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Microclimate Mapping of Cold Storage Using Arduino-Based Sensor System

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ABSTRACT

Temperature and relative humidity are crucial parameters to monitor within a cold storage room. This paper focuses on mapping the fluctuations in temperature and relative humidity in cold storage. A mapping system was developed using a DHT22 temperature sensor and an Arduino Mega to create a portable monitoring system. The system was evaluated by placing sensors at various locations to measure temperature and relative humidity accurately, detecting fluctuations within the range of 0.3°C to 1°C. These findings can serve as a reference for developing monitoring systems that require sensor deployment at multiple locations within a storage chamber.

Keywords: Cold Storage, Microclimate Parameter, Modular Unit, Monitoring

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INTRODUCTION

Cold storage is typically a component of a cold chain, encompassing the transportation, storage, and distribution of temperature-sensitive products from their source to the final consumer. Cold storage facilities are recognized as one of the most effective solutions for reducing post-harvest losses, which can affect up to 40% of the country's agricultural production (Aravindaraj et al., 2020). India currently has 6,227 cold storage units, with a combined storage capacity of up to 30 million tonnes (Yenare et al., 2024). Uneven temperature distribution within these facilities often results in unsuitable storage conditions for commodities, increased energy consumption by the cooling equipment, and higher associated costs. It is crucial to identify the uneven distribution of temperature and relative humidity within the storage space to prevent storing perishables in locations that could lead to quality deterioration. However, the distribution of airflow within cold storage depends on the positioning of the cooling coil and the stacking arrangements. It may happen due to nonuniform airflow, causing uneven temperature and relative humidity throughout the storage space depending upon the airflow distribution pattern.

In agricultural research and applications, collecting data often involves multiple locations, including remote and isolated areas where manual data collection is challenging due to its tedious, costly, and time-consuming nature. Moreover, these measurements must be dependable, precise, and practical to conduct. The use of a datalogger for measuring temperature and relative humidity data from different locations inside the storage chamber has been reported by Fennir (2018); Alkandari et al. (2017); Bishnoi and Aharwal (2021). The data collection devices, known as data loggers, are prohibitively expensive, require specialized software (which adds cost and necessitates specific skills), and need a constant power supply or a PC connection. Additionally, conventional data loggers often do not align well with the sensors being measured, lacking accuracy, sufficient input channels, or appropriate channels for specific sensors like digital sensors. These costs and technological limitations prompted us to design and develop a low-cost, flexible monitoring system. Our main goal is to create a system with the following features: (a) affordability, using readily available hardware and free software; (b) autonomous operation with low energy consumption, independent of a computer; (c) simplicity in construction and use; and (d) efficient data acquisition and file creation with minimal modifications.

Arduino boards feature a printed circuit board (PCB) that includes a microprocessor, flash memory, and various pins. These boards can be programmed using an open-source integrated development environment (IDE), making it accessible for users with limited programming knowledge to create their code (Badamasi, 2014). Like any microcontroller, an Arduino is a circuit board with a programmable chip that can perform a wide range of tasks. The extensive variety of commercially available sensors and actuators for Arduino boards makes them an exceptionally versatile tool, useful not only for hobbyist projects but also for agricultural applications, including monitoring and control systems (Karami et al., 2018; Ardiansah et al., 2020; Khaing et al., 2020). The expense associated with measurement devices, including the requirement for a data logger and multiple sensors, can be

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prohibitive. The benefits of using these types of systems for monitoring include the flexibility of Arduino setups and their affordability, allowing the creation of inexpensive and reliable devices for extensive mapping studies. Therefore, the availability of an affordable device for data collection and analysis is crucial to ensure mapping assessments that are economically feasible and enable thorough identification of environmental conditions. The system described in this paper provides benefits by substituting commercial data loggers with Arduino devices, thereby reducing costs, and enhancing flexibility and simplicity in integrating multiple sensors for mapping study.

MATERIALS AND METHODS

The hardware units, which include the DHT22 temperature and relative humidity sensor, a micro-SD card data storage module, a DS3231 real-time clock, an LCD for the display unit, and a power supply unit (Fig. 1), along with the software (utilizing the Arduino integrated development environment). These components create a low-cost system for mapping cold storage microclimate parameters. The temperature and humidity sensors will log microclimate data from their respective locations, which will then be processed by a microcontroller. The sensor's accuracy is within ±0.5°C for temperature and ±2% for humidity. Data from the sensors are detected and transmitted to the microcontroller via digital pins for processing and storage. The C programming language is used for processing sensor data. After processing, the data is displayed on the LCD and stored on the SD card for future use. The block diagram is shown in Fig. 1, and Fig. 2 presents the schematic diagram of the developed mapping system.

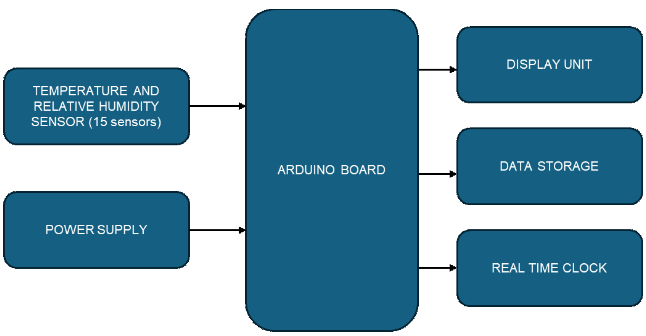

Fig. 1: lock diagram of the developed mapping system for the cold storage parameters

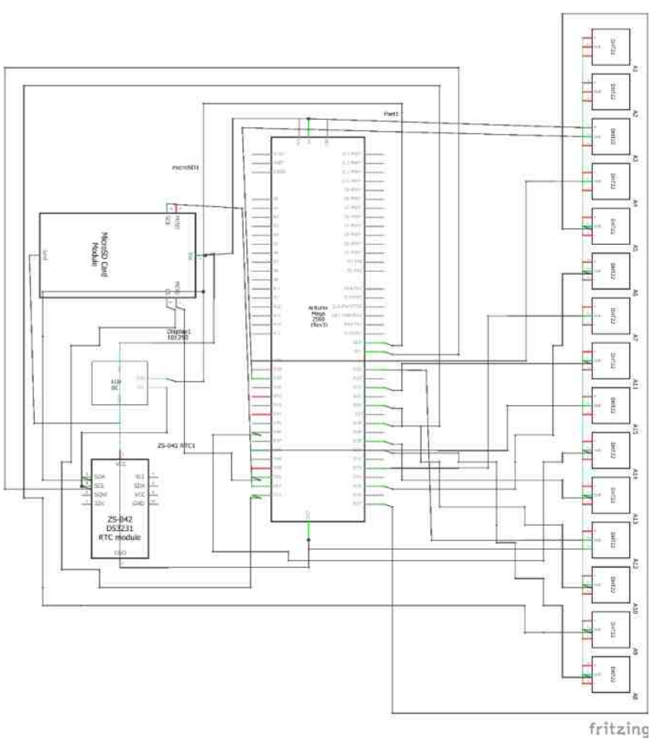

Fig. 2: Schematic diagram of the developed system for mapping

Experimental facility

A single chamber cold storage room for the experiment has a dimension of 3.05 m (L) × 3.05 m (W) × 2.4 m (H) and a total internal volume of 22.65 m3. The cold room is equipped with a cooling unit having one evaporator and a fan, located near the ceiling at the wall opposite the door of the cold storage room. The sensor deployment locations on the three planes are based on the study by Bishnoi et al. (2021). The total number of temperature and humidity sensors used for the study is 15 and deployed in three horizontal planes. The measurement points of the room are shown in detail in figure 3. The cold room is divided into three planes at a height of 0.4 m, 1.22 m, and 2.04 m respectively. Fifteen sensors, connected by wires to the microcontroller board and suspended from the ceiling, were logging both temperature and relative humidity in the cold storage room. These sensors were arranged in a grid of three columns and nine wired lines, positioned at three different heights. The sensor numbers were linked to the regular coordinates X, Y, and Z as reference points to manage the positions.

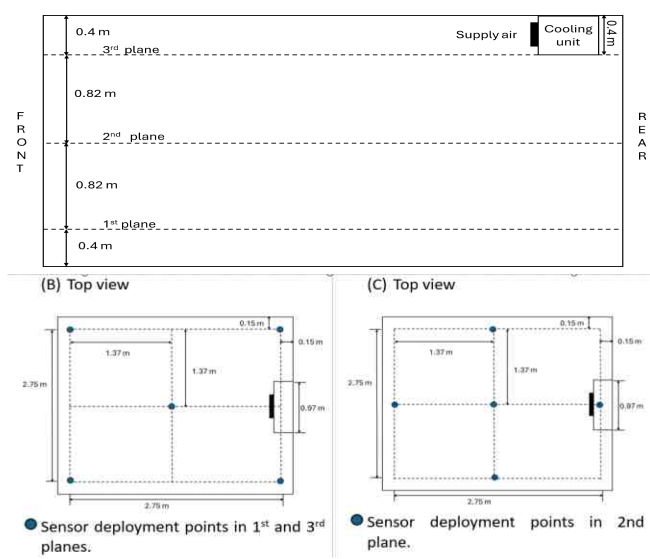

Fig. 3: Temperature and relative humidity measurement points layout (A) side view showing three planes; (B) and (C) top view of the sensor placement points in all the three planes.

Microcontroller Unit

Arduino Mega is a basic microcontroller that is very easy to adapt to any design due to the advantages mentioned above, therefore Arduino Mega was selected and accounts for the logging of temperature and relative humidity data for the mapping experiment. Different types of connection ports, including digital input/output, PWM output, UART TTL (5V) serial communication, and analog input, make the Arduino Mega board a powerful and cost-effective hardware for data collection purposes. The Arduino Mega, built on the ATmega2560, features 54 digital input/output pins (15 of which can serve as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a USB connection, and a power jack. It includes all the necessary components to support the microcontroller. The board can be powered by an external source such as a USB cable, an AC/DC adapter, or a battery, with a voltage range of 7 V to 12 V.

Sensing Unit

The DHT22 sensor was chosen for temperature and humidity measurement due to its accuracy, affordability, and suitable range, as compared to the DHT11 (Table 1). The DHT22, also known as AM2302, connects to the microcontroller through 15 digital pins and provides digital output for temperature and relative humidity readings. Its sensing element is integrated with an 8-bit single-chip computer. The sensor is recognized for its anti-interference capabilities, low power consumption, high integration, high precision, small size, and low cost. It stores calibration coefficients in its OTP program memory, which are used in calculations during measurements. The compact size, low power consumption, and long transmission distance (20 m) make it suitable for various demanding applications.

Display module and other accessories

To organize all the collected sensor data by their respective locations, it is essential to store the data in files. Given the limited capacity (4 KB) of the Arduino Mega board's internal EEPROM, a 16 GB SD flash memory was selected as the data storage module. This SD card, operating via SPI (Serial Peripheral Interface) bus, offers high storage density, fast read and write speeds, and is cost-effective. The Arduino Mega 2560 was connected to the card's clock pin, chip select pin, MOSI (Master Output Slave Input) pin, and MISO (Master Input Slave Output) pin.

The LCD (Liquid crystal display) module allows the system to display an output corresponding to a specific input. In this system, a 16 × 2 LCD was interfaced with an Arduino board. The LCD breakout board has 4 communication pins and utilizes the I2C (Inter-Integrated Circuit) interface for essential connectivity. The LCD module was used to display the data for all the 15 sensors.

The DS3231 RTC is powered by a clock chip driven by a temperature-compensated 32 kHz crystal oscillator. This temperature-compensated crystal oscillator (TCXO) provides a stable and precise reference clock, enabling the RTC (real-time clock) to maintain an accuracy of ±2 minutes per year. The addition of a battery enhances the reliability of the RTC. The SDA (serial data) and SCL (serial clock) lines are connected to the SDA and SCL pins on the Arduino Mega, with VCC (voltage common collector) connected to 5V and GND (ground) to the ground pin. Communication between the sensor and microcontroller is handled using the RTC modules with DS3231 chips.

A steady power supply to the system is delivered by the +12 Volt power source through an AC adapter.

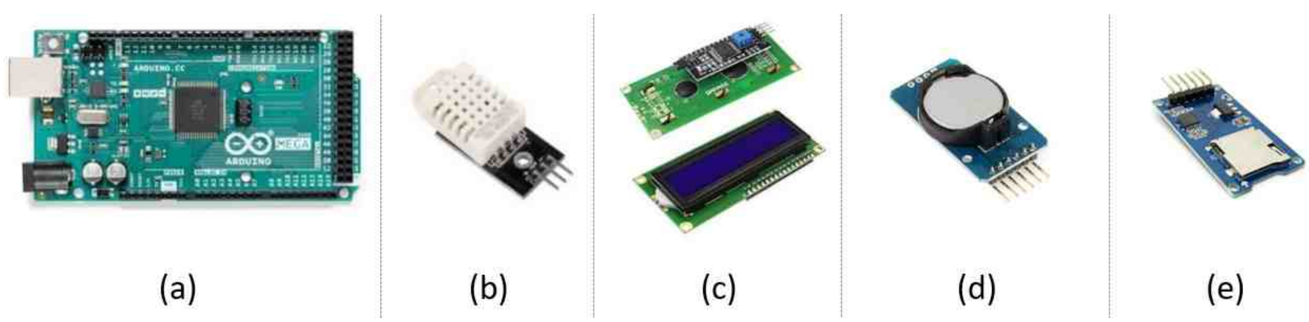

Fig. 4: Hardware components (a) Arduino mega; (b) DHT22 temperature and relative humidity sensor (c) LCD display module; (d) DS3231 RTC module; (e) Micro SD card module

System Architecture

The system consists of fifteen sensors that measure temperature and relative humidity. These sensors monitor and transmit data from various locations where they are installed. In particular, five sensors per plane are placed inside the cold storage room. All communications with the DHT22 sensors are managed using an Arduino Mega 2560 microcontroller. Figure 5 provides a schematic representation of the system architecture used for mapping. Additionally, the system includes other modules, such as an LCD, an RTC module, and a micro SD card module (Fig. 4e). Figure 6 provides a schematic representation of the system architecture used for mapping. The firmware of the developed system was implemented using the Arduino platform language in the IDE. It belongs to the C-family programming languages.

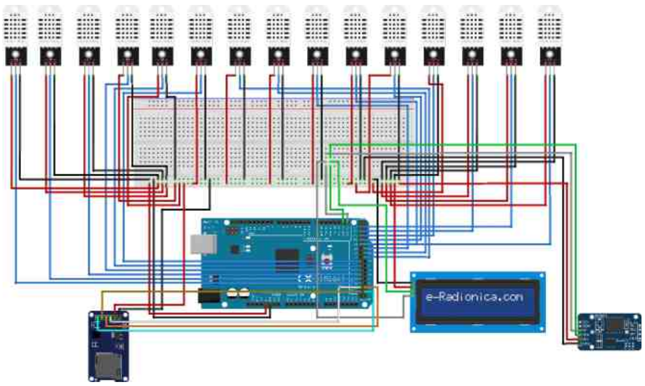

Fig. 5: Connection diagram of the sensor system for mapping.

RESULTS AND DISCUSSION

Performance tests of the developed modular mapping system were conducted on the cold storage room of 22.65 m3 capacity, which was designed to detect variations in temperature and relative humidity within the space. The system demonstrated a fast response time of less than 10 seconds, indicating its quick logging capability of every second. It measures temperature with a resolution of 0.1°C within the range of -40 to 80°C and can measure humidity up to approximately 100%. Table 1 displays the temperature and relative humidity measurements from the fifteen locations. The experimental measurements of temperature and relative humidity were carried out by setting the cold room at 5 . The variations in temperature and relative humidity at a particular time are depicted in Figures 6 and 7, respectively.

Table 1: Temperature and relative humidity of sensors at different locations

Sensor number	Plane	Temperature (°C)	Relative Humidity (%)
1	2nd	5.2	89.5
2	3rd	5.2	86.5
3	2nd	5.2	89.7
4	1st	5.1	89.9
5	2nd	5.4	90.6
6	1st	4.8	92.9
7	1st	5.2	91.2
8	1st	5.4	93.2
9	3rd	5.2	87.4
10	3rd	5.0	89.9
11	1st	5.1	90.2
12	3rd	5.2	86.6
13	2nd	5.1	87.6
14	3rd	5.3	84.3
15	2nd	5.2	89.9

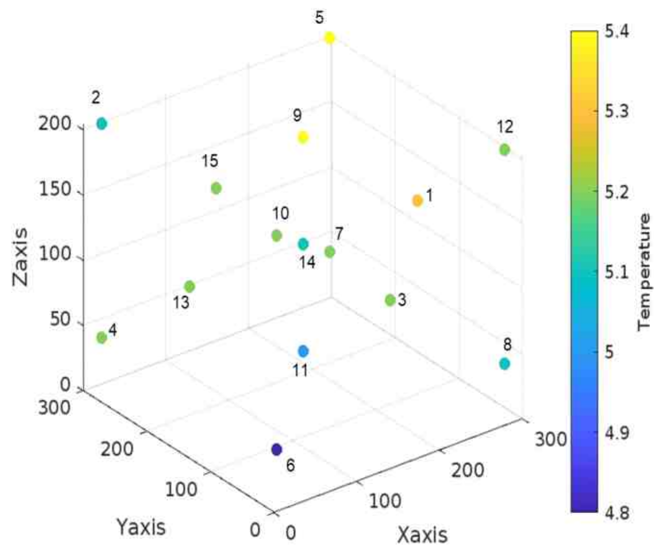

Fig. 6: Temperature profile of deployed sensors at various locations inside the cold storage chamber (sensor numbers are shown adjacent to the dots).

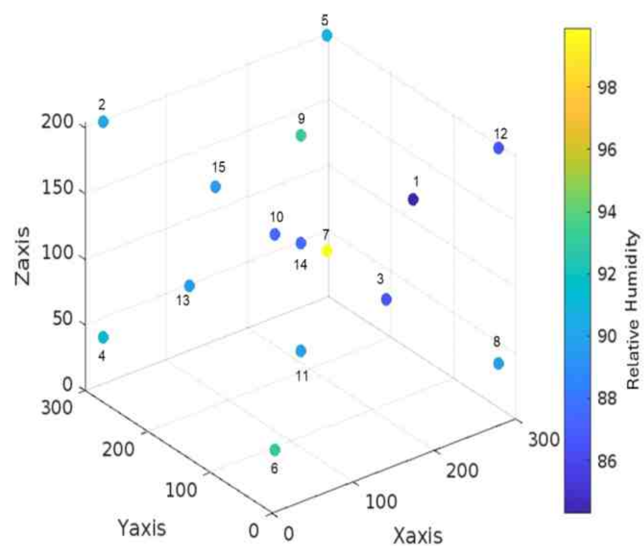

Fig. 7: Relative humidity profile of deployed sensors at various locations inside the cold storage chamber.

The variations in temperature and relative humidity across different locations and over time are illustrated in Figure 8 and 9. The sensor data were collected over 2 hours with the temperature set at 5°C, as listed in Table 2.

Table 2: Temperature and relative humidity measurements of various locations inside the cold storage

Sensor number	Temperature ( ) and Relative humidity (%)	Time (min)											
		10	20	30	40	50	60	70	80	90	100	110	120
1	T1	5.5	5.7	5.6	6.1	5.7	5.6	5.5	5.4	5.3	5.2	5.1	5.1
	RH1	88.8	89	90.1	78.9	91.7	91.7	91.5	91.3	91.1	90.9	90.8	90.7
2	T2	5.5	5.6	5.5	5.3	5.7	5.5	5.5	5.2	5.1	5.0	5.0	5.1
	RH2	86.4	89	89	82.9	89.4	89.3	89	88.5	88.4	88	87.8	87.7
3	T3	5.3	5.8	5.8	5.3	5.7	5.7	5.7	5.4	5.2	5.2	5.0	5.1
	RH3	87.1	90.4	91.9	82.8	92.3	92.4	91.9	91.7	91.4	91.2	91.0	90.9
4	T4	5.4	5.5	5.4	5.4	5.5	5.4	5.3	5.2	5.1	5.0	4.9	4.9
	RH4	87.9	91.1	91.5	82.9	91.8	91.7	91.5	91.3	91.1	90.8	90.7	90.6
5	T5	5.8	5.8	5.7	5.9	5.8	5.8	5.8	5.5	5.5	5.4	5.3	5.3
	RH5	91.2	93.4	93.4	88	93.4	93.6	93.3	92.9	92.7	92.3	92	92.2
6	T6	5.3	5.4	5.3	5.3	5.3	5.3	5.2	5.2	5.3	5.2	5.1	5.1
	RH6	90.8	93.4	94.3	86.4	94.5	94.4	94.2	90.8	90.1	91.3	92.2	90.6
7	T7	5.5	5.6	5.5	5.4	5.6	5.5	5.5	5.4	5.4	5.5	5.4	5.3
	RH7	86.2	88.1	89.2	91.1	91.5	92.4	86.1	88.5	91.1	88.1	89	90.4
8	T8	5.6	5.7	5.4	5.5	5.5	5.6	5.5	5.3	5.3	5.2	5.1	5.1
	RH8	91.3	93.8	94.1	87.2	94.3	94.3	94.1	93.8	93.3	92.8	92.6	92.3
9	T9	5.3	5.9	5.8	4.9	5.9	5.9	5.8	5.6	5.5	5.4	5.0	5.0
	RH9	91.6	93.4	94.3	90.2	94.6	94.6	94.4	94.1	94	93.8	90.1	90.4
10	T10	5.1	5.7	5.7	4.7	5.7	5.7	5.6	5.5	5.3	5.2	5.1	5.1
	RH10	83.2	86.6	89.4	80.5	89.7	89.8	89.4	89	88.7	88.6	88.4	88.3
11	T11	5.4	5.6	5.7	5.1	5.5	5.7	5.5	5.4	5.2	5.0	4.9	5.1
	RH11	88.5	91.2	91.8	85.3	92	91.9	91.6	91.4	91.3	90.9	90.9	90.7
12	T12	5.2	5.6	5.6	5.2	5.6	5.5	5.5	5.3	5.2	5.0	4.9	4.9
	RH12	86.7	90.5	91.6	81.8	92	92.1	92	91.8	91.7	91.5	91.5	91.4
13	T13	5.5	5.7	5.6	5.4	5.7	5.6	5.6	5.4	5.3	5.2	5.1	5.1
	RH13	86.7	89	89.2	82.3	89.4	89.3	89.1	88.7	88.4	88.1	87.8	87.7
14	T14	5.5	5.7	5.6	5.6	5.6	5.6	5.5	5.3	5.2	5.1	5.0	5.0
	RH14	86.3	88.7	90.1	78.7	90.6	90.5	90.3	90.1	90	89.6	89.3	89.1
15	T15	5.6	5.6	5.8	5.5	5.7	5.5	5.6	5.5	5.2	5.2	5.1	5.2
	RH15	83.8	87	87.1	80	87.5	87.4	87.1	86.7	86.4	85.9	85.7	85.5

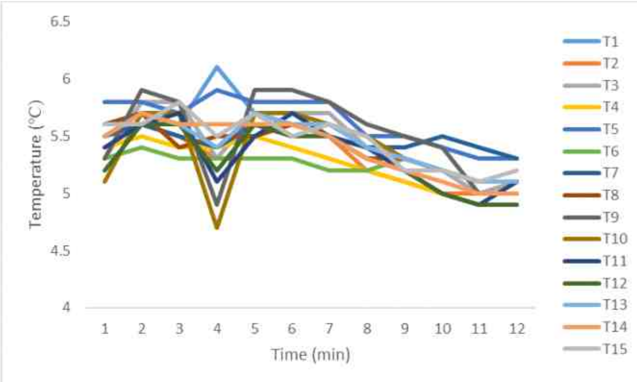

Fig 8: Variation of temperature of 15 locations with time.

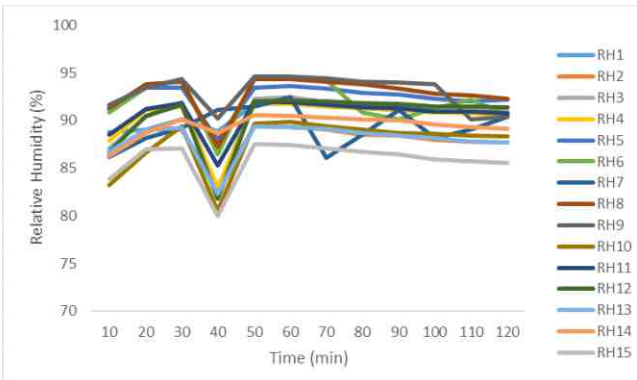

Fig 9: Variation of relative humidity of 15 locations with time.

Figure 8 illustrates the temperature fluctuations in the cold storage room, which range from 0.3°C to 1°C. The temperature variations at any given location within the cold storage do not exceed 1°C. Regarding relative humidity, Figure 9 shows fluctuations ranging from 3.8% to 13.1%. It is evident from Figures 8 and 9 that the temperature fluctuation inside the cold storage varies between 0.3°C and 1°C, consistent with the findings reported by Wu et al. (2018). The temperature fluctuation trends across the three layers are generally similar. However, the fluctuation in the first (lowest) layer ranges from 0.3°C to 0.8°C. In contrast, the second (middle) and third (top) layers have equal fluctuations, ranging from 0.6°C to 1.0°C, which are less than the fluctuations observed in the first layer. It has been demonstrated that the current configuration of cooling coils and ceiling fans in cold storage facilities is unable to evenly distribute cold air throughout the storage chamber. This is due to significant variations in air velocity, which in turn cause notable differences in temperature (Chourasia and Goswami, 2007). Achieving a uniform set temperature within the cold storage room is therefore challenging.

Understanding the temperature and moisture distributions within a cold storage room is essential for evaluating their impact on the stored produce. Temperature variation is due to heat generated by sources like fan motors, external heat infiltration, solar radiation, and similar factors (Ambaw et al., 2016). Temperature variations occur both spatially and temporally inside the cold storage which is also reported by Ambaw et al. (2016). These temperature variations could be attributed to the continuous operation of fans throughout the experiment's set-point duration. Nonetheless, air circulation fans can significantly contribute to the heat load within the cold storage room.

The developed monitoring system can detect fluctuations in temperature and relative humidity inside the cold room. Additionally, this system can be utilized for sensor node localization within a storage chamber, enhancing the efficiency of data collection, network management, and overall system performance.

CONCLUSION

In this paper, we have introduced a modular sensor network system that incorporates an Arduino board, temperature and relative humidity sensors, a display unit, an RTC module, a data storage module, and an open-source software IDE to monitor microclimate parameters, such as temperature and humidity, at various locations within the cold storage room. The system has several advantages, including being low-cost, compact, scalable, customizable, easy to deploy, and easy to maintain. A key benefit of the design is the integration of various modules into a single, compact, low-power microcontroller. This design is highly applicable for environmental monitoring and data collection tasks. The design and measurement results provided in this paper demonstrate the system's effectiveness. For future work, the presented system design can be expanded in several ways. For instance, additional sensors can be integrated to cater to different gas monitoring needs and the collected data can help validate simulation models of storage chambers.

Declaration: The authors declare no conflict of interest.

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