

Eco-Friendly Solar Refrigerator: Peltier Cooling, Remote Monitoring for Sustainable and Efficient Energy Consumption

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| Article Info | ABSTRACT |
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| <p>Article History:</p> <p>Received February 03, 2025 Revised May 07, 2025 Accepted May 29, 2025 Published Online August 17, 2025</p> <hr/> <p>Keywords:</p> <p><i>DHT sensor refrigerators seebeck effect solar panel TEC peltier 12706</i></p> <hr/> <p>Corresponding Author:</p> <p>Meqorry Yusfi Email: meqorryyusfi@sci.unand.ac.id</p> | <p>Electricity is essential for everyday needs, including food preservation through refrigeration. However, access to electricity remains uneven in remote regions due to geographical constraints. Solar energy offers a promising alternative, especially in areas with abundant sunlight, highlighting the need for compact, portable, and eco-friendly cooling system. This study aims to design an eco-friendly cooling system using the Seebeck Effect in Peltier TEC 12706 modules powered by solar energy. The system consists of two Peltier TEC 12706 modules, a 50 Wp solar panel, and a 33 Ah accumulator, with a cooling chamber measuring $26 \times 17 \times 10$ cm. Temperature and humidity were remotely monitored via the Blynk application. Experimental results showed the lowest temperature achieved was 15°C between 08:00 AM and 10:00 AM. In comparison, the most significant temperature drop of 11.7°C occurred between 12:00 PM and 02:00 PM, with an average light intensity of 176,846.15 Lux. Although the system demonstrated cooling performance, the minimum temperature of 15°C does not meet the standard refrigeration temperature of around 0°C. Therefore, the current system is not yet suitable for replacing conventional refrigerators, but it shows potential as an environmentally friendly alternative cooling solution with further development.</p> <p style="text-align: right;"><i>Copyright © 2025 Author(s)</i></p> |

1. INTRODUCTION

The development of electricity infrastructure plays a vital role in supporting economic growth and ensuring equitable welfare. Although Indonesia's national electrification ratio reached 99.79% in 2023, electricity distribution remains uneven, particularly in remote areas such as Papua, Maluku, and Nusa Tenggara (Sansuadi, 2025). Indonesia's vast archipelagic geography and widely dispersed population present significant challenges (Alhusain, 2019). To address this, renewable energy sources like solar power (PLTS) offer promising solutions, given Indonesia's year-round tropical sunlight (Saputra et al., 2023). Electricity is also essential for household appliances such as refrigerators, which help preserve food and beverages. The growing demand for portable cooling devices highlights the need for compact, mobile, and eco-friendly systems to replace conventional refrigerants that are harmful to the environment (Setiawan et al., 2024).

A more sustainable alternative involves replacing conventional refrigerants with thermoelectric Peltier modules, which utilize the Seebeck effect to provide silent, compact, and environmentally friendly cooling (Yudianto and Yudhana, 2022; Remeli et al., 2020; Jouhara et al., 2021; Purwiyanti et al., 2018; Yusfi et al., 2017). To address energy consumption issues, solar power offers a sustainable

solution, converting sunlight into electricity without relying on conventional sources (Amifia et al., 2022; Swarnakar and Datta, 2016; Wallies and Balekundri, 2014; Harahap et al., 2020; Kumar Sah et al., 2018; Rusdi et al., 2024).

Several studies have explored the potential of solar-powered thermoelectric cooling systems. Ebong et al., (2022) designed a portable refrigerator for vaccine storage using TEC 12706 modules, achieving a temperature drop from 28°C to 5°C in one hour. However, overheating on the hot side of the module after 15 minutes necessitated the use of fan coolers. The Coefficient of Performance (COP) was successfully improved from 0.6 to 0.7. Manik et al., (2019) was applied to preserve fruits and vegetables, achieving a minimum temperature of 17.32°C by utilizing four TEC 12706 modules, two 12V 100 Wp solar panels, and a 12V 70 Ah battery, while Suryadi and Firmansyah (2020) created a cold chamber powered by conventional electricity with a maximum temperature drop of 11.28% for 200 mL of water.

In terms of energy performance Bansal and Martin (2000) conducted a comprehensive study on the energy efficiency of cooling systems with comparable capacities (~50 liters) and reported that vapor compression systems achieved a COP of 2.59, substantially higher than thermoelectric systems, which recorded a COP of only 0.69. These findings highlight that, despite their environmental advantages, thermoelectric systems still face significant challenges in terms of energy efficiency when compared to conventional refrigeration technologies

This study builds upon the work of Puspita and Yusfi (2025), who investigated the cooling performance of two thermoelectric chambers with different dimensions. They found that a smaller chamber (26 × 17 × 10 cm) could achieve temperatures up to 4°C lower than a larger chamber (38 × 23 × 21 cm) under the same testing period, using a 12 V 30 A AC-DC adapter as the power source. Building upon these findings, the present study focuses on the same smaller-sized chamber, which has proven to be more efficient. However, it introduces a different approach by utilizing renewable energy as the primary power source, in the form of a 50 Wp solar panel connected to a 12 V 33 Ah battery. Experiments are conducted at three different time intervals (08:00 AM – 10:00 AM, 10:00 AM – 12:00 PM, and 12:00 PM – 02:00 PM) to evaluate the effect of solar intensity on system performance. The cooling system employs two TEC 12706 Peltier modules and four 12 V 0.15 A cooling fans to maintain thermal stability within the chamber. Temperature and humidity are monitored in real time using a DHT22 sensor integrated with the Blynk application. Through this approach, the study aims to assess the feasibility of a solar-powered cooling system as a sustainable solution, particularly for off-grid or remote areas lacking access to conventional electricity.

2. METHOD

2.1 System Planning

The system design can be seen through the system block diagram in Figure 1. Solar panels absorb light, releasing electrons in the semiconductor material to generate an electric current. The Solar Charge Controller (SCC) regulates this current and distributes it to a chargeable accumulator, powering the TEC 12706 Peltier. A cooler fan ensures proper airflow and distributes cold air in the cooling chamber, while heatsinks remove excess heat. The DHT22 sensor, placed inside the chamber, detects temperature and humidity. NodeMCU ESP8266 processes the sensor data, and the Blynk app displays the temperature and humidity readings.

2.2 Overall System Design

The hardware design involves assembling and integrating tools in the system, as shown in Figure 2. Solar panels capture light, releasing electrons in the semiconductor material that generate an electric current. The SCC regulates this current, distributing part of it to the accumulator for storage as direct current, which powers the Peltier TEC 12706 and fan cooler without needing an inverter. The Peltier's cold side, placed inside the cooling chamber, absorbs heat, while the hot side, placed outside, dissipates it. Three external fans prevent overheating of the Peltier, and one internal fan distributes cold air within the chamber. Heatsinks assist in removing excess heat. The DHT22 sensor detects temperature and

humidity inside the chamber, compared against AZ HT-02 and FY-11 measurements. NodeMCU ESP8266 processes the sensor data, with the Blynk app displaying the results on a smartphone.

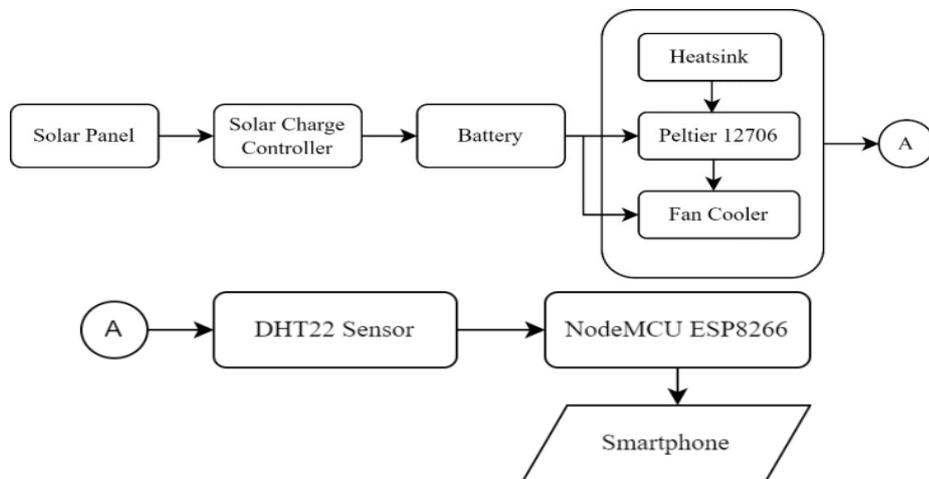


Figure 1 Overall block diagram of an eco-friendly solar refrigerator.

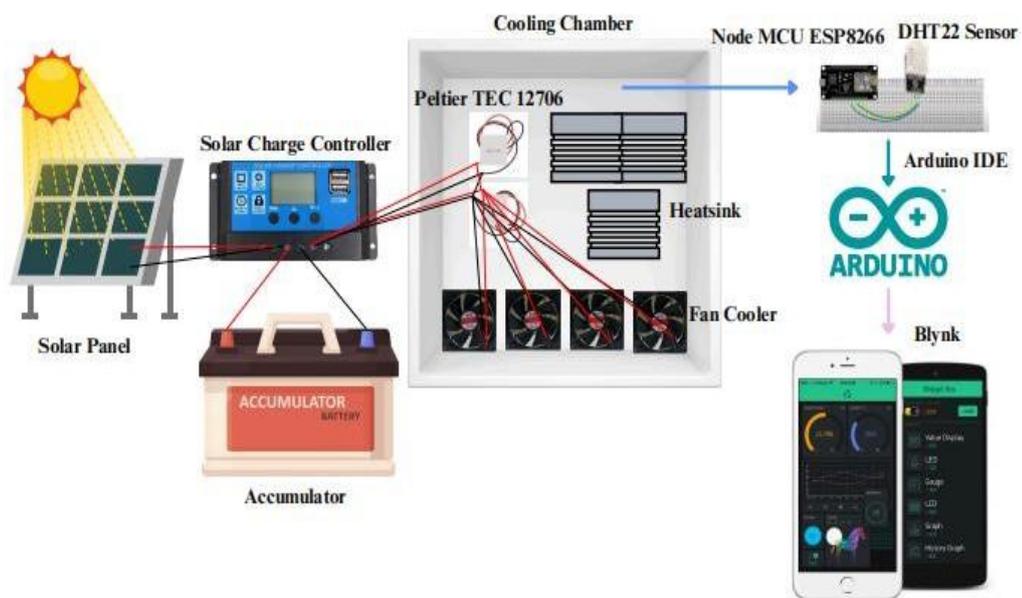


Figure 2 Overall system design for eco-friendly solar refrigerator

3. RESULTS AND DISCUSSION

3.1 Data Collection with A System Connected to a Solar Panel Only

In Indonesia, the maximum solar energy conversion typically occurs over an average duration of 6 hours, from 08:00 AM to 02:00 PM (Gunoto and Sofyan, 2020). Accordingly, data were collected by connecting the system to a 50 Wp solar panel during this period to evaluate the system's performance. The experimental results are presented in Figure 3. The results indicate a temperature decrease 10.2°C. from 29.8°C to 19.6°C. This demonstrates the system's capability to operate without an accumulator.

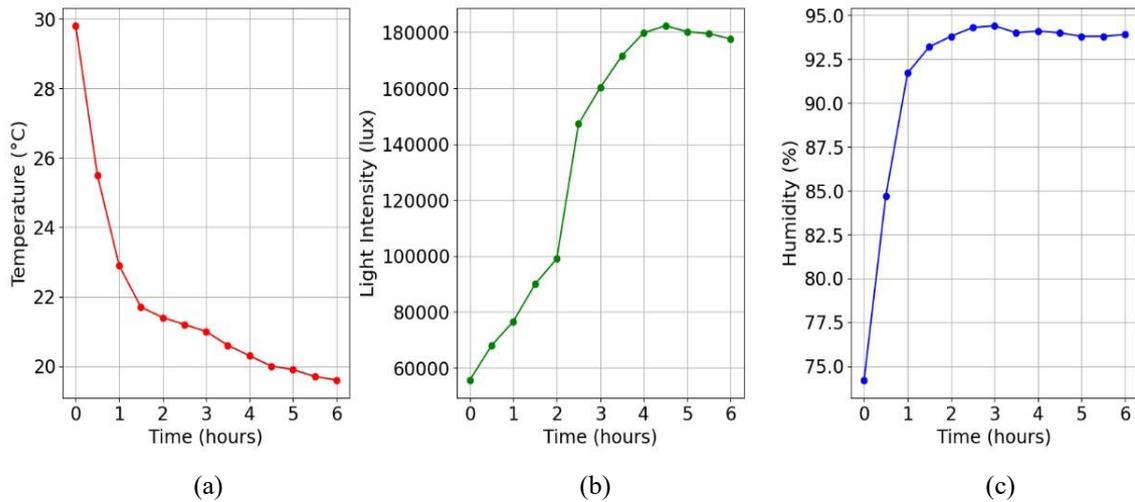


Figure 3 (a) Graph of the relationship between time (hours) vs temperature (°C), (b) Graph of the relationship between time (hours) vs light intensity, (c) Graph of the relationship between time (hours) vs humidity (%)

3.2 Data Collection with A System Connected to an Accumulator Only

Data was collected by connecting the system to a 33 Ah accumulator from 07:00 PM until the system shut down. The results are illustrated in Figure 4. Based on Figure 4, data collection starts at 7:00 PM, indicating that the system could operate until 09:40 PM, demonstrating a total operational duration of 2.67 hours. The temperature drops within the cooling chamber reached 11.5°C, from 28.8°C to 17.3°C. These findings indicate the system can operate at night using a 33 Ah accumulator.

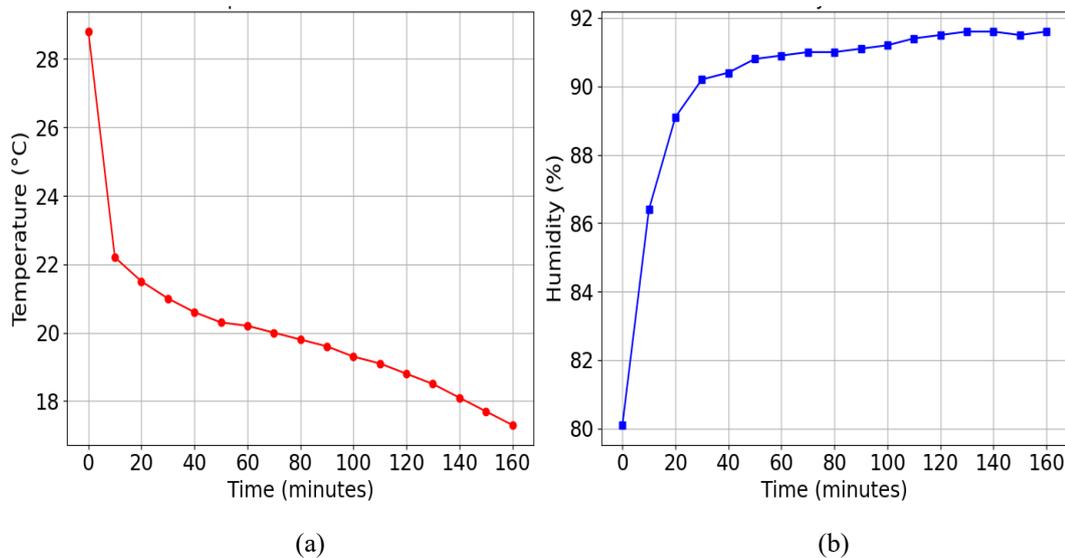


Figure 4 (a) Graph of the relationship between time (minutes) vs temperature (°C) (b) Graph of the relationship between time (minutes) vs humidity (%)

3.3 Data Collection with A System Connected to a Solar Panel and Accumulator

Data was collected by connecting the system to a 50 Wp solar panel and a 12 V 33 Ah accumulator for 2 hours daily. The first data collection was carried out from 08:00 AM to 10:00 AM (Figure 5). Furthermore, the second data collection was conducted from 10:00 AM to 12:00 PM (Figure 6) and the third data collection was conducted from 12:00 PM to 02:00 PM (Figure 7).

Data collection conducted for two hours per day, with data intervals of 10 minutes, revealed similar patterns. Figure 5 shows a temperature drop from 28.3°C to 15°C, with a temperature decrease of 10.3°C in the first 10 minutes. Figure 6 shows a temperature drop from 32.6°C to 19.3°C, with a temperature decrease of 10.2°C in the first 10 minutes. Figure 7 shows a temperature drop from 33.3°C

to 19.6°C, with an 11.2°C temperature decrease in the first 10 minutes. The temperature drops exceeding 10°C in the first 10 minutes are due to the efficient heat transfer from the Peltier TEC 12706 to the heatsink through conduction. The heatsink and fan on the hot side of the Peltier TEC 12706 enhance the efficiency of this heat transfer to the environment through convection. In the subsequent 10 minutes until the end of data collection, the temperature decrease was not as significant as in the first 10 minutes. Figure 5 shows a reduction of no more than 1.6°C, Figure 6 shows no more than 0.8°C, and Figure 7 shows no more than 1.6°C. This is due to the system nearing thermal equilibrium and the reduced heat transfer efficiency leading to heat accumulation.

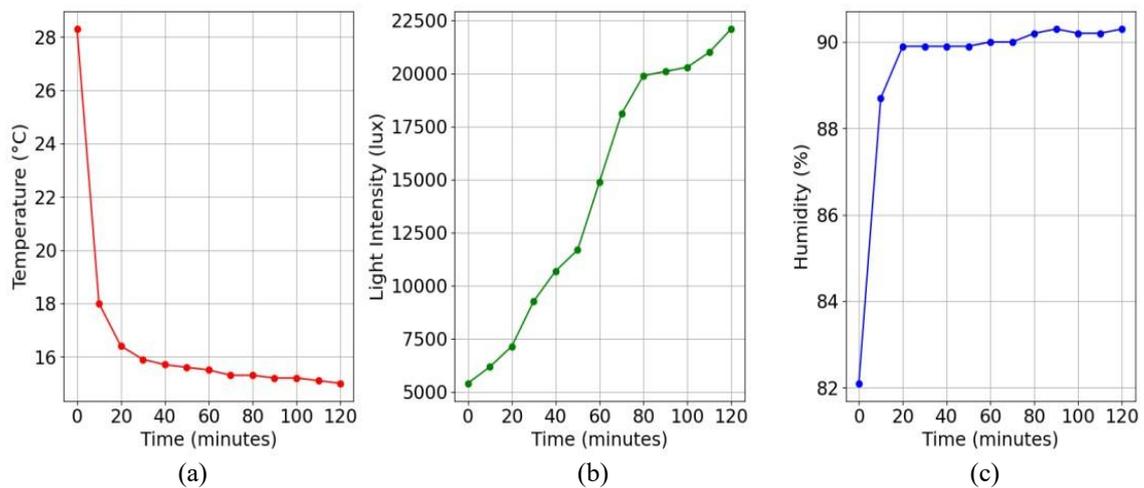


Figure 5 (a) Graph of the relationship between time (minutes) vs temperature (°C) (b) Graph of the relationship between time (minutes) vs light intensity (lux) (c) Graph of the relationship between time (minutes) vs humidity (%) from 08:00 AM to 10:00 AM.

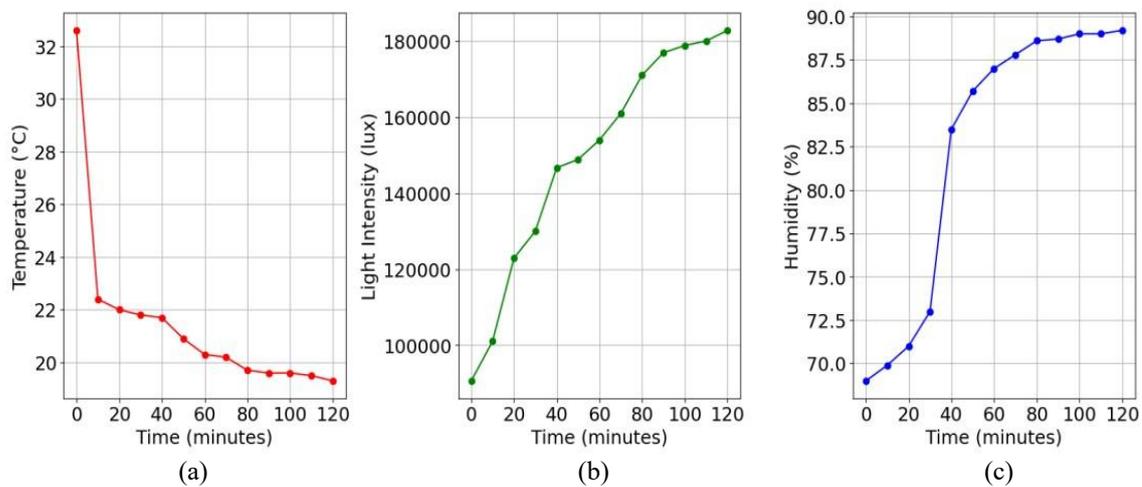


Figure 6 (a) Graph of the relationship between time (minutes) vs temperature (°C) (b) Graph of the relationship between time (minutes) vs light intensity (lux) (c) Graph of the relationship between time (minutes) vs humidity (%) from 10:00 AM to 12:00 PM

In addition to the decrease in temperature, the Peltier TEC12706 also caused an increase in humidity. Figure 5 shows an increase in moisture from 82.1% to 90.3%, with a 6.6% increase in the first 10 minutes. Figure 6 shows an increase in humidity from 69% to 89.2%, with a 10.2% increase in the first 10 minutes. Figure 7 shows an increase in humidity from 73% to 89.2%, with a 15.6% increase in the first 10 minutes. The significant increase in moisture is due to the drop in temperature of the Peltier TEC12706, which causes frost formation containing water vapour, which is then distributed by the fan throughout the room, thus increasing the humidity as the temperature from the Peltier TEC12706

decreases. The highest increase in humidity of 15.6% occurred in the first 10 minutes, corresponding with the most significant temperature drop. In the subsequent 10 minutes until the end of data collection, the increase in humidity was very slow due to the slow temperature decrease.

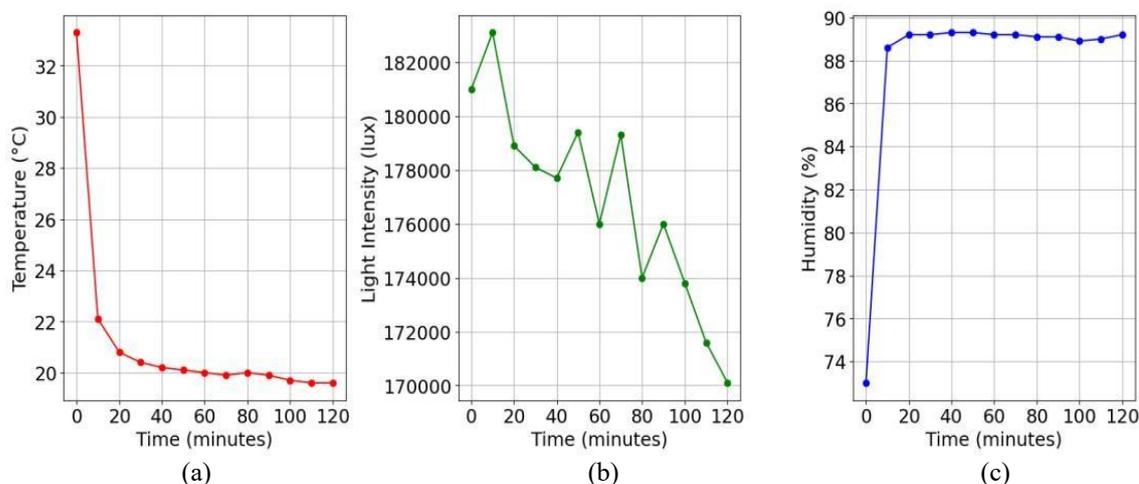


Figure 7 (a) Graph of the relationship between time (minutes) vs temperature (°C) (b) Graph of the relationship between time (minutes) vs light intensity (lux) (c) Graph of the relationship between time (minutes) vs humidity (%) from 12:00 PM to 02:00 PM

The results from the three periods indicate that data collected from 08:00 AM to 10:00 AM achieved the lowest temperature of 15°C, influenced by external temperatures. As the external temperature decreases, the system finds it easier to lower the temperature inside the chamber. Conversely, the most significant temperature drop of 11.7°C occurred during data collection from 12:00 PM to 02:00 PM, due to the highest light intensity, averaging 176,846.2 Lux, resulting in greater power output from the system than in other periods.

This study reinforces previous research on Peltier-based cooling systems powered by solar energy. The overheating issue of the TEC 12706 module reported by Ebong et al., (2022) was addressed here by using four 12 V fans. Compared to Manik et al., (2019), this system is more energy-efficient, utilizing only two TEC modules, a 50 Wp solar panel, and a 33 Ah battery, yet still effectively lowering the temperature. Unlike Suryadi and Firmansyah (2020), who relied on conventional electricity, this study demonstrates the efficiency of solar energy as the primary power source. Furthermore, this study enhances previous research by implementing the Blynk application for real-time monitoring of temperature and humidity utilizing the highly accurate DHT22 sensor. The results are further supported by graphical analyses illustrating the relationships among time, temperature, humidity, and light intensity, thereby elucidating the influence of light intensity on the operational performance of the solar-powered cooling system.

4. CONCLUSION

Based on the results and analysis obtained in this study, it can be concluded that an eco-friendly solar-powered refrigeration system incorporating Peltier modules and remote monitoring has been successfully developed to support sustainable and efficient energy usage. The system demonstrated the ability to operate using three different power sources: solar panels, an accumulator, and a combination of solar panels and an accumulator. During testing, with the system connected to the solar panel and the accumulator, the lowest recorded temperature was 15°C, observed between 08:00 AM and 10:00 AM. The most significant temperature drop, recorded at 11.7°C, occurred between 12:00 PM and 02:00 PM, with an average light intensity of 176,846.15 Lux. However, the target temperature of 0°C was not achieved. The system's inability to reach lower temperatures is primarily attributed to the limited

cooling capacity of the two Peltier TEC 12706 modules and the suboptimal thermal insulation of the cooling chamber. These limitations indicate that the current system is not yet suitable for use as a conventional refrigerator, which typically requires temperatures around 0°C. To improve system performance, several enhancements are recommended: increasing the number of Peltier modules; using metallic materials for the cooling chamber to minimize air leakage and enhance insulation; and integrating a relay with the DC fan for better temperature and humidity regulation. These improvements are expected to optimize the system's cooling capabilities and support its application in practical, real-world scenarios.

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