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Design of Solar-Powered Cold Storage with Thermoelectric Cooling to Improve Fruit Storage Quality: A Case Study of Local Fruit Sellers

Hendra[1], Desmarita Leni[2*], Mulyadi[3], Zinvi Fu[4], Sir Anderson[5]

[1]Departement Mechanical Engineering, Politeknik Negeri Padang,
Jl. Kampus, Limau Manis, Kec. Pauh, Kota Padang, Sumatera Barat, 25164, INDONESIA
[2]Departement Mechanical Engineering, Universitas Muhammadiyah Sumatera Barat,
Jl. Pasir Jambak No.4, Pasie Nan Tigo, Kec. Koto Tangah, Kota Padang, Sumatera Barat 25586, INDONESIA
[3]Departement Mechanical Engineering, Politeknik Negeri Padang, INDONESIA
Jl. Kampus, Limau Manis, Kec. Pauh, Kota Padang, Sumatera Barat, 25164, INDONESIA
[4]Department of Mechanical Engineering, Politeknik Ibrahim Sultan
KM 10, Jalan Kong Kong, 81700 Pasir Gudang, Johor MALAYSIA
[5]Departement Mechanical Engineering, Politeknik Negeri Padang,
Jl. Kampus, Limau Manis, Kec. Pauh, Kota Padang, Sumatera Barat, 25164, INDONESIA

*Corresponding Desmarita Leni, desmaritaleni@gmail.com
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Abstract

The main problem faced by local farmers and fruit vendors is the lack of efficient and energy-saving storage facilities, causing fruits to often experience quality degradation and spoilage. This study aims to design and test a prototype of solar-powered cold storage with a thermoelectric cooling system (TEC) as an energy-efficient and environmentally friendly storage solution. The prototype uses a 100-watt solar panel as the primary energy source, combined with a Peltier TEC1 module to generate cooling. The test results show that the system can lower the internal temperature to 12°C within 3 hours. The system also achieves an energy efficiency of 18.07%, which is considered sufficient for small-scale thermoelectric applications. The use of solar energy enables the system to operate independently without relying on conventional electricity, offering an energy-saving and environmentally friendly solution. This prototype is deemed suitable for application in tropical regions, such as Indonesia, which has abundant solar energy potential throughout the year. This technology is expected to be a practical solution for farmers and small-scale vendors to reduce post-harvest losses while supporting carbon emission reduction efforts in the agricultural sector.

Keywords: *cold storage, solar energy, thermoelectric, energy efficiency, fresh fruit storage.*

INTRODUCTION

Local fruit vendors often face significant challenges in maintaining product quality due to the lack of adequate storage facilities. Fruits received from farmers or distributors are frequently stored under suboptimal conditions in limited storage spaces. Without proper control of temperature and humidity, fruits become highly susceptible to damage, quality degradation, and rapid spoilage. This situation not only diminishes the market appeal of their products but also leads to significant stock losses and reduced income for the vendors. Furthermore, local fruit sellers also struggle with high electricity costs required to operate storage equipment such as refrigerators or cold storage units. Cold storage is a specialized storage technology designed to preserve perishable products such as fruits, vegetables, meat, and other items requiring specific temperatures to maintain freshness. This technology typically consists of a room equipped with cooling systems that can precisely regulate temperature according to the needs of the stored products [1]. For local fruit vendors, using cold storage can enable them to store larger quantities of products while maintaining their quality before being sold to consumers. However, this technology requires considerable electrical power when operated daily, resulting in high electricity costs that become an additional burden for local fruit businesses.

A study [2] on the financial feasibility of selling frozen products in local markets revealed that operational costs for cold storage account for approximately 30% of vendors' total monthly expenses. These costs include electricity consumption to maintain optimal temperatures, equipment maintenance, and other expenses related to temperature regulation and monitoring. High electricity rates significantly reduce their profitability, especially when cooling equipment must run continuously to keep fruits fresh. This puts local fruit vendors at a disadvantage compared to competitors who have better access to cheaper energy sources. Therefore, an innovative solution for energy-efficient fresh fruit storage is urgently needed. Such a solution aims to help local fruit vendors increase their profit margins, enabling them to remain competitive in an increasingly demanding market.

Several studies have shown that cold storage systems utilizing solar cells and thermoelectric coolers can significantly reduce energy costs and increase profit margins for players in the fruit industry [3],[4]. In these systems, solar panels are installed to capture sunlight and convert it into electricity, which is then used to power the cooling system. A thermoelectric cooler serves as the main cooling device, maintaining the internal temperature of the cold storage at an optimal level for fruit preservation. This technology enables the cold storage to operate independently without relying on conventional electricity supply, thus reducing dependency on expensive and unstable energy sources. The implementation of cold storage systems using solar cells and thermoelectric coolers is highly feasible in Indonesia, given the country's abundant sunlight potential. Solar panels can harness solar energy and convert it into clean, renewable electricity, making these systems both environmentally friendly and cost-effective. A study [5] indicates that Indonesia experiences longer average sunlight exposure per month compared to developed countries like Japan and Germany, with an average solar radiation of 4.8 kWh/m²/day. This positions Indonesia as an ideal region for the adoption of solar-powered technologies.

This research aims to enhance the profit margins of local fruit vendors by applying cold storage technology equipped with solar cells and thermoelectric coolers. The significant potential of this technology lies in its ability to align with Indonesia's status as an agrarian and maritime country, where agricultural and fishery products form the backbone of local economies. By employing solar-powered cold storage, fruit industry players and fishermen can extend the shelf life of their commodities while reducing operational costs. Such advancements not only improve economic efficiency but also support sustainable practices in energy usage and agricultural logistics.

RESEARCH METHODS

This research methodology is designed to guide the process of designing, testing, and evaluating a cold storage system powered by solar cells and thermoelectric coolers to enhance the quality of fresh fruits for local fruit vendors. The methodology consists of several stages, as illustrated in **Figure 1**. These stages are further elaborated with more specific research activities to ensure a comprehensive approach.

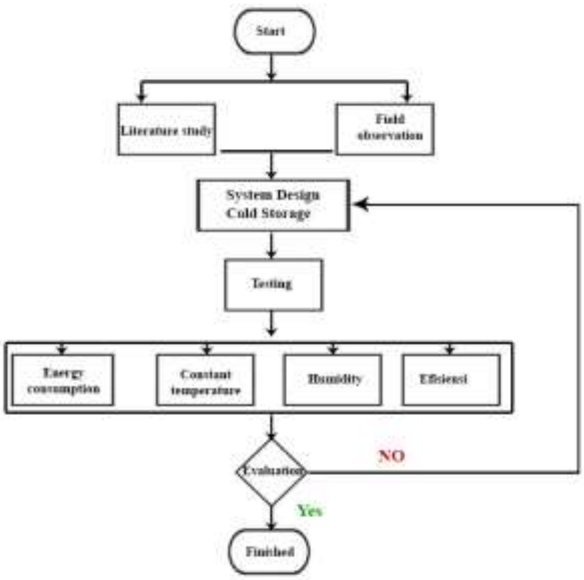

Fig 1. Research flow diagram

2.1 Literature Rewiew

The initial stage involves conducting a literature review to identify and analyze previous studies or case studies relevant to this research. This step provides in-depth insights into cold storage technology, the use of solar cells, and thermoelectric coolers for food preservation. It also includes an examination of the working principles, advantages, and limitations of these technologies in improving the quality and shelf life of fresh fruits. The literature review forms the foundation for understanding how these technologies can be integrated effectively to meet the objectives of this study.

2.2 Field Observation

In this stage, interviews or surveys will be conducted with local fruit vendors in Padang City to identify their needs and preferences related to fresh fruit storage. Additionally, the observation will include an analysis of applicable fresh fruit storage standards, covering aspects such as ideal storage temperature, humidity levels, and room ventilation requirements. This phase is critical for determining the technical specifications of the cold storage system, including storage capacity and the energy requirements necessary to operate the system effectively

2.3 Cold Storage System Design

Following the identification of vendor needs and requirements, as well as the review of applicable fresh fruit storage standards, the next step is to design the cold storage system. This stage involves creating a conceptual design for the cold storage, including room layout, cooling devices, solar panels, and temperature regulation systems. Furthermore, an automated control system will be developed to monitor and regulate temperature, humidity, and overall system performance. The design of the solar-powered thermoelectric cooling-based cold storage system is illustrated in Figure 2.

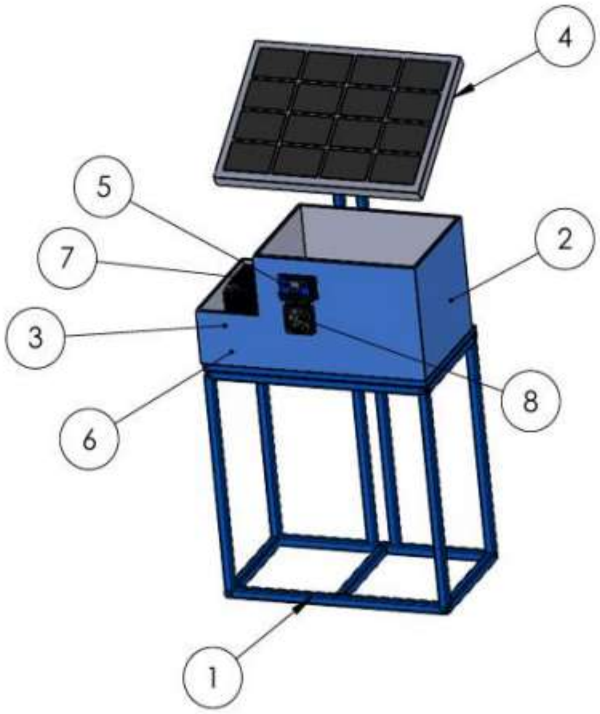

Fig 2. Storage Cooler

The following are the components of the storage cooler design:

1. Storage Frame
2. Styrofoam Box with Stainless Steel
3. Arduino Box with Stainless Steel
4. Solar Panel
5. Solar Charge Controller
6. Arduino and Sensors Inside the Box
7. Battery in the Box

8. DC Fan

After completing the Cold Storage System Design phase, the next step is Prototype Testing. In this phase, the cold storage prototype is constructed based on the previously developed design. Functional testing is conducted to verify the cooling operation, energy consumption, and the system's ability to maintain a constant temperature under varying environmental conditions. The test results are observed and documented, with areas requiring improvement or enhancement identified to ensure the system's performance aligns with expectations. The proposed testing scheme is illustrated in Figure 3.

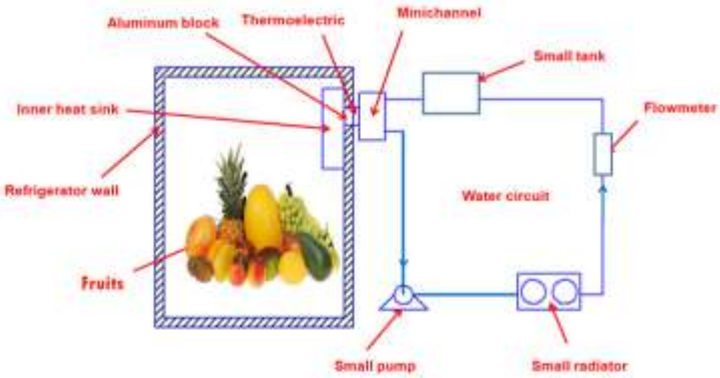

Fig 3. Cold storage test scheme

2.4 Perfoemance Evaluation

After completing the Prototype Testing phase, the next step is Performance Evaluation. This phase involves analyzing the test data to assess the performance of the cold storage prototype. The test results are compared against the quality standards for fresh fruit storage established in literature and regulations. Additionally, this phase identifies the strengths and weaknesses of the prototype, as well as its potential impact on improving fresh fruit quality and energy efficiency. The evaluation is crucial to ensure that the prototype meets the established requirements and delivers the expected benefits. Cooling efficiency and total efficiency are calculated using Equations 1 and 2, providing quantitative metrics to measure the system's effectiveness. This comprehensive assessment ensures that the system is both functional and practical for real-world applications.

$$\text{Internal Temperature Reduction Efficiency} = \frac{\Delta\text{Internal Temperature}}{\text{Energy Consumption}} \ldots\ldots\ldots\ldots\ldots(1)$$

Where Δ Internal Temperature refers to the change or reduction in temperature inside the cold storage (measured in °C), while Energy Consumption refers to the energy used by the cooling system to achieve the temperature reduction (measured in Wh). This efficiency is used to evaluate the performance of the cooling system. The higher the efficiency value, the more effective the system is in utilizing energy to lower the temperature.

Total energy efficiency can be calculated by comparing the energy used to achieve a given temperature reduction with the theoretical (ideal) requirement.

$$\text{Energy Efficiency} = \frac{\text{Actual Energy}}{\text{Ideal Energy}} \text{X } 100\% \ldots\ldots\ldots\ldots(2)$$

Where Ideal Energy refers to the theoretical energy required to perform a process perfectly without any energy loss, Actual Energy refers to the real energy consumed by the system to achieve the same result, while Energy Efficiency is used to evaluate the performance of the system. Ideal energy can be calculated using the following formula:

$$Q = m \, . \, c \, . \, \Delta T$$

where m is the mass of the commodity, C is the specific heat of the commodity, and ΔT is the decrease in temperature of the commodity.

RESULTS AND DISCUSSION.

Cold storage has become a vital component in modern food supply chains, particularly in maintaining the quality of fresh products such as fruits. This need is amplified in Indonesia, an agrarian and maritime country with immense potential for storing products under cold conditions to preserve their quality. As an agrarian nation, Indonesia produces abundant fruits, vegetables, and other agricultural products [6]. By utilizing cold storage, these products can be kept under optimal conditions to slow the ripening process and maintain their quality until they are sold. Additionally, as a maritime country with a large number of islands, Indonesia has a significant demand for fresh product storage, especially for items produced in remote and hard-to-reach areas.

3.1 Cold Storage System Design

The storage cooler design was developed as an efficient and practical cold storage solution with a compact size of 530 mm x 360 mm x 380 mm. Its dimensions make the unit easy to place in various locations without occupying much space. The main materials used include hollow steel for the frame, ensuring strength and durability, and stainless steel, which is rust-resistant and suitable for long-term use. With a weight of only 14 kg, the unit is lightweight and easy to move when needed.The cooling system is powered by a 100-watt solar panel, utilizing sunlight as the primary energy source. The energy from the solar panel is regulated by a 20 A solar charge controller, ensuring safe and efficient battery charging. The energy is stored in a 12 V, 12 Ah battery, allowing the unit to function even during cloudy weather or at night.

The interior is lined with 25-liter styrofoam, which helps maintain a cool temperature by preventing heat transfer from the outside. The cooling system uses a Peltier TEC1 module, a thermoelectric technology that is energy-efficient and does not require harmful chemical refrigerants. To ensure even distribution of cool air inside the storage space, the unit is equipped with a DC 12V fan. With this design, the storage cooler becomes an environmentally friendly, energy-efficient, and practical solution, especially for use in tropical regions like Indonesia, which has abundant solar energy potential. This device is ideal for farmers, small vendors, or anyone needing cold storage without relying on conventional electricity. The design is simple yet effective, making it easy to operate and maintain. Figure 4 illustrates the cold storage unit powered by a solar cell as its cooling energy source.

Fig 4. Cold storage using solar cells

The primary goal of cold storage is to preserve the quality of perishable products, such as fruits, vegetables, meat, and other items requiring low temperatures to remain fresh and durable. The temperature in cold storage is typically set lower than room temperature, often ranging between 0°C and 10°C, depending on the type of product stored [7]. Additionally, the humidity level within the cold storage is controlled to meet the specific requirements of the stored products. Maintaining optimal humidity is crucial, as low humidity can lead to dehydration of products, while high humidity increases the risk of mold growth and spoilage [8]. An efficient ventilation system ensures proper air circulation within the storage space. This aids in distributing the temperature evenly throughout the room, preventing hot spots that could damage the stored products. Some cold storage systems are equipped with gas control mechanisms, such as regulating oxygen and carbon dioxide levels in the storage environment [9]. Such controls are vital for managing the ripening process and preserving the quality of stored products. By maintaining appropriate temperature, humidity, and air circulation, cold storage slows down ripening processes, inhibits the growth of microorganisms, and minimizes physical damage to products. This ensures that items like fresh fruits can remain fresh for longer periods and retain their quality throughout storage. The test results of the solar-powered thermoelectric cooling-based cold storage system, specifically for storing 1 kg of mangoes, are presented in Figure 5. This data illustrates the system's effectiveness in maintaining optimal storage conditions to extend the shelf life of fresh produce.

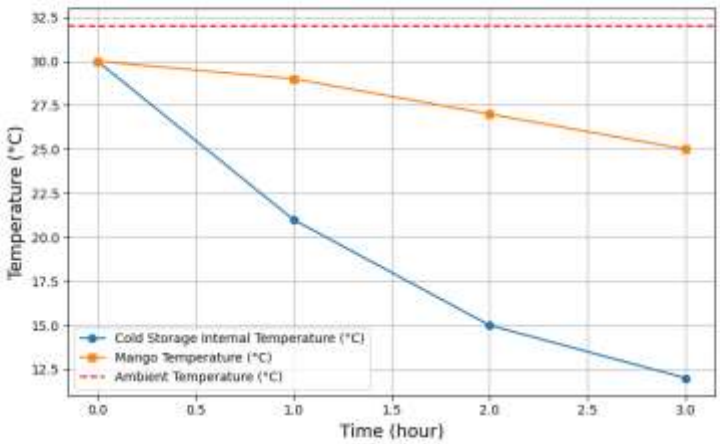

Fig 5. Cold Storage Test Data for Mango Storage (1 kg)

The test results demonstrate that the solar-powered thermoelectric cooling-based cold storage system can significantly lower the internal temperature from 30°C to 12°C within 3 hours. This consistent temperature reduction validates the effectiveness of the TEC1 module as the primary cooling system, even when operating in an environment with an average ambient temperature of 32°C. Alongside the internal temperature reduction, the mangoes' temperature gradually decreased from 30°C to 25°C within the same period. However, the temperature drop in mangoes occurred at a slower rate compared to the internal temperature due to the thermal properties of fruit, which have a higher heat capacity. This phenomenon aligns with findings in the literature on food storage.

The cooling system's performance meets the optimal storage temperature standards for mangoes, ranging from 12°C to 15°C, as outlined in previous research [10]. Within this temperature range, fruit respiration activity and microbial growth are suppressed, enabling the quality and freshness of mangoes to be preserved for a longer duration. This success is further supported by the use of Styrofoam insulation, which has a low thermal conductivity. Styrofoam minimizes heat transfer from the external environment to the storage unit, a feature corroborated by findings in similar studies [11]. In terms of energy efficiency, the system consumes an average of 10 Wh per hour, resulting in a total energy consumption of 30 Wh over 3 hours. This demonstrates the advantages of thermoelectric cooling systems for small-scale applications compared to traditional compressor-based cooling systems. Additionally, the use of a 100-watt solar panel enables the unit to operate independently of conventional electricity sources, making it highly suitable for tropical regions with abundant solar radiation, such as Indonesia. Previous studies [12][13] also support the adoption of this technology to significantly reduce energy costs, which is critical for the sustainability of small-scale businesses like local fruit vendors. With reliable cooling performance, high energy efficiency, and the integration of renewable energy, this system provides a practical and sustainable solution for the challenges of agricultural product storage. The combination of thermoelectric cooling technology, high-quality thermal insulation, and solar panels makes this cold storage unit not only energy-efficient but also environmentally friendly and economically viable for small-scale businesses. The overall test results underscore the tool's relevance and effectiveness in preserving product freshness, particularly in tropical regions like Indonesia.

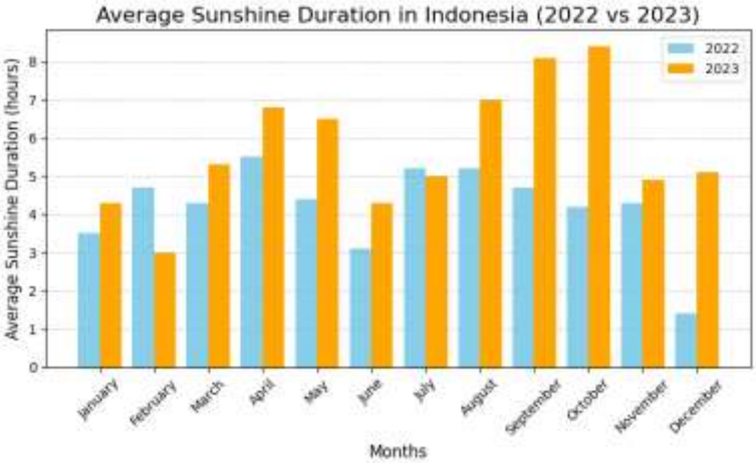

Fig 6. Average Solar Radiation Duration in Indonesia

The results show the average duration of sunlight in Indonesia for 2022 and 2023. In general, sunlight duration in 2023 was higher than in 2022, particularly during the period from April to October, which recorded over 8 hours of sunlight per day. Conversely, the lowest sunlight duration was observed in December 2022, with only 1.4 hours per day. This data highlights Indonesia's significant potential for utilizing solar energy, especially during the dry season when sunlight duration is longer. However, the shorter durations during the rainy season emphasize the need for efficient energy storage strategies to ensure optimal utilization of solar energy throughout the year.

This high solar energy potential is highly relevant for solar-powered cold storage applications, particularly for storing agricultural produce such as fruits and vegetables. Solar-powered cold storage systems can maintain product freshness by utilizing renewable energy, reducing dependence on conventional electricity, which is often costly. During the dry season, these systems operate efficiently due to abundant sunlight, providing significant advantages for farmers and local vendors in storing their harvests at low operational costs. However, challenges arise during the rainy season when sunlight duration decreases. To address this, the system requires batteries with sufficient capacity to store solar energy generated during the day for use when sunlight is limited.

The benefits of solar-powered cold storage extend beyond operational cost savings to support environmental sustainability. Solar energy is a renewable and environmentally friendly resource that can help reduce greenhouse gas emissions. Furthermore, these systems enable farmers to minimize post-harvest losses by preserving the quality of agricultural products for longer periods, thereby increasing their income. By integrating the right technologies, such as solar panels, efficient thermal insulation, and energy storage systems, solar-powered cold storage becomes a practical, economical, and sustainable solution for meeting storage needs in Indonesia, particularly in tropical regions with abundant sunlight potential.

3.2 Cold Storage Performance Evaluation

The performance evaluation phase was conducted to analyze the test data of the cold storage prototype and ensure the system meets the standards for storing fresh fruits. The test results were compared with literature and regulations concerning key parameters such as temperature, humidity, and energy efficiency. The results indicated that the thermoelectric cooling system (TEC) was capable of lowering the internal temperature of the cold storage by 0.6°C for every 1 Wh of energy consumed, reflecting a reasonably good performance in energy utilization for cooling purposes. Moreover, the system's total energy efficiency reached 18.07%, which falls within the acceptable range for thermoelectric technology. As reported in research [14], TEC systems typically exhibit efficiencies between 10% and 20%. Although a significant portion of the energy is lost as heat during the cooling process, this efficiency level demonstrates that the system has been optimally designed for small-scale applications like cold storage. Research [15] also highlighted that TEC systems can typically reduce temperatures by 0.5°C to 0.7°C per Wh of energy consumed, making the observed 0.6°C/Wh temperature reduction consistent with prior studies. This finding confirms the system's effectiveness, particularly for small-capacity applications. However, inefficiencies caused by heat dissipation on the hot side of the TEC module remain a common challenge in thermoelectric technology. As stated in research [16], poor heat management on the hot side can significantly reduce efficiency, suggesting that better heatsinks or advanced heat management technologies could enhance system performance. Aligned with research [17], the TEC cooling system is particularly well-suited for solar energy applications due to its low energy consumption and its capability to operate with limited power availability.

This compatibility with renewable energy sources positions TEC systems as a promising solution for sustainable cooling. Overall, the thermoelectric cooling system demonstrates reliable performance in temperature reduction while offering significant potential for integration with solar energy technology. With improvements in design, such as optimizing the efficiency of TEC modules and enhancing heat management, this system could evolve into an energy-efficient, reliable, and sustainable cooling solution for small-scale applications

CONCLUSIONS.

This research successfully designed and tested a solar-powered cold storage prototype with a thermoelectric cooling system (TEC). The test results demonstrated that the prototype could reduce the internal temperature to 12°C within 3 hours, meeting the standards for fresh fruit storage as stated in the literature. The cooling system effectively maintained optimal storage temperatures to slow fruit respiration and inhibit microbial growth, ensuring the freshness of the fruit throughout the storage period. The system achieved an energy efficiency of 18.07%, which is considered adequate for thermoelectric cooling technology in small-scale applications. Although this efficiency is lower compared to compressor-based cooling systems, it is sufficient for solar-powered applications, where low energy consumption is a priority. By utilizing a 100-watt solar panel, the prototype operated independently of conventional electricity, making it an environmentally friendly and energy-efficient solution. These results indicate that the system is reliable enough to support solar-powered operations, particularly in tropical regions with abundant sunlight, such as Indonesia. This research highlights the potential of integrating thermoelectric cooling technology with renewable energy sources to provide practical, sustainable, and cost-effective solutions for fresh fruit storage.

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