



International Journal of Research in Agronomy

E-ISSN: 2618-0618

P-ISSN: 2618-060X

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www.agronomyjournals.com

2024; 7(12): 99-105

Received: 21-10-2024

Accepted: 22-11-2024

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Design and evaluation of a control circuit to improve cooling efficiency in solar refrigerated evaporatively cooled structure

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DOI: <https://doi.org/10.33545/2618060X.2024.v7.i12b.2099>

Abstract

Refrigerated storage is often considered to be the best method for preserving fresh fruits and vegetables. The Indian Agricultural Research Institute in New Delhi has designed a solar refrigerated evaporatively cooled (SREC) structure which is off-grid and battery-free, that can be constructed directly on the farm and operates without the need for electricity. To maintain a pre-set room temperature, the SREC system typically has a coil thermistor and an air thermistor which automatically cuts off the compressor. The minimum temperature that can be achieved is 16°C, which is a pre-set temperature by the refrigeration system manufacturer. In order to improve the efficiency of the refrigeration system, the control system is connected to a coil thermistor and an air thermistor of the refrigeration system. The SREC structure operated on on-grid and hybrid types of inverters with varied combination of coil thermistor resistances and air thermistor resistances. There were twelve treatments with a combination of inverter, coil and air thermistor resistance performed on the SREC structure. The cooling capacity, cooling efficiency, energy efficiency ratio and coefficient of performance (COP) were studied. The control system's connection helped lower the SREC structure's temperature from 16°C to 4°C. Hence, the cooling efficiency of the refrigeration system improved by 1.61 times. The highest cooling efficiency improvement of 2.29 times was found in the off-grid/ hybrid inverter with coil and air thermistor resistances of 39.4 kΩ and 21 kΩ, respectively. Highest COP value of 7.40 was found in on-grid inverter, coil and air thermistor resistances of 45 kΩ and 18.91 kΩ, respectively. The average improvement of COP was 0.79 times among the twelve treatments. The control system with an off-grid inverter refrigeration system is beneficial in enhancing the cooling performance of the SREC structure and establishing cold storage at remote locations.

Keywords: Solar refrigeration system, control system, coil & air thermistor, cooling efficiency, coefficient of performance

1. Introduction

Agriculture is the backbone of the Indian economy, providing livelihood to approximately 58% of the population. As of the 2023-2024 fiscal year, agriculture contributes approximately 17.7% to India's Gross Value Added (GVA) at current prices. India's horticulture production for the 2023-24 season is estimated to be 353.19 million tonnes, according to the third advance estimate released by the Ministry of Agriculture and Farmers Welfare, showcasing steady growth (Press Information Bureau, 2024). However, significant post-harvest losses remain a challenge, with studies indicating that 30-40% of fruits and vegetables and around 10% of food grains are lost due to inadequate storage and processing facilities (Rezaei & Liu, 2015) ^[13].

Cold storage plays a critical role in reducing post-harvest losses by extending the shelf life of perishable commodities. The high capital required and lack of uninterrupted power supply makes it difficult for farmers to build cold stores (Chopra *et al.*, 2022) ^[13]. Conventional refrigeration, however, relies heavily on grid electricity, which is not always accessible in rural areas. Globally, refrigeration systems consume approximately 15% of electricity production (Perier-Muzet *et al.*, 2014) ^[10]. Renewable energy alternatives, particularly solar-powered cold storage, offer a promising solution to address these challenges.

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A solar-refrigerated evaporatively-cooled (SREC) system that operates without reliance on conventional electricity grids. This structure integrates passive evaporative cooling and a split refrigeration system to achieve temperatures as low as 5-10°C, even in extreme heat. It is designed for self-construction using locally available materials, significantly reducing costs and increasing accessibility (Chopra *et al.*, 2023) [4]. However, the SREC system faces challenges due to fluctuating solar energy, resulting in temperature variations that can impact stored products.

Numerous studies have focused on enhancing the energy efficiency and stability of refrigeration systems. For instance, Azzouz *et al.* (2008) [2] demonstrated that incorporating phase change materials (PCM) into refrigeration systems improves energy efficiency by 5-15%. Similarly, reported that subcooled refrigeration systems with energy storage increase the coefficient of performance (COP) by over 15%. Al-Doori *et al.* (2017) [1] found that water spraying on condensers can improve COP by up to 5.5%, while Ndukaife and Nnanna (2019) [9] observed that evaporative cooling enhances COP by 44% and reduces power consumption by 20%. The study by Juengjaroennirachon *et al.* (2017) [6] revealed that thermosyphon-based systems could achieve a 22.75% improvement in COP and a 19.62% increase in cooling capacity. This study focuses on optimizing performance of the SREC structure by designing a control circuit to enhance its cooling efficiency and stabilize power consumption. By integrating

resistance-based thermistors and evaluating the system under hybrid and on-grid inverters, the research aims to ensure consistent refrigeration performance and mitigate the impact of fluctuating solar energy. This effort contributes to the development of sustainable and cost-effective cold storage solutions, addressing both energy efficiency and post-harvest loss challenges in agriculture.

2. Material and Methods

2.1 The Solar Refrigerated Evaporatively Cooled (SREC) structure

The study was conducted at the Division of Agricultural Engineering, ICAR-IARI, and New Delhi. The SREC structure is a hybrid cold storage system for agricultural produce, combining evaporative and forced cooling. It has a capacity of 10 x 10 x 10 ft³ and operates using a 5-kW rooftop solar panel system connected to an inverter that powers a 1.5-ton refrigeration unit (GREE Wall Mount Ductless Mini Split Air Conditioner & Heat Pump, Zhuhai, China), (Chopra *et al.*, 2023) [4].

The refrigeration system cools water in an internal tank using refrigerant coils. This cooled water is circulated through PVC pipes, forming a water battery that helps maintain a stable temperature inside the structure, particularly during non-solar hours. This design ensures efficient temperature regulation for extended cold storage of produce.

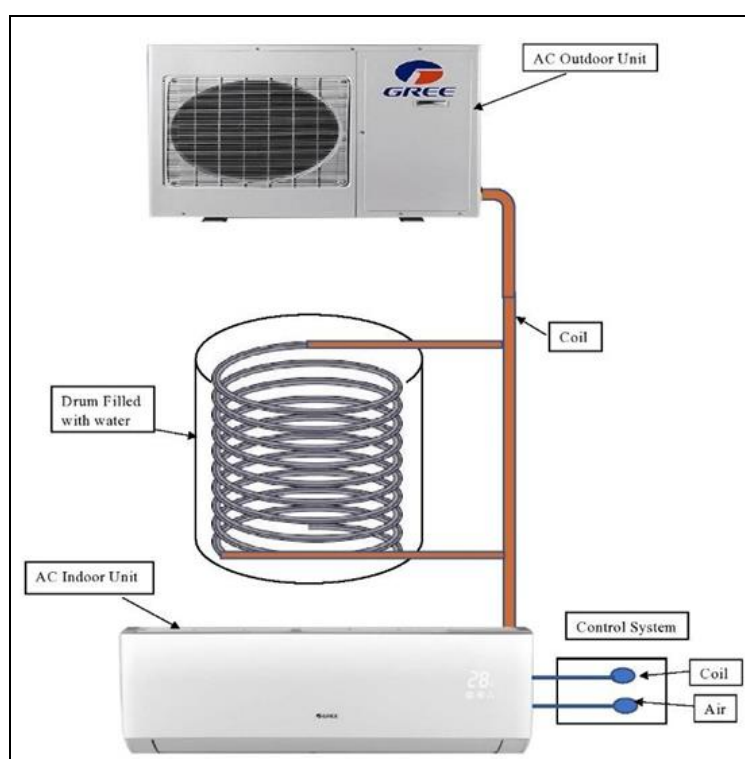


Fig 1: Refrigeration system of the SREC structure with control circuit

2.2 Coil and air thermistor in refrigeration system

To maintain a pre-set room temperature, a refrigeration system typically has a coil thermistor and an air thermistor which automatically cuts off the compressor. The minimum temperature, 16 °C is a pre-set temperature by the manufacturer. If the aim is to use this system for storing perishables, the efficiency of the cooling must be increased, for this coil thermistor and an air thermistor was connected with control circuit (Chopra *et al.*, 2023) [4].

2.3 Development of control circuit

The thermistors of the SREC structure's refrigeration system were analysed using manufacturer-provided datasheets. Based on these, equations were derived to correlate thermistor resistance with temperature.

$$\text{Coil temperature (}^{\circ}\text{C)} = \frac{\ln(\text{resistance value}) - \ln(56.958)}{(-0.037)}$$

$$\text{Air temperature } (^{\circ}\text{C}) = \frac{\ln(\text{resistance value}) - \ln(42.733)}{(-0.037)}$$

Using these equations, it was determined that maintaining coil temperatures between 6-10°C and air temperatures between 19-25°C required coil thermistor resistances of 38-48 kΩ and air

thermistor resistances of 16-21 kΩ.

A PCB board, resistors, potentiometers and connecting wires are the components of the control circuit. The circuit diagram of the control circuit was designed using MATLAB software as per the below figure.

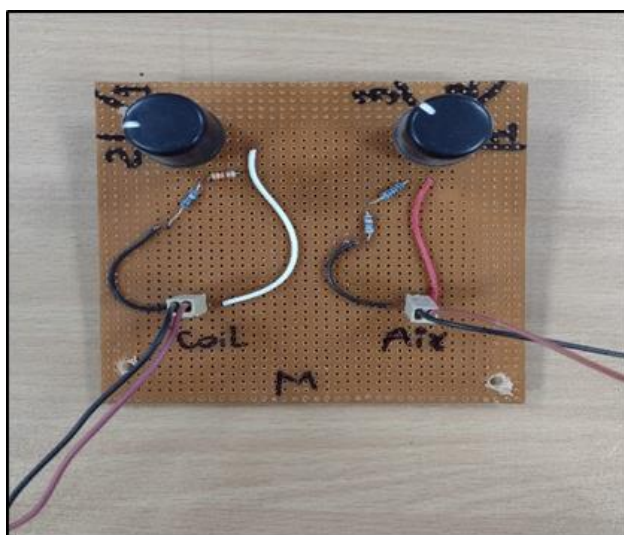


Fig 2: Control circuit

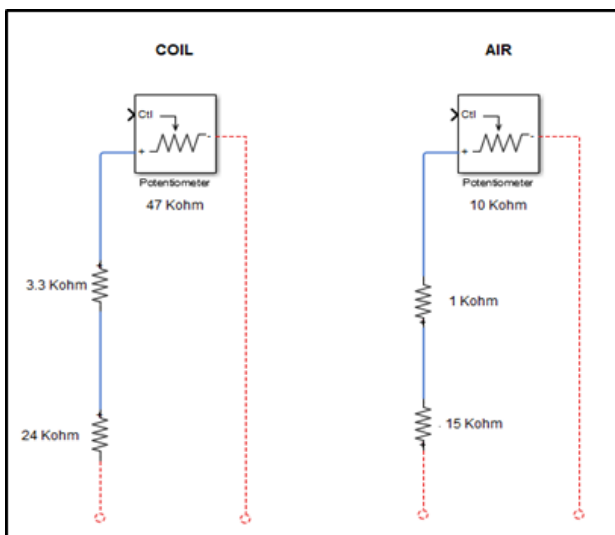


Fig 3: Circuit diagram

2.4 Testing of a control circuit with Inverters

For the refrigeration system of the SREC structure with the control circuit, two types of inverters were used: on-grid and hybrid. An SMA India on-grid solar inverter was selected for the study. On-grid systems connect to the local utility grid, allowing excess solar energy to be fed back into the grid without requiring battery storage. An MPP off-grid/hybrid solar inverter was also tested. This inverter can operate without a battery and functions independently of the utility grid, providing continuous power

directly from solar panels.

The 5-kW solar panels supply direct current (DC), which is converted to alternating current (AC) by the inverter to power the refrigeration system. In this study, the off-grid inverter refrigeration system was operated without battery storage, relying entirely on solar energy once started with a temporary grid connection.

The connection of the inverter to the SREC structure was done as per the following circuit diagram.

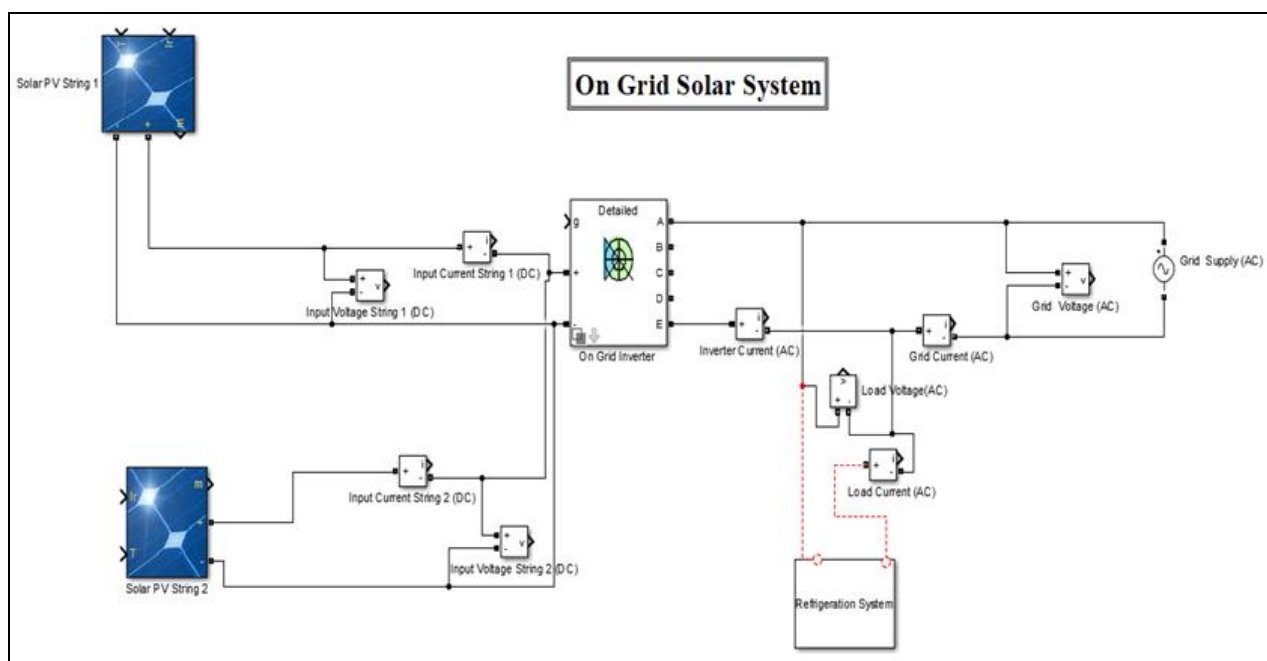


Fig 4: Circuit diagram of on grid solar system of the SREC structure

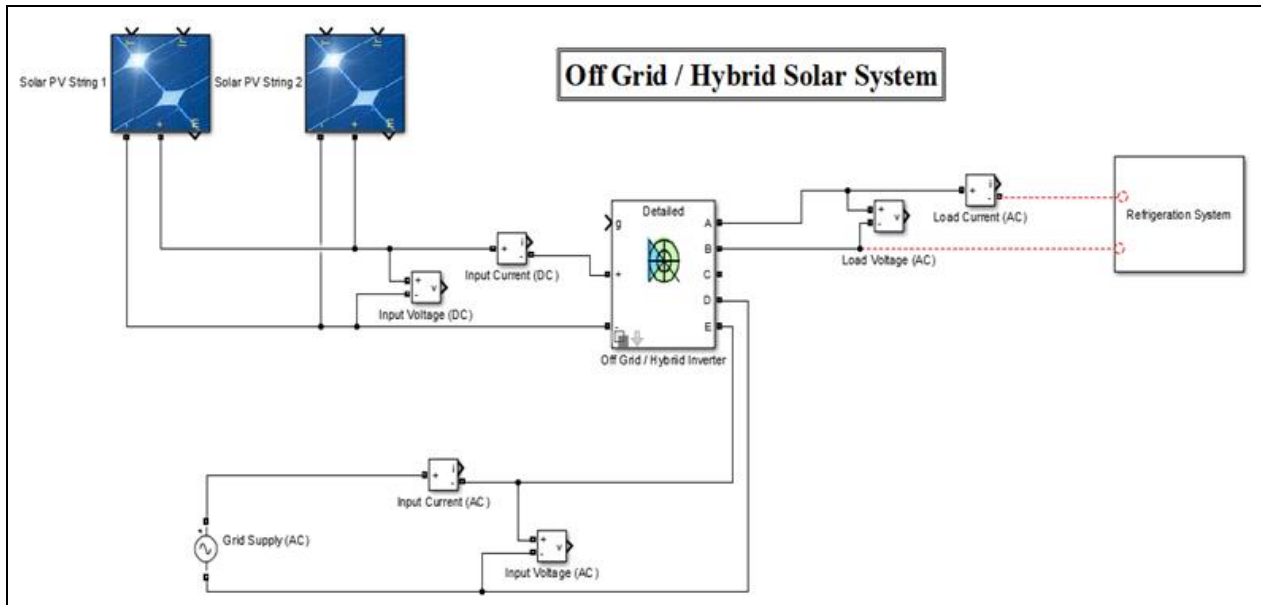


Fig 5: Circuit diagram of off grid/hybrid solar system of the SREC structure

2.5 Treatment detail of experiment

The study involved 12 treatments combining two types of inverters, off-grid/hybrid (X_1) and on-grid (X_2), two levels of coil thermistor resistance ($A_1 = 45 \text{ k}\Omega$ and $A_2 = 39.4 \text{ k}\Omega$), and three levels of air thermistor resistance ($B_1 = 21 \text{ k}\Omega$, $B_2 = 18.91 \text{ k}\Omega$, and $B_3 = 16.94 \text{ k}\Omega$), with three replications for each treatment. These treatments, denoted as T_1 to T_{12} and T_1 is a combination of an off-grid inverter (X_1), coil resistance A_1 , and air resistance B_1 . Similarly, T_4 represents off-grid inverter X_1 with coil resistance A_2 and air resistance B_1 . This structured approach allowed for a comprehensive analysis of the impacts of these configurations on the system's performance.

2.6 Data collection

T-type thermocouples (copper-constantan) with a detection range of -270 to 400°C were installed to measure ambient and internal temperatures in the SREC structure. Temperature data were recorded using a Campbell Scientific CR10 data logger. Electrical parameters, including solar panel input, inverter output, and system power consumption, were monitored from the control panel (Chopra *et al.*, 2023) [4]. Treatments T_1 to T_{12} were evaluated, with one treatment repeated over three days, and power consumption recorded every 30 minutes during the day.

2.7 Cooling Capacity

Cooling capacity refers to the energy required to lower the temperature inside the SREC structure. It was calculated for all treatments (T_1 to T_{12}) at 16°C using the equation:

$$Q = m \times C_p \times \Delta T \quad (Q\text{-energy } kJ, m\text{-mass } kg, C_p\text{- specific heat } kJ/kg^\circ\text{C}, \Delta T\text{- temperature difference } ^\circ\text{C}) \quad \text{Equation 3.3}$$

The system's cooling capacity at 16°C was compared with and without a control circuit to evaluate cooling efficiency.

2.8 Cooling Efficiency

Improved cooling efficiency was calculated using the equation:

$$\text{Improved cooling eff. (\%)} = \frac{\text{Cooling capacity at } 4^\circ\text{C} - \text{Cooling capacity at } 16^\circ\text{C}}{\text{Cooling capacity at } 4^\circ\text{C}}$$

Equation 3.4

2.9 Energy Efficiency Ratio (EER) and Coefficient of performance (COP)

For a typical, real refrigeration cycle, the working fluid (refrigerant) absorbs heat energy at evaporator temperature and releases heat at condenser temperature. This is expressed in British thermal unit (BTU). The electrical energy transformed per cycle exceeds the corresponding work W done on the refrigerant due to dissipative losses in the machinery and because of the existence of a blower fan needed to circulate the air being cooled. The total electrical energy transformed per cycle can be written as W (Watts), (Leff *et al.*, 1978) [7].

EER is the net cooling capacity (Btu/hr) divided by the total electrical power input (W):

$$\text{EER} = \frac{\text{Output cooling energy, BTU / hr}}{\text{Input electrical energy, W}} \quad \text{Equation 3.5}$$

COP, expressed as a dimensionless EER, represents the system's efficiency and is calculated as:

$$\text{System COP} = (0.293) \times \text{EER} \quad \text{Equation 3.6}$$

2.10 Statistical analysis

Turkey's test was done using the computer software R to study the significant effect of different variables.

3. Results and Discussion

3.1 Ambient temperature of the experimental site

The ambient temperature and inside temperature of the SREC structure were measured from 10:00 AM to 4:30 PM at an interval of half an hour. The inside temperature data during T_1 to T_{12} treatments of the SREC structure are shown in Fig. 8. For all treatments, the variation in ambient temperature with regard to time is similar throughout the day and the average ambient temperature was found at 23.52°C . The temperature in the environment was low at the start of the day, at 17 – 19°C .

3.2 Inside temperature of the SREC structure

After the connection of the control circuit, the temperature of the refrigeration starts to lower from 16°C . Among the 12

treatments, a minimum temperature of 3-4°C was achieved. According to Fig. 8, the internal temperature of the SREC structure does not vary much across treatments. The average temperature was 4.40°C. The minimum temperature was found at 3.53°C during the treatment T₄ and the maximum temperature was found at 5.45°C during the T₆ treatment.

3.3 Cooling Capacity

The cooling capacity of the refrigeration system with and without a control circuit was calculated by equation 3.3. When the refrigeration system was running with and without a control

circuit, the average cooling capacity was 8.24×10^5 kJ and 3.22×10^5 kJ, respectively (Figure 6). With a control circuit, the highest cooling capacity was 9.39×10^5 kJ, 9.18×10^5 kJ and 9.14×10^5 kJ respectively. The lowest cooling capacity was 7.78×10^5 kJ, 7.86×10^5 kJ and 7.92×10^5 kJ, respectively. Without a control circuit, the highest cooling capacity was 4.32×10^5 kJ, 4.18×10^5 kJ and 4.12×10^5 kJ respectively. The lowest cooling capacity was 2.36×10^5 kJ, 2.66×10^5 kJ and 2.78×10^5 kJ, respectively. The cooling capacity was highest when the refrigeration system was running with a control circuit.

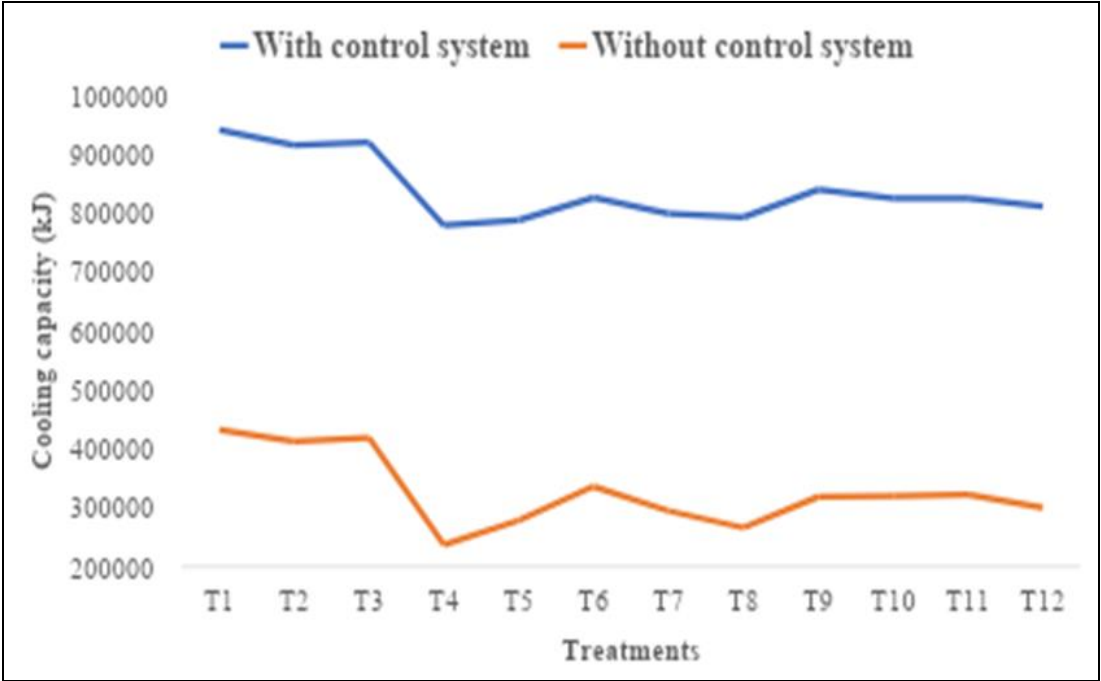


Fig 6: Cooling capacity (kJ)

3.4 Cooling Efficiency

The cooling efficiency was calculated by equation 3.4. The average improvement in the cooling efficiency was 1.61 times. According to Fig. 7, the highest improvement in the cooling efficiency was 2.29 times in T₄ treatment, whereas the second

highest improvement of 1.98 times was in treatment T₈. The first three lowest improvements in cooling efficiency among the twelve treatments were 1.18, 1.20 and 1.22 times in the treatments of T₁, T₃ and T₂, respectively.

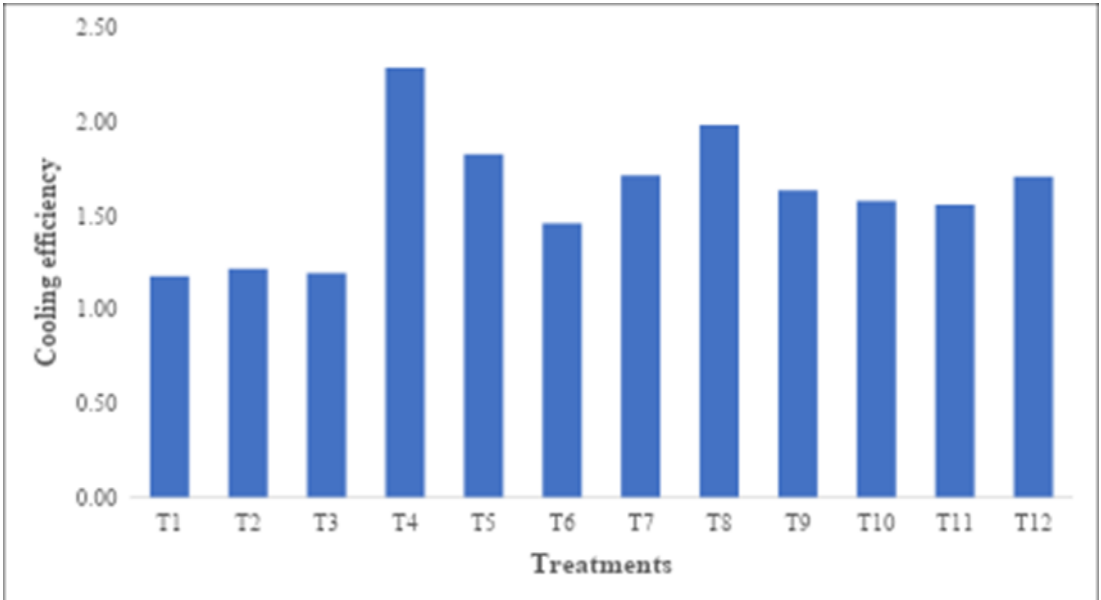


Fig 7: Cooling efficiency

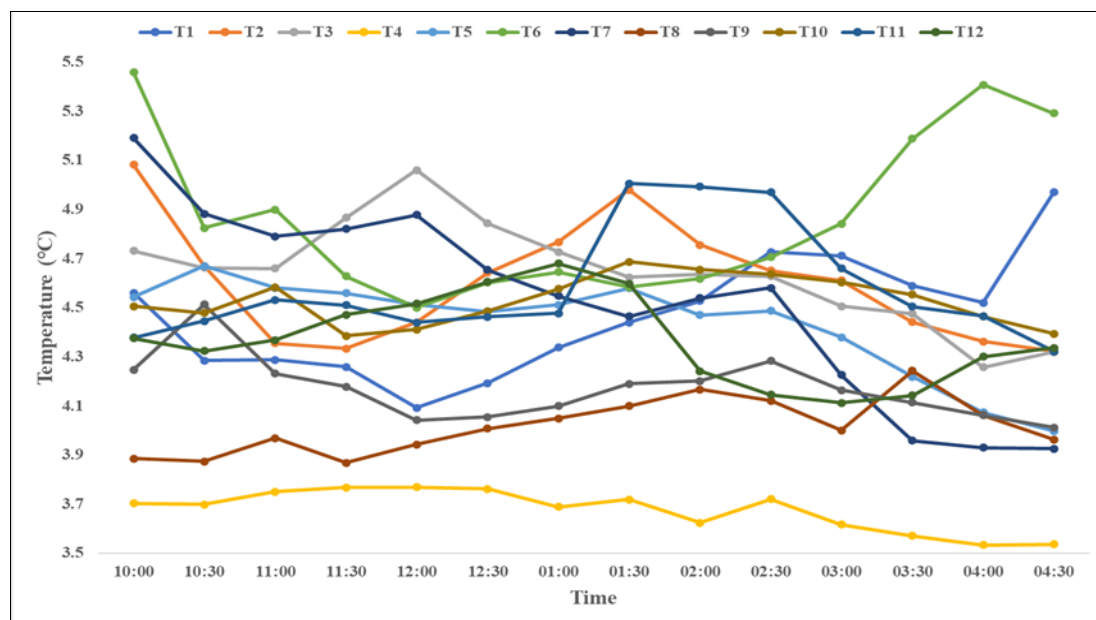


Fig 8: Average periodic variation of temperature in the SREC structure (°C)

3.5 Coefficient of Performance (COP)

The COP of the refrigeration system with and without a control system was calculated by equations 3.5 & 3.6. When the refrigeration system was running with and without a control system, the average COP was 6.19 and 3.47, respectively (Fig. 9). With a control system, the highest COP was 7.40, 7.05 and

6.89, respectively. The lowest COP was 5.12, 5.17 and 5.75, respectively. Without a control system, the power consumption of the refrigeration was the same throughout the study, so the COP value did not vary. The approximate value of COP was 3.47. The COP was highest when the refrigeration system was running with a control system.

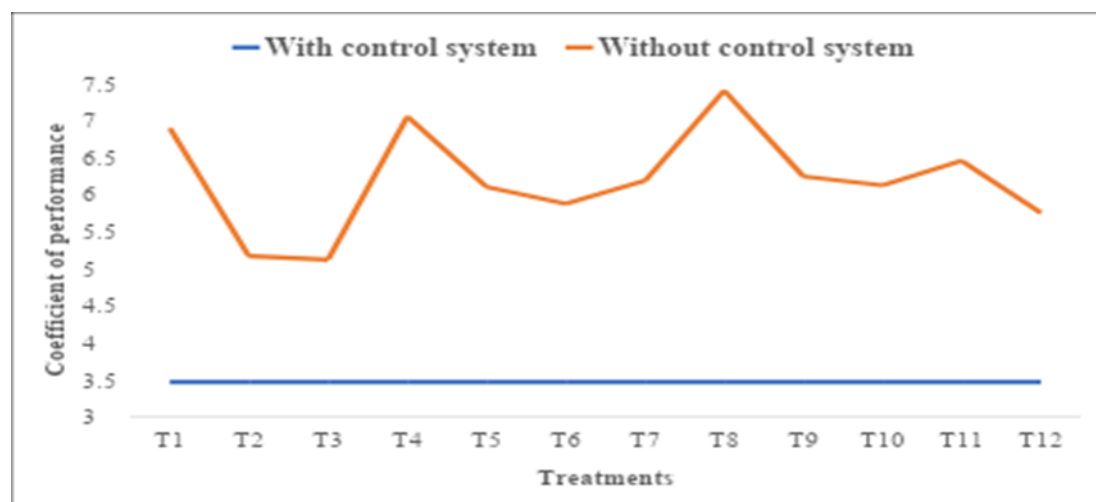


Fig 9: Coefficient of performance

Table 1: Mean table for coefficient of performance (COP)

Treatment	Mean
T ₁	7.40 ^a
T ₂	7.05 ^{ab}
T ₃	6.89 ^{ab}
T ₄	6.45 ^{ab}
T ₅	6.24 ^{ab}
T ₆	6.18 ^{ab}
T ₇	6.12 ^{ab}
T ₈	6.10 ^{ab}
T ₉	5.87 ^{ab}
T ₁₀	5.82 ^{ab}
T ₁₁	5.17 ^{ab}
T ₁₂	5.12 ^b
CV (%)	12.39
Turkey test	5.10

4. Conclusion

The study investigated the impact of a control system on the cooling efficiency and power consumption of a refrigeration system. The control system, which included adjustable coil and air thermistor resistances, was integrated with two types of inverters: off-grid and hybrid. It was found that the optimal configuration of minimum coil resistance and maximum air resistance significantly enhanced the cooling performance. This setup not only stabilized the system but also allowed it to operate efficiently under reduced sunlight conditions, demonstrating its adaptability to variable energy inputs.

The connection of the control system substantially reduced power consumption compared to the system operating without it. This reduction directly improved the coefficient of performance (COP), showcasing the system's enhanced energy efficiency. Moreover, temperature fluctuations inside the refrigeration

system were less pronounced during treatments T_7 to T_{12} , indicating better temperature stability. The stability and consistency of the inside temperature were evident across all treatments, with T_4 and T_8 identified as the most effective configurations based on statistical analysis using the Turkey test. In addition, the system proved highly suitable for remote locations where energy resources are limited. The integration of the control system with an off-grid inverter ensured efficient operation, even with inconsistent sunlight availability. In conclusion, the implementation of the control system improved cooling efficiency, reduced power consumption, and enhanced overall performance, making it reliable and supporting income stabilization for farmers by minimizing post-harvest losses and reducing spoilage of perishable goods, thereby enhancing rural livelihoods and contributing to sustainable agriculture.

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