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CONSTRUCTION OF A THERMOELECTRIC COOLBOX SYSTEM WITH ICE PACK MODIFICATION FOR MANGO STORAGE BASED ON THE INTERNET OF THINGS

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Abstract. This study aims to design a thermoelectric system for a coolbox utilizing additional ice pack components for mango storage by leveraging a TEC1-12706 Peltier element based on IoT technology. Thermoelectric is an energy conversion technology that directly converts thermal energy into electrical energy and vice versa through thermoelectric materials. The system operates based on the Peltier effect, which generates a temperature difference between two sides of the material when an electric current is applied. Based on the test results, the developed thermoelectric system achieved a cabin temperature of up to 12.6 ºC within 60 minutes, according to the ideal storage temperature requirements for mangoes (12–15 ºC). The addition of an ice pack plays a significant role in accelerating the temperature reduction inside the cabin. The cold sink and heatsink components function effectively in absorbing and releasing heat to the environment. This system achieved a COP of 0.60 with an efficiency of 60%. The thermoelectric system has also been successfully integrated with IoT technology through the Blynk application, enabling users to monitor temperature and humidity in real-time via an internet-connected smartphone, thereby facilitating the control of mango storage conditions.

Keywords: thermoelectric coolbox system, ice pack, mangoes, IoT

1. INTRODUCTION

Mangoes are one of the important horticultural commodities in Indonesia. The abundant production of mangoes in Indramayu [1] often encounters post-harvest challenges, particularly in storage and maintaining fruit quality [2]. Mangoes are climacteric fruits that continue to ripen after being harvested, making them prone to damage and spoilage if not properly handled. Post-harvest losses can lead to significant economic losses for farmers and traders [3], [4]. The ideal storage temperature for mangoes generally ranges between 12–15 °C, with relative humidity of 85–90% [5], [6]. Conventional storage methods, such as using ice blocks or open-air storage, are often less effective in maintaining mango quality over an extended period. Ice blocks have limitations in maintaining stable temperatures, while open-air storage is highly dependent on environmental conditions. Therefore, a more effective and controlled storage solution is required to extend the shelf life and preserve the quality of mangoes [7].

Thermoelectric technology offers an environmentally friendly and efficient cooling solution. Thermoelectric systems operate based on the Peltier effect, which generates a temperature difference between two sides of a material when an electric current is applied. Thermoelectric cooling systems have several advantages, including compact size, the absence of refrigerants, and precise control capabilities [8], [9]. Permana et al. successfully designed a thermoelectric refrigeration system utilizing solar energy for banana storage, achieving a minimum cold-side temperature of 12.7 °C after 180 minutes of operation [10]. Aziz et al. developed a temperature control system for fruit and vegetable storage applications using TEC1-12706 thermoelectric coolers, demonstrating cabin temperature stability at 15 °C, which is considered suitable for storing fruits and vegetables [11]. Another thermoelectric system developed by Tuapetel et al. managed to cool 1.2 liters of water to 14.9 °C

[12]. Despite extensive development of thermoelectric systems, their efficiency remains relatively low [13], [14], necessitating modifications to thermoelectric materials and module designs to improve performance.

One modification that can be implemented is the addition of ice packs. Ice packs act as supplementary cold storage, prolonging cooling time and reducing temperature fluctuations inside the coolbox [15]. Furthermore, thermoelectric systems can be integrated with Internet of Things (IoT) technology, enabling real-time and remote monitoring and control of temperature, humidity, and other parameters, thereby improving system efficiency. IoT also facilitates damage prediction and preventive actions, providing significant benefits in system maintenance in terms of convenience, accuracy, and efficiency. Based on the above considerations, this study focuses on constructing a modified thermoelectric coolbox system with ice packs, integrated with IoT via the Blynk application, to optimize mango storage. This system is expected to maintain the quality and extend the shelf life of mangoes efficiently and economically.

2. METHODS

2.1 Tools and Materials

The tools and materials used in this study include Krisbow screwdrivers, Tekiro measurement tape, Wipro saw, Krisbow hammer, magnetic spirit level, TEC1-12706 thermoelectric cooler, heatsink, cold sink, power supply, wooden blocks, plywood, stainless steel plates, polyurethane polymer, aluminum foil, DC fan, 2 kg of mangoes, Monotaro Group terminal block, Eterna cables, ESP32 Series Wemos D1 R32, switches, 2-channel relays, DHT11 sensor, and a 16 x 2 I2C Liquid Crystal Display (LCD). All these tools and materials were prepared to design the construction of an IoT-based thermoelectric coolbox system.

2.2 Construction of the Thermoelectric Coolbox System

The construction of the thermoelectric system consists of two parts: a trainer table and a coolbox cabin, as shown in Figure 1(a). The trainer table is made of 3 x 3 cm² wooden blocks and 65 x 50 cm² plywood. Meanwhile, the coolbox cabin is constructed using a combination of stainless steel, polyurethane polymer, and aluminum foil to maximize cooling efficiency and thermal insulation. In detail, the layout of each component in this thermoelectric cooler box system is also presented in Figure 1(a).

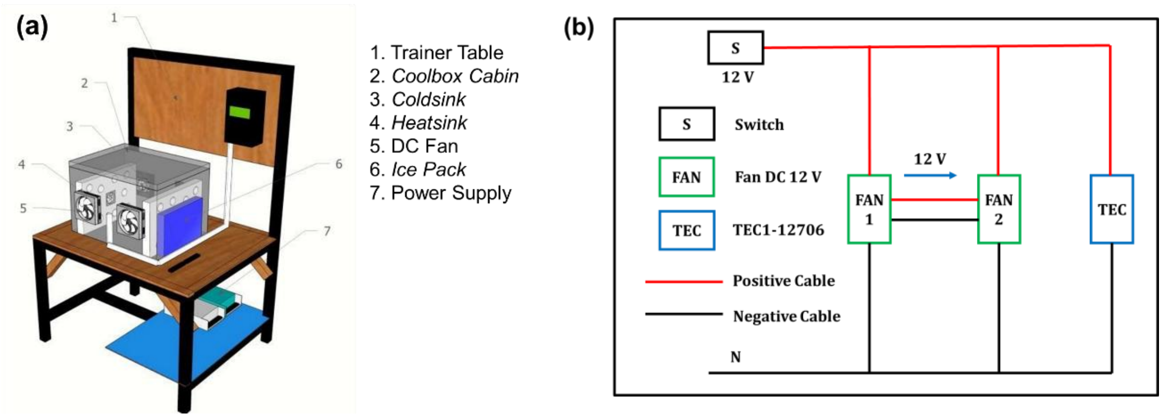

Figure 1. (a) Construction of the thermoelectric coolbox system and (b) electrical wiring diagram for the thermoelectric system

Figure 1(b) presents the electrical wiring diagram of the thermoelectric system in the coolbox, which maps the connections between the load, control devices, safety devices, and measurement instruments. To prevent short circuits, the positive and negative wires are placed at a distance from each other [10]. A 12-volt DC unidirectional current from the power supply flows through the cooling fan on the heatsink and coldsink, as well as the Peltier element.

2.3 IoT-Based System Design

The IoT-based system is designed using ESP32, DHT11 sensor, relay, power supply, fan, and LCD. All of these components are assembled according to the wiring diagram shown in Figure 2(a). Based on this diagram (Figure 2a), the DHT11 sensor is connected to the ESP32 with the Vcc pin to 3V3, GND to GND, and Data to GPIO19. Next, the GND, Vcc, SDA, and SCL pins on the LCD are connected to the GND, Vin, GPIO21, and GPIO22 pins of the ESP32, respectively. The Vin pin of the ESP32 is then connected to a 3.3-volt power supply to activate and operate the system [16]. A summary of the steps for reading sensor data, processing it, displaying it on the LCD, and sending it to the IoT platform can be seen in Figure 2(b). After all the component pins are installed according to the diagram in Figure 2(a), the system is programmed using the Arduino IDE software.

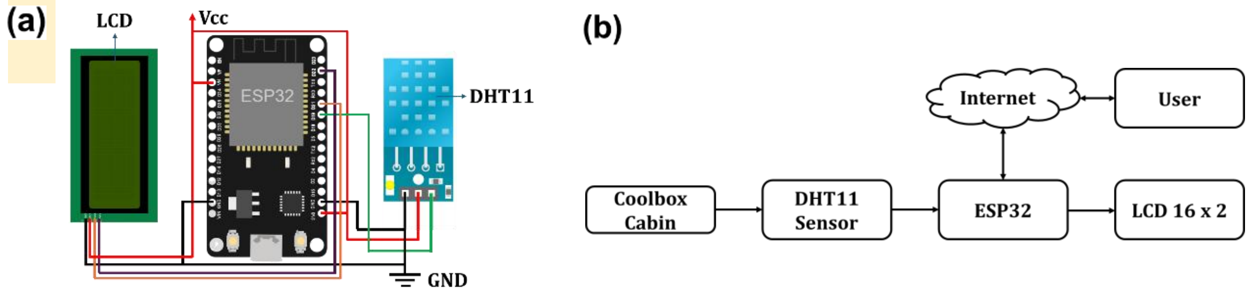

Figure 2. IoT-based system design. (a) wiring diagram and (b) block diagram

2.4 System Operating Principle

This mango storage system works by utilizing the thermoelectric Peltier effect to generate cooling. To enhance cooling efficiency, the system is equipped with an ice pack as a secondary cooler and a heat transfer system consisting of a DC fan, cold sink, and heatsink mounted on the coolbox. The operation of the system begins with applying DC current to the thermoelectric component (Peltier), which creates a temperature difference between the two sides: one side becomes cold, and the other becomes hot. The cold side is further cooled by the cold sink and circulated into the coolbox with the help of the fan. The ice pack helps maintain the temperature inside the coolbox. Meanwhile, the heat from the hot side of the Peltier is dissipated into the environment through the heatsink and fan. On the other hand, the DHT11 sensor detects the temperature and humidity in the coolbox cabin, and then sends this data to the ESP32. The ESP32 then sends the data to the LCD and the Blynk application for display. Users can easily monitor the temperature and humidity data in real time through the Blynk application.

3. RESULTS AND DISCUSSION

3.1 Design Data

Before the data collection process, calculations were performed for the design of the thermoelectric coolbox system. These calculations serve as guidelines for testing and data collection on the system. The transmission load can be calculated using Eqs. (1) and (2) as follows:

$$Q_T = U\,.\,A\,.(T_{ambient} - T_{cabin}) \tag{1}$$

$$U = \frac{1}{\frac{1}{f_{in}} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} + \frac{1}{f_{out}}} \tag{2}$$

where Q_T is the transmission load (W); U is the heat transfer coefficient (W/m^{2}K); A is the surface area of the outer wall (m^2); $T_{ambient}$ is the ambient temperature (K); T_{cabin} is the cabin temperature (K); f_{in} dan f_{out} is the heat transfer coefficients for the inner and outer surfaces of the cabin wall (W/m^{2}K), respectively; x is the thickness of each layer of wall material (m); and k is the thermal conductivity of each wall material layer (W/mK). By employing the system specifications in Table 1, the calculated heat transfer coefficient *(U)* and transmission load *(Q)* are 1.24 W/m²K and 15.8 W, respectively.

Table 1. Specification of The Thermoelectric Coolbox System

Parameter	Specification
Coolbox dimensions	0.4 x 0.34 x 0.27 m^3
Wall material	
1. stainless steel plate (k_1)	1. thickness 0.3 mm, thermal conductivity 15.1 W/mK [17]
2. polyurethane (k_2)	2. thickness 20 mm, thermal conductivity 0.03 W/mK [17]
3. aluminum foil (k_3)	3. thickness 4 mm, thermal conductivity 0.033 W/mK [17]
4. still air (f_{in})	4. convection coefficient 9.37 W/m^{2}K [17]
5. moving air (f_{in})	5. convection coefficient 22.7 W/m^{2}K [17]
Ambient temperature	$T_{ambient}$ = 32 ºC = 305.15 K
Cabin temperature	T_{kabin} = 13 ºC = 286.15 K

The product load for mangoes can be calculated using Eq. (6) as follows:

$$Q_1 = m \times c_a \times (T_{ambient} - T_{kabin}) \quad (3)$$

$$Q_2 = m \times L_f \quad (4)$$

$$Q_3 = m \times c_b \times (T_{ambient} - T_{kabin}) \quad (5)$$

$$Q_P = \frac{Q_1 + Q_2 + Q_3}{n} \quad (6)$$

where Q_1, Q_2, and Q_3 are sensible heat above freezing, latent heat, and sensible heat below freezing (W), respectively; m is the mango mass (kg); c_a is the specific heat of mango above freezing (kJ/kgK); L_f is the latent heat of mango (kJ/kg), c_b is the specific heat of mango below freezing (kJ/kgK), Q_P is the product load (W), and n is the cooling duration (s). By employing the design data shown in Table 2, the calculated product load is 211.72 W.

Table 2. Thermal Data and Cooling Time of Mango Fruit

Parameter	Value
Mass of mango product, m	2 kg
Specific heat of mango above freezing point, c_a	3.74 kJ/kgK [6]
Specific heat of mango below freezing point, c_b	1.95 kJ/kgK [6]
Latent heat of mango, L_f	273 kJ/kg [6]
Cooling time, n	3600 s
Setpoint temperature of the cabin, T	13 ºC = 286.15 K

By using Equation (7), the total load of the system is calculated to be 227.52 W.

$$Q_{Total} = Q_T + Q_P \quad (7)$$

The performance of the thermoelectric system is influenced by several interrelated factors, including the Seebeck coefficient (α), electrical resistance (R), thermal conductivity (K), heat absorbed by the cold side (Q_c), heat absorbed by the hot side (Q_h), power consumption (P), coefficient of performance (COP), and efficiency (η). These parameters are calculated using Eqs. (8)–(15).

$$\alpha = \frac{V}{\Delta T} \quad (8)$$

$$R = \frac{V}{I} \times \frac{(T_h - \Delta T)}{T_h} \quad (9)$$

$$K = \frac{V \times I \times (T_h - \Delta T)}{2 \times T_h \times \Delta T} \quad (10)$$

$$Q_c = \alpha \times T_c \times I - \frac{1}{2}(I^2 \times R) - K(T_h - T_c) \quad (11)$$

$$Q_h = \alpha \times T_h \times I - \frac{1}{2}(I^2 \times R) - K(T_h - T_c) \quad (12)$$

$$P = W_{te} + W_{fa} + W_{hs} \quad (13)$$

$$COP_{total} = \frac{Q_c}{W} \quad (14)$$

$$\eta = COP_{total} \times 100\% \quad (15)$$

To determine the values of the above quantities, thermoelectric design data as shown in Table 3 were used.

Table 3. Design Data for the Thermoelectric System

Parameter	Measured Result
Heatsink temperature, T_h	39 °C = 312.15 K
Coldsink temperature, T_c	10 °C = 283.15 K
Voltage, V	12.3 V
Current, I	6 A

Based on the calculation results, the performance parameters of the thermoelectric system were obtained as presented in Table 4.

Table 4. Performance of the Designed Thermoelectric System

Parameter	Calculation Results
Seebeck coefficient, α	0.42 V/K
Electrical resistance, R	1.86 Ω
Thermal conductivity, K	1.15 W/K
Heat on cold side, Q_c	653.62 W
Heat on cold side, Q_h	727.42 W
Power consumption, P	1106 W
COP	0.59
Efficiency, η	59 %

3.2. Testing Data

The thermoelectric system was operated for one hour to cool 2 kg of mangoes. Figure 3 compares the measured temperatures inside the coolbox/cabin and the mango product. Data was collected every five minutes up to the 60th minute. The measured cabin temperature was consistently lower than the product temperature, as the cooling system actively maintained a low cabin temperature. Over time, thermal equilibrium was achieved, with the cabin and product temperatures equalizing at the 60th minute [18]. The cabin temperature decreased by 1°C every five minutes, stabilizing at 12.6 °C, which aligns with the recommended setpoint of 13 °C (see Table 2). This temperature indicates that the system meets the ideal storage temperature requirements for mangoes [5], [6].

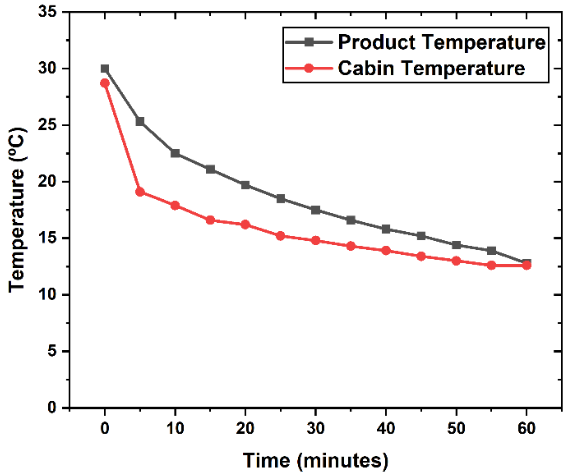

Figure 3. Cabin and product temperatures in the thermoelectric system

Figure 4 presents the temperature measurement results for the cabin, coldsink, and heatsink with and without the mango product. At the beginning of the measurement (minute 0), a significant temperature drop is observed across all components, especially the cold sink (COTSP and COTWP) and the cabin (CTSP and CTWP). This indicates that the cooling system is operating effectively during the initial phase. A comparison between the graphs with the product (CTWP, COTWP, and HTWP) and without the product (CTSP, COTSP, HTSP) shows the effect of the product's presence on the temperature. The cabin temperature with the product (CTWP) tends to be higher than the cabin temperature without the product (CTSP), although the difference is not significant. This phenomenon suggests that the product slightly slows the temperature drop in the cabin. The temperature difference between the cold sink with and without the product (COTWP and COTSP) is relatively small. The heatsink with the product (HTWP) also shows a slightly higher temperature compared to the heatsink without the product (HTSP).

After the initial drop, the temperatures of all components tend to stabilize after approximately 15-30 minutes, although there is still some ongoing slight reduction in temperature for a few components. This indicates that the cooling system reaches a steady-state condition after the initial cooling period. The cold sink (COTSP and COTWP) reaches a lower temperature compared to the cabin, while the heatsink (HTSP and HTWP) maintains a higher temperature than the cold sink. These conditions are consistent with the roles of the cold sink and heatsink as heat absorbers and heat emitters, respectively.

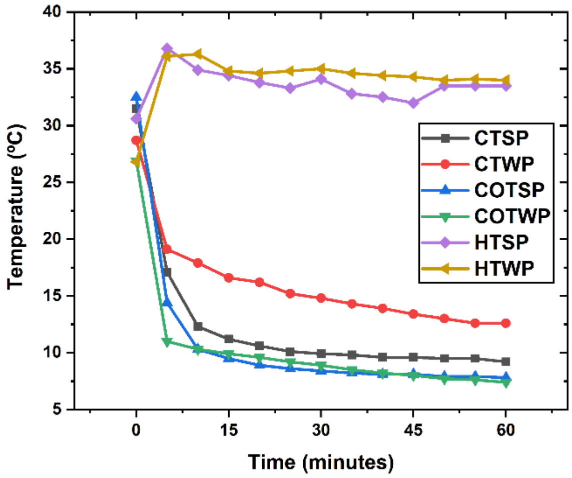

Figure 4. Temperatures of the cabin, coldsink, and heatsink with and sans the product. CTSP (cabin temperature sans product, black); CTWP (cabin temperature with the product, red); COTSP (coldsink temperature sans product, blue); COTWP (coldsink temperature with the product, green); HTSP (heatsink temperature sans product, purple); and HTWP (heatsink temperature with the product, brown).

To evaluate cooling effectiveness, the system's performance was assessed using measurement data from TEC1-12706, as presented in Table 5.

Table 5. Measurement Data of TEC1-12706

Parameter	Measured Result
Heatsink temperature, T_h	34 °C = 307,15 K
Coldsink temperature, T_c	7,4 °C = 280,55 K
Voltage, V	12,3 V
Current, I	6 A

The performance parameters of the thermoelectric system were obtained from the tests, using Eqs. (8) – (15), were compared with the design data previously obtained (see Table 6).

Table 6. Comparison of Thermoelectric System Performance between Design Data and Test Results

Parameter	Design Data	Test Results
Seebeck coefficient, α	0.42 V/K	0.46 V/K
Electrical resistance, R	1.86 Ω	1.87 Ω
Thermal conductivity, K	1.15 W/K	1.27 W/K
Heat on cold side, Q_c	653.62 W	707.92 W
Heat on cold side, Q_h	727.42 W	781.72 W
Power consumption, P	1106 W	1179.86 W
COP	0.59	0.60
Efficiency, η	59 %	60 %

Based on Table 6, the test results show that the system's performance data is not significantly different from the design data. This indicates that the developed thermoelectric system is consistent with the initial design. To assist users in monitoring mango temperature and humidity inside the coolbox, the thermoelectric system was integrated with IoT technology via the Blynk application, as shown in Figure 5. The system utilizes temperature and humidity sensors placed inside the coolbox. Data captured by the sensors is sent to an ESP32 microcontroller connected to the internet via WiFi. The Blynk application serves as a dashboard displaying the data in real time through graphs and numerical values. Users can access this information anytime and anywhere, provided they have internet access.

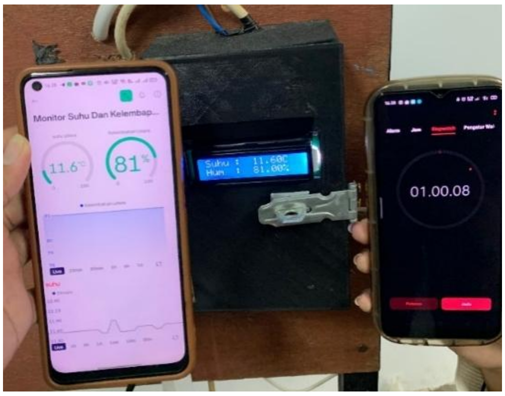

Figure 5. Data transmission to the Blynk application

4. CONCLUSION

The thermoelectric coolbox system modified with ice packs for storing 2 kg of mangoes successfully reached a cabin temperature of 12.6 ºC within 60 minutes. This result demonstrates that the system meets the ideal temperature requirements for mango storage. The addition of ice packs played a crucial role in accelerating the temperature drop inside the cabin. The cold sink and heatsink components functioned effectively in absorbing and releasing heat to the environment. Based on the tests, the thermoelectric coolbox achieved a COP of 0.60 with an efficiency of 60%.

The thermoelectric system has also been successfully integrated with IoT technology via the Blynk application, facilitating users in monitoring the temperature and humidity data of mangoes stored in the coolbox. Users can access this data through their smartphones anytime and anywhere, as long as the device is connected to the internet.

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