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Peltier Module Based Cooling System for Food Security and Reducing Post Harvest Losses with Temperature Regulation

Mahalingam.M[(1)],Hemanth.D[(2)],Subramanian.K[(3)],
[(1) (2)] UG Student, National Engineering College, Kovilpatti.
[(3)] Assistant Professor in Electronics and Communication engineering department, National Engineering College, Kovilpatti.
National Engineering College, Kovilpatti

Abstract:- Global food security faces a critical challenge due to post-harvest losses of fruits and vegetables. In regions with warm climates and limited infrastructure, inadequate cooling and storage facilities lead to rapid spoilage. This is-sue demands an innovative solution, and a Peltier module-based cooling system offers a promising approach. By utilizing the Peltier effect, this system achieves energy-efficient and eco-friendly thermoelectric cooling. Unlike traditional refrigeration methods, it avoids the use of potentially harmful refrigerants, making it a sustainable choice. Integrated temperature and humidity sensors enable the system to monitor and adjust conditions within the cooling chamber in real-time. This ensures optimal preservation of various produce types. The system's potential impact on food security is substantial. By extending the shelf life of fresh produce, it can dramatically reduce wastage, allowing more food to reach consumers. This holds profound implications for small-scale farmers and vendors, particularly in areas with limited market access. The system's affordability and accessibility empower them to improve product preservation, boost their income, and contribute to greater food availability within their communities. Moreover, the portability and potential for off-grid operation using solar or alternative energy sources make it suitable for areas with unreliable electricity, further expanding its reach and impact.

Keywords*:* Peltier effect, thermo electric cooling, post harvest losses, temeperature regulation.

1. Introduction

A confluence of factors is driving the global food crisis, including rising fuel prices, dwindling freshwater resources, declining cereal stocks, extreme weather events and land degradation caused by urban expansion further shrinking farm-land [1]. The global demand for food, housing, and other essentials rises by an estimated 230,000 people every day, with the most significant population growth anticipated in Asian nations like India, China, and Southeast Asia [2]. In 2023, India's horticulture sector produced an estimated 350.9 million tonnes of fruits and vegetables, with fruits accounting for 107.7 million tonnes and vegetables for 212.5 million tonnes [3]. Despite being one of the largest producers of agricultural products India ranks 111th in the Global Hunger Index (GHI) 2023 [4] which is categorized to be a serious condition. In India, around a million children die prematurely before becoming one month old each year, and about half of all children suffer from malnutrition. Due to severe malnutrition, 48% of children under the age of five are stunted and 43% are underweight in India (3 out of every 10 children are stunted) [5]. The starvation condition could be attributed to the significant amount of post-harvest losses. The post-harvest losses of agricultural products such as Cereals, Pulses, Oil Seeds, Fruits, and Vegetables stand at 3.89-5.92, 5.65-6.74, 2.87-7.51, 6.02-15.05, and 4.87-11.61 respectively [6,7].

For many years the focus had been on grain crops which are the main staple food in the country. Several innovations, technologies and procurements were directed towards grain crops. However, it is projected that the share of non-grain crops, such as fruits, vegetables, and edible oils, will rise from 29% in 2000 to 33% in 2025 and 37% in 2050. Compared to other developing nations, where the per capita consumption of vegetables and fruits is 170 Kcal/person, Indians consume 96 Kcal/person. However, it is anticipated that vegetable and fruit consumption will rise rapidly due to rising urbanization and income [8]. Table 1 lists the projected future demand for vegetables and fruits.

S. No	Year	Fruits	Vegetables
1	2000	40	70
2	2025	67	142
3	2050	106	180

Table 1 Projected growth in the demand of vegetables and fruits in million tonnes [8]

Significant losses of highly perishable fruits and vegetables arise from poor post-harvest management practices, lack of storage facilities, lack of processing infrastructure, inaccurate demand forecasting, and lack of information about new technologies [9,10,11,12]. A significant amount of agricultural produce is forfeited in the process of transportation and storage. For instance, around 7.86% of produced mangoes are spoiled during transportation and storage, which accounts for half of the post-harvest losses of 12.74% [7]. These losses do not only threaten food security of the country, in addition to that it causes severe economic losses to the farmers. The Associated Chambers of Commerce and Industry of India (ASSOCHAM) reported that the post-harvest losses on fruits and vegetables totaled $33,745 million in 2011–12 and could surpass that amount in 2013–14 [13]. This could severely affect the agricultural sector, which has already been already hit by erratic weather, pest infestations and climate change. Temperature plays a significant role in the postharvest quality of fruits since their rate of deterioration is influenced by temperature fluctuations. Elevated temperatures accelerate processes that contribute to fruit deterioration, including respiration and ethylene production. The rate of chemical reactions typically increases 2-3 times for every 10°C increase in temperature. Therefore, lowering the temperature of fruits is essential for decreasing their rate of deterioration, reducing the respiration, ethylene production, and ethylene sensitivity consequently extending their shelf-life.

2. Literature Survey

Several techniques have been utilized in extending the shelf-life of highly perishable fruits and vegetables. Modified atmosphere packaging (MAP) is a widely adopted technique as it helps in significantly extending the shelf-life of fresh and fresh-cut produce [14]. MAP employs a technique where the gas environment surrounding a product is either modified or completely replaced with inert gases prior to sealing the container or package [15]. Preserving fresh and fresh-cut fruits and vegetables has been significantly aided by the usage of pressurized inert gases [16]. Meng et al., found that treating fresh-cut green peppers with pressurized argon (4 MPa) for one hour effectively reduced water loss and mobility. This treatment also helped preserve ascorbic acid, chlorophyll content, and cell integrity by inhibiting the production of malondialdehyde (MDA) and suppressing the activity of enzymes catalase (CAT) and peroxidase (POD), ultimately hindering the growth of yeast and molds [17]. Food irradiation is considered to be a major breakthrough technology for enhancing food preservation since, irradiation effectively preserves the original taste, color, nutrients, and overall quality of food products. The most common type of food irradiation in-volves exposing food to gamma rays emitted from either cobalt-60 or, less frequently, cesium-137. This process is primarily used to extend shelf life [18]. Pulsed light (PL) technology offers a non-thermal approach to rapidly decontaminating food and packaging surfaces. This method utilizes short pulses of high-powered light to inactivate microorganisms on the surface [19]. Ultraviolet (UV) light is a form of non-ionizing radiation of wavelengths range from 100 to 400 nanometers [20]. Microbial inactivation by UV light is primarily caused by the direct damage it inflicts on the DNA of living organisms, hindering their ability to function and reproduce [21]. Cold plasma, a cutting-edge non-thermal technology, is rapidly gaining traction in the food industry due to its potential applications in food preservation and decontamination [22]. During cold plasma treatment, the energetic particles in the plasma interact with the food's surface, releasing their stored energy and impacting the targeted bacteria or viruses, rendering them inactive [23]. Acidic electrolyzed water presents a potential breakthrough in food safety, offering potent microbial inactivation without altering the taste, nutritional value, or posing risks to human health. In recent years, the potential benefits of acidic electrolyzed water (AEW) as a safer and gentler alternative to chlorine decontamination have led to its adoption for sanitizing and extending the shelf life of fresh-cut fruits and vegetables [24].Silver nanoparticle is a potent antimicrobial material known for its antibacterial properties against a large number of microorganisms [25]. Silver ions inflict attack on microorganisms, damaging DNA, disrupting antioxidants, altering proteins, and cell membranes [26]. Air-conditioning based fruit storage system for apricots have been proposed previously. Efficacy of the peltier module-based cooling system could be proved through comparison. According to a previous study air conditioners typically use around 3000 Watt power to cool a space, whereas peltier module-based cooler offered a more energy-efficient alternative, consuming only about 200 Watt power. Peltier module-based coolers consume around 6% of electrical consumption of conventional air conditioning systems. Lumin Shi et al. [26] analyzed the economic aspects of the peltier module with different numbers of devices. Several works have been reported on commercial scale implementation and viability of peltier module cooling systems.

3. Competitive Survey

This section analyzes the advantages of the proposed system compared to existing techniques. A comprehensive evaluation of several relevant patents and products has been conducted.From the below comparison it can be concluded that there are lot of drawbacks in the existing techniques which needs to be fixed. MAP has been in usage for many decades, however, it is not an optimal storage procedure since there are certain limitations.

Techniques	Features	Drawbacks
Modified atmosphere packaging [14,15]	Enhanced shelf-life of fruits	Browning (at low O2 levels),Development of russet spotting
Pressurized inert gases [16,17]	Inhibition of microbial growth	Reduced firmness
		Loss of total phenols, ascorbic acid
Electron beam irradiation [18]	Retaining freshness of fruits and vegetables	Strict restrictions on irradiation levels
Pulsed light [19]	Disinfection	Browning of cut surface due to thermal damage,Severe weight loss and appearance of wrinkles
Ultraviolet light [20,21]	Wide range of target microbes	Negative effect onnutritional components,Decrease in vitamin C,Electrolyte leakage and weight loss

Table 2 Pros and cons of existing techniques with respect to proposed peltier module

Even though irradiation is considered to be a breakthrough it causes significant damage to agricultural produce. Furthermore, the advent of nanotechnology is a new horizon. It still possesses the threat of potential toxicity making it a critical approach.

4. Methodology

The proposed system regulates the temperature with the help of peltier effect. Sensory module of the system senses changes in the surroundings then based on the functional logic the device is turned on/off for maintenance of the preset conditions. The architecture of the proposed Peltier module cooling system (PMCS) is given below.

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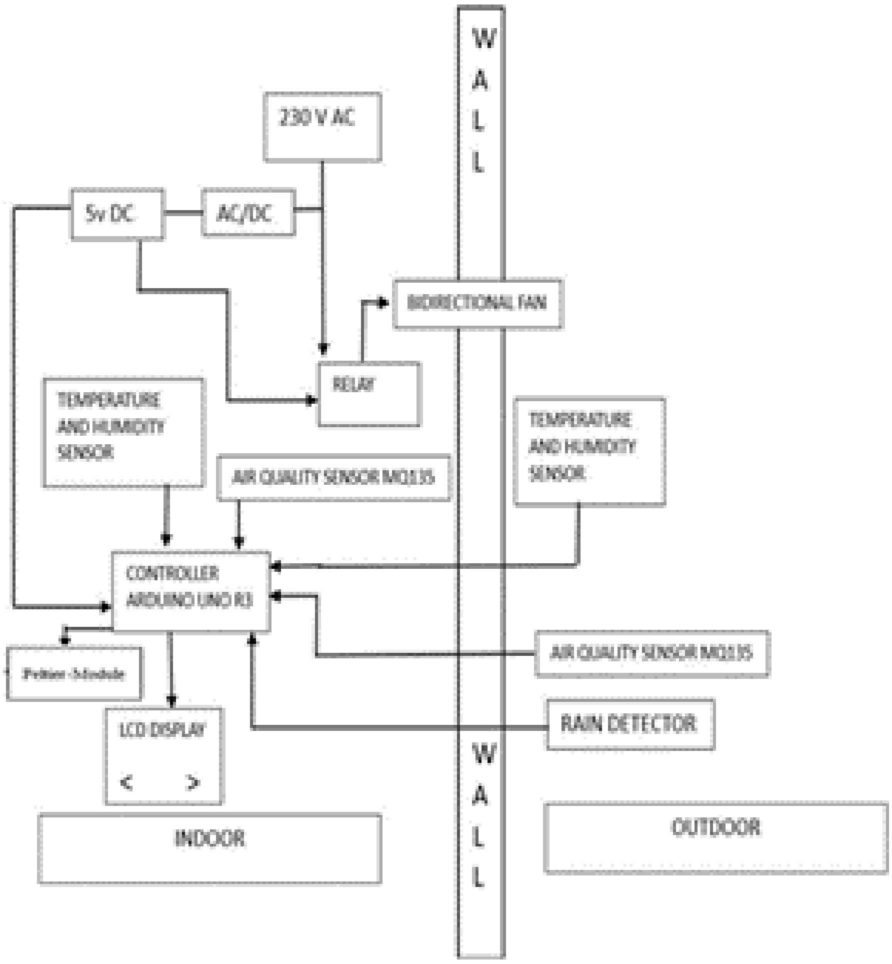


Figure 1 Architecture of PMCS

As depicted in figure 1 key components of PMCS includes sensors, microcontroller, peltier module, and exhaust fan.Peltier effect thermoelectric coolers, use the Peltier effect to achieve cooling. The thermoelectric cooler has two sides. When a direct current (DC) passes through it, heat is transferred from the interior to the exterior. As a result, the inside cools down while the outside becomes warmer. A heat sink keeps the hot side of the device at room temperature, allowing the cool side to reach sub-ambient temperatures. Utilizing multiple coolers in parallel allows for achieving significantly lower temperatures.

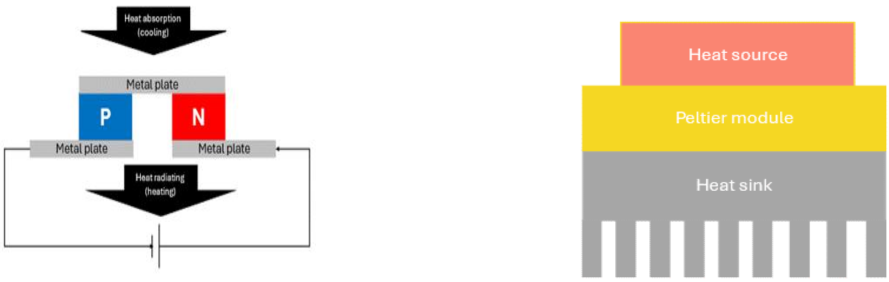


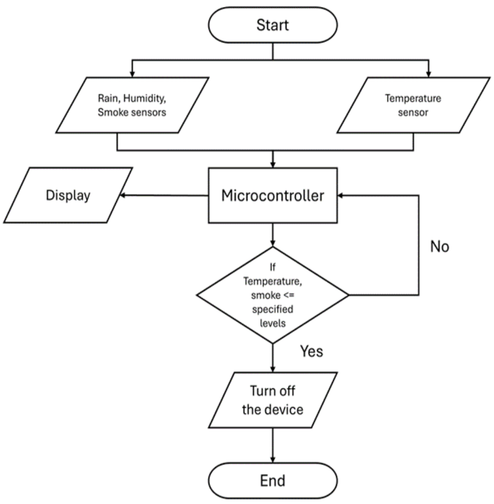
Figure 2 (a)Working of a thermoelectric module **(b) Schematic diagram of thermoelectric cooler**

Figure 2(a) depicts the thermoelectric effect involved in a single thermoelectric cell comprising two elements of semiconductor. The device utilizes two specially semiconductor elements, primarily Bismuth Telluride. These elements are heavily doped to create either an excess (n-type) or deficiency (p-type) of electrons. Due to the Peltier effect, the cold side of the module absorbs heat, which is then transferred to the side attached with a heat sink for dissipation.The PMCS consists of the following components

- Arduino UNO
- Sensors
- Peltier module
- Exhaust fan

The Arduino Uno is a microcontroller board built around the 8-bit AVR AT-mega328P processor, featuring a 16 MHz clock speed. It provides 14 digital I/O pins (6 with PWM) for interfacing with various digital components and 6 analog inputs with 10-bit resolution for reading analog sensor data. Programmability is achieved through the Arduino IDE. The on-board bootloader facilitates code upload via USB. The Uno's EEPROM offers non-volatile storage for data retention even after power cycles. Arduino Uno has been preferred because it is relatively inexpensive, with its array of digital and analog I/O pins, the board can be interfaced with various electronic components. MQ135, DHT22 and rain sensors have been used in the process of environment perception. The MQ135 is a member of the MQ series gas sensors, designed for broad-spectrum air quality monitoring. It detects and measures various gases including ammonia, alcohol, benzene, smoke, and carbon dioxide. The sensor comprises a ceramic element coated with SnO_2. When this element interacts with a particular gas, its conductivity undergoes a change. The alteration in conductivity is subsequently transformed into an electrical signal that can be quantified and analyzed.

The DHT22 sensor is a digital temperature and humidity sensor. It employs a capacitive humidity sensor and a thermistor to gauge the ambient air conditions. Subsequently, it generates a digital signal on the data pin. A rain sensor is a type of switching device designed to detect rainfall. The raindrop sensor uses nickel-coated lines to detect rain based on changes in resistance. When it is dry, the sensor has high resistance, which means it conducts less electricity.The TEC1 12706, a 40x40mm, 6A Peltier module, utilizes the principle of the Peltier thermoelectric effect, where applying an electric current creates a temperature difference on opposite sides of the module. Composed of 127 tiny semiconductor couples packed within a 40 x 40mm area, this module could reach temperatures as low as 90°C below ambient. A small axial fan has been chosen due to its compact size, low power consumption, and quiet operation. It can be controlled using a motor driver module to adjust the fan speed or turn it on and off.



The PMCS system is initiated with the sensed value from smoke, rain, humidity and temperature sensors. The data from the sensor is processed by the microcontroller based on the programmed preset values. When the air quality of the environment inside the box is above 200 ppm then the exhaust fan is turned on to push the contaminated air outside. Another exhaust fan pulls fresh air into the chamber. Similarly, the same mechanism is also involved in pushing hot air out-side the chamber and drawing cold air into the chamber. When the air quality of the external environment rises to 200 ppm the exhaust fans are turned off obstructing the entry of contaminated air into the chamber. The data from the DHT22 sensor also drives the exhaust fan. When the internal and external temperatures are in equilibrium then the peltier module is turned on to cool down the chamber. Rain sensor plays a crucial role in avoiding excessive moisture entering into the chamber.

The entire system has been efficiently designed to provide maximum temperature regulation using minimal energy.The connections were made upon a dotted PCB. The components were soldered as per the prepared schematic layout. Arduino was programmed to execute the expected operations. GitHub repository link for the custom Arduino program: https://github.com/Mahalingam21/AAESTR.git

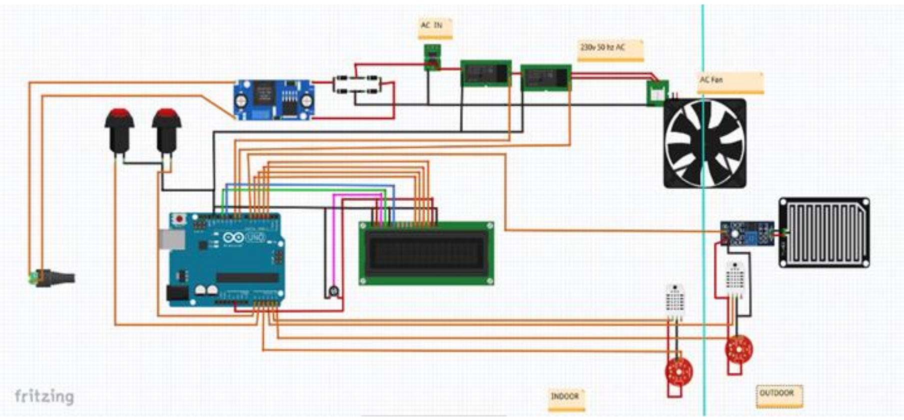


Figure 5 Circuit diagram of PMCS designed using fritzing software

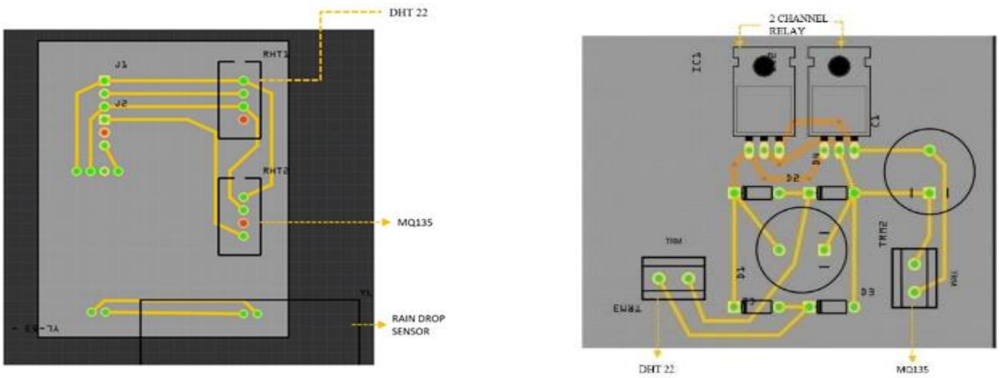


Figure 6(a) PCB schematic diagram of PMCS(outdoor) 6(b)PCB schematic diagram of PMCS (indoor)

Figure 7 Outdoor module with MQ135, DHT22 and rain sensor

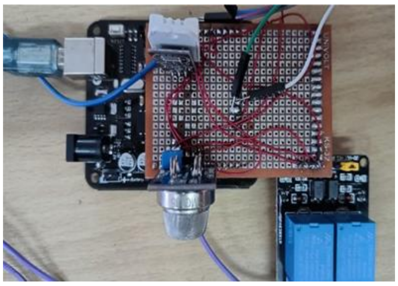


Figure 8 Indoor module with MQ135 and DHT22 sensors mounted on Arduino

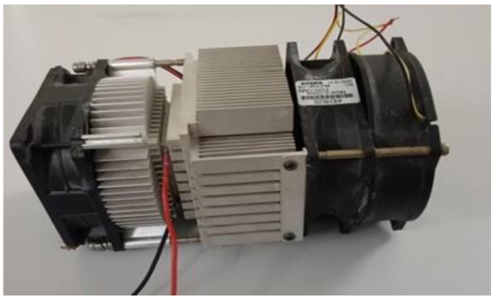


Figure 9 Peltier module integrated with heat sink

Thermal load estimation is crucial in several applications, regulating elements such as equipment selection, building design, and energy efficiency. Accurate thermal load calculations are critical for building design and planning, ensuring proper sizing of HVAC systems. An underestimation can lead to an insufficient system, resulting in discomfort for occupants or inadequate preservation of temperature-sensitive materials. Conversely, overestimation can lead to unnecessary costs for oversized equipment and wasted energy consumption. Thermal load calculations guide the selection of appropriate HVAC equipment capacity. Choosing the right size ensures the system can meet the cooling or heating demands of the space efficiently. An undersized system will struggle to maintain desired temperatures, while an oversized system will operate inefficiently and potentially incur higher energy costs. Thermal load calculations contribute to optimizing energy efficiency in buildings. Understanding the actual thermal demands of a space helps in the design and implementation of energy-saving measures like efficient equipment selection, proper insulation, and natural ventilation strategies. This reduces energy consumption and associated costs while minimizing environmental impact. Therefore, thermal load has been calculated for the experimental setup.

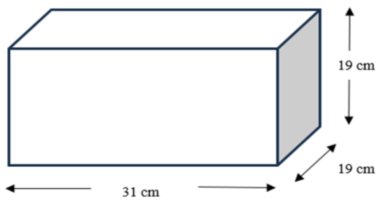


Figure 10 Dimensions of experimental chamber

Calculate volume of room in cubic meter

Room volume (ft^3) = 1.017ft X 0. 0.62ft X 0.62ft = 0.411 ft^3

Calculate heat load (btu/hr)

Rule of Thumb 1: Acceptable Design for Tropical Weather & Humidity = 6 btu/hr/ft^3

Heat Load (btu/hr) = Volume(ft^3) X Design Heat Load per unit Volume (btu/hr.ft^3)

$= 0.411ft^3$ X 6 $btu/hr/ft^3$

= 2 btu/hr

Power rating = Voltage (in Volts) X Current (in Ampere)

= 5 V X 33 mA

= 0.165 Watt

Energy Efficiency Ratio

$$Energy\ Efficiency\ Ratio = \frac{Heat\ Load\ (btuhr^{-1})}{Power\ rating}$$

$$= \frac{2\ btuhr^{-1}}{0.165\ Watt}$$

= 12.12 BTU/Wh

The energy efficiency ratio rating of commercially available air conditioning systems is found to be 3.68 BTU/Wh. The proposed PMCS provides an energy efficiency ratio twice that of the commercially available air conditioning systems.

5. Results and Discussions

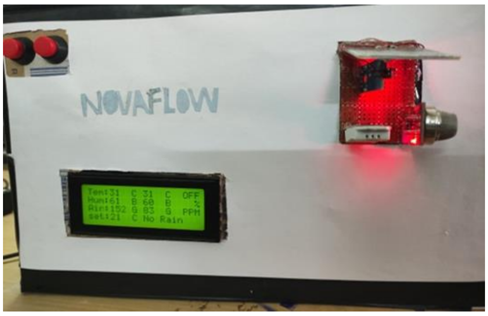


Figure 11 PMCS unit

Figure 11 Shows the operational state of the Peltier module and exhaust fan within the chamber, incorporating sensory data.

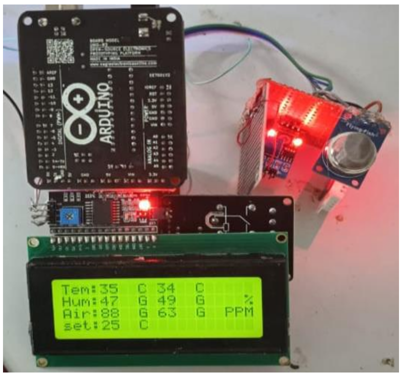


Figure 12 Functioning of the integrated outdoor-indoor modules with the data being provided on the display

Figure 12 depicts the operational status of the outdoor indoor modules along with sensory data before being integrated in the chamber

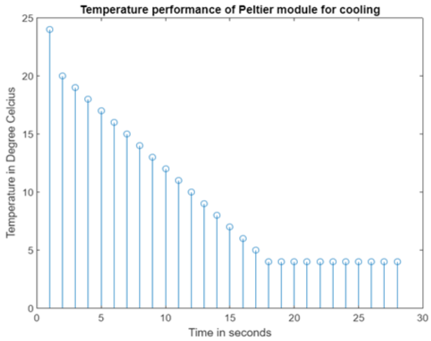


Figure 13 Temperature performance of peltier module

Figure 13 depicts the drop in the internal temperature of the chamber as a function of time. The cooling process started at 24º C and reached 4º C. The temperature was maintained at 4º C. Microbial activity ceases at temperature below 5º C. Therefore, it is ensured that the obtained temperature is suitable for preservation of fruits. Maintaining temperatures below 5ºC is imperative for fruit preservation, effectively halting microbial growth. By inhibiting the proliferation of bacteria, yeasts, and molds, this temperature range safeguards fruit freshness and nutritional quality for extended periods. It acts as a natural defense mechanism against spoilage, enabling consumers to enjoy fruits at their peak while minimizing the wastage of food resources.

The PMCS operates based on the Peltier effect, which involves a DC voltage running through two junctions joined by thermocouples. These thermocouples consist of electrical conductors with different coefficients. PMCS provide direct and localized cooling, eliminating the energy losses associated with cooling entire rooms in AC systems. PMCS typically utilize environmentally friendly materials and do not require harmful refrigerants. PMCS presents a promising alternative for situations demanding efficient and targeted cooling. Their superior efficiency, scalability, and environmental friendliness make them well-suited for various applications, particularly in electronic cooling.

6. Conclusion

The Green Revolution transformed the Indian agricultural landscape, boosting production through advanced equipment and practices. However, the paradox of increased production coexisting with persistent starvation and malnutrition high-lights a complex challenge. A key contributor to this issue is the lack of adequate storage facilities across the agricultural supply chain. Farmers, traders, and retailers all face the need to preserve fresh produce after harvest and during transportation to ensure its quality and reduce losses. Unfortunately, the massive capital costs and operating expenses associated with traditional cold storage facilities pose a significant barrier, limiting their widespread adoption.This is where the proposed Peltier Module-based Cooling System (PMCS) offers a solution. Its affordability, energy efficiency, and potential for off-grid operation address the core constraints plaguing the development of widespread storage infrastructure. By making such technology accessible, farmers can preserve their harvest more effectively, reducing immediate post-harvest losses and potentially negotiating better prices. Traders and retailers can extend the shelf life of produce during transportation and storage, minimizing wastage and offering consumers higher-quality fruits and vegetables.In conclusion, the PMCS unit offers a practical and scalable solution to bridge the critical gap in India's agricultural supply chain. By empowering stakeholders with accessible preservation technology, it has the potential to reduce food loss, improve nutrition, and support the economic well-being of those involved in the production and distribution of fresh produce.

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