, increases monitoring efficiency, and is crucial in minimizing food spoilage and ensuring food safety.

TABLE IV MATHEMATICAL MODELS FOR IOT MONITORING AND ALERT SYSTEM

S.No	Parameter	Formula
1	Data Transmission Rate	$R = \frac{D}{t}$
2	Network Latency	$L = t_{receive} - t_{send}$
3	Signal Strength (RSSI)	$RSSI = P_r$
4	Alert Condition	$T > T_{max}$ or $G > G_{max}$
5	Packet Loss Ratio	$PLR = \frac{P_{lost}}{P_{sent}}$
6	System Efficiency	$\eta = \frac{Valid\ Data}{Total\ Data} \times 100$

The table 4 shows the key formulae utilized in the IoT-based real-time monitoring and alert system to analyze the performance and reliability of communication. Data transmission rate defines the efficiency of sensor data transmission to the cloud and network latency defines the delay between data transmission and reception. Signal strength (RSSI) signals the level of the wireless connection, which guarantees the stable communication. The alert state assists in raising a notification in case of gas or temperature exceeding the safe levels. Packet loss ratio is used to determine the reliability of data transmission, and system efficiency is used to determine the accuracy of the data that is transferred successfully. Collectively, these parameters guarantee efficiency in monitoring, prompt alerts, and efficient performance of the system.

IV. RESULTS AND DISCUSION

The performance of the Smart Cold Storage System in averting food spoilage in various operating environments is assessed in the results and discussion section. A variety of food items were used in the test, and both manual and preset temperature modes were tested. The findings indicate that the system was able to bring and sustain the necessary temperatures in all the cases. The correct performance was achieved through real-time monitoring, automatic control, and sensor integration. The results show that the system can preserve food better and decrease spoilage and increase the total efficiency of storage.

Fig.3.Manual Mode Temperature Control Display

This figure 3 indicates the control panel of the smart cold storage system in the manual mode. LCD shows that the desired temperature is reached (32o C) and the message says that the target is reached, which proves that the desired temperature was reached successfully. The keypad interface enables the user to manually set and change temperature settings when necessary. The mode offers flexibility to store food items that demand particular temperature settings but not preset. The outcome illustrates the capacity of the system to regulate and maintain user-controlled temperatures precisely to ensure appropriate food preservation and effective operation of the system.

Fig.4Auto Mode Food Preset Selection Display

This figure 4 represents the control panel under auto mode, in which programmed food selections, including rice, tomato, banana and puff, are shown on the LCD display. Each preset is related to a certain temperature, which is optimized to that food item. The Target Reached message will indicate that the system has automatically kept the required temperature at the desired level. The system is easy to use with the keypad allowing easy selection of presets. This number shows how it is possible to automate the system and save on the manual effort, yet keep the system in control of proper temperature to various food preservation needs.

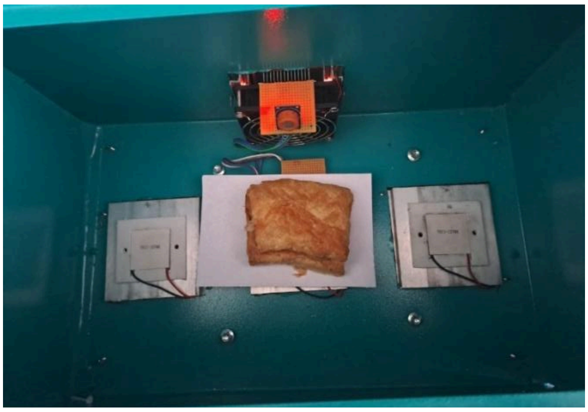

Fig.5 Internal Storage Chamber with Heating/Cooling Setup

This figure 5 depicts the internal arrangement of the smart cold storage chamber where a food sample (puff pastry) is at the center. The system consists of heating/cooling components, sensors, and a fan to evenly distribute the temperature. The constituents collaborate to sustain the desirable environmental conditions within the chamber. Their thermal modules on both sides facilitate good heat transfer, and the sensor constantly measures the temperature. This system shows the practicality of the system, showing that the system is capable of keeping the situation stable to preserve the quality, texture and produce of the food effectively.

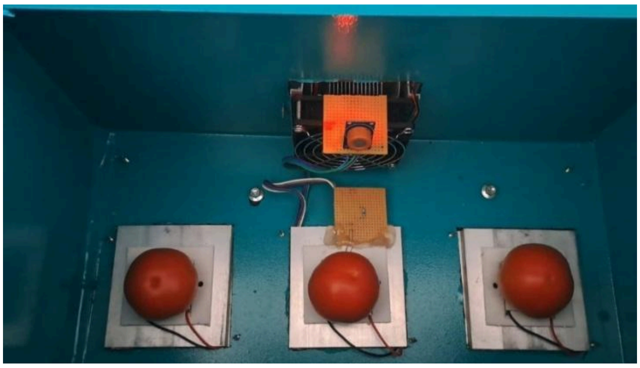

Fig.6 Tomato Preservation in Auto Mode at 12°C

The figure 6 shows that the smart cold storage system is in auto mode of preserving tomatoes. The preset options are displayed on the LCD display, and the system automatically regulates the necessary temperature of 12 o C, such as tomato. The message Target Reached is a confirmation that the desired state of storage has been attained. Storing tomatoes under such temperature conditions will retard the ethylene production rate, thus retard the process of tomato ripening and increase the shelf life of the tomatoes. The keypad interface enables easy choice of the preset mode. This value shows that the system can offer automated temperature control, which is very accurate and ensures that the storage conditions are optimal and minimize food spoilage.

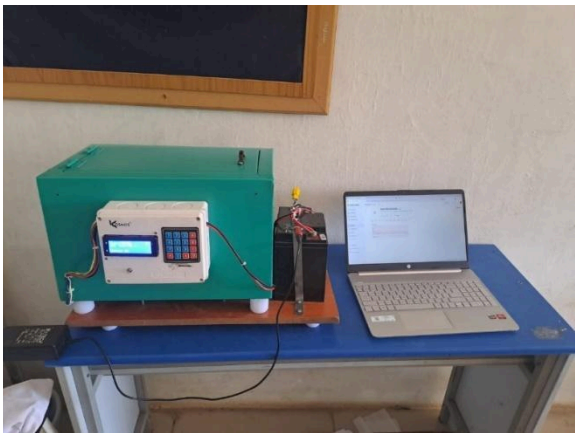

Fig.7 Fabricated Smart Cold Storage System Prototype

The prototype of the Smart Cold Storage System in fabricated form which is to be used in preventing the spoilage of food is demonstrated in this figure 7. The installation will consist of a sealed storage space with heating/cooling components, temperature sensors and a fan to maintain even air distribution. The food sample is centralized in order to have equal exposure to the controlled environmental conditions. Each side has its own thermal modules that aid in controlling the temperature efficiently and the sensor controls the internal conditions constantly. It is interconnected to a microcontroller to be automatically controlled and monitored. This simulated system illustrates how the proposed system can be practically implemented and show that it is effective in ensuring optimal storage conditions.

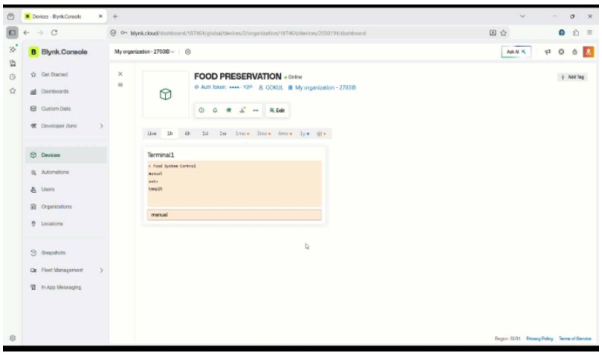

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Fig.8 Manual Mode Operation Using Keypad Interface

The figure 8 shows the smart cold storage being used in the manual mode and using the keypad interface. The temperature is set manually and the LCD display indicates the value of the temperature set and the message that indicates the system has reached the desired state of operation is the Target Reached. With this mode, users are able to enter temperature settings directly according to the specific requirements of storing a particular food instead of using presets. The keypad offers an easy and convenient means of parameter adjustment. The feature provides flexibility and exact control, allowing the storage of various types of food under customized conditions to keep all efficient and without spoilage.

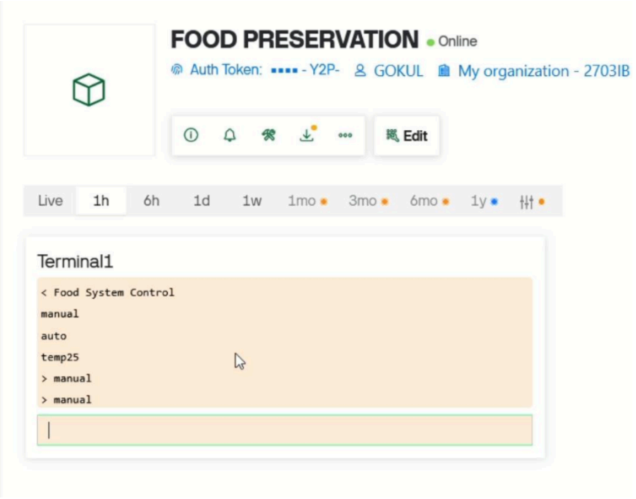

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Fig.9 Food Storage System Control in Manual and Auto Modes

This figure illustrates the overall control operation of the smart food storage system, highlighting both manual and auto modes for temperature regulation. In manual mode, the user can directly set the desired temperature using the keypad interface, allowing flexibility for different food storage requirements. In auto mode, predefined presets for various food items automatically select the optimal temperature. The LCD display continuously shows the selected mode, temperature settings, and system status. Once the required temperature is achieved, the system indicates “Target Reached.” This figure demonstrates the system’s dual-mode functionality, ensuring accurate, user-friendly, and efficient temperature control for effective food preservation.

V. CONCLUSION

The Smart Cold Storage System for Food Spoilage Prevention effectively addresses the challenges of improper food storage by integrating real-time monitoring, automated control, and IoT-based alert mechanisms. The system successfully maintains optimal temperature conditions, detects harmful gases, and ensures timely response to environmental changes, thereby reducing food spoilage and improving food safety. Its user-friendly interface and energy-efficient operation make it suitable for various applications such as households, supermarkets, and warehouses. In the future, the system can be enhanced by integrating artificial intelligence for predictive analysis and smart decision-making. Advanced sensors, cloud analytics, and mobile applications can further improve accuracy, scalability, and remote accessibility, making the system more efficient and adaptable to large-scale cold storage management.

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