Development of a Thermoelectric Insulin Storage Box with a TRIAC-based Automatic Transfer Switch

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Abstract

Insulin is highly sensitive to temperature variations, and improper storage can significantly reduce its therapeutic effectiveness. Household refrigerators often have unstable temperature profiles, and power interruptions further compromise safe storage. This study presents the design and experimental evaluation of an insulin storage box that uses a thermoelectric cooling system integrated with a TRIAC-based Automatic Transfer Switch (ATS) to maintain uninterrupted temperature regulation during power outages. The cooling system uses Peltier modules with liquid-assisted heat dissipation to maintain thermal stability. Experiments under empty, half-filled, and fully loaded conditions showed that the system consistently maintained the recommended insulin storage temperature range of 2°C–8°C, reaching a minimum of 2°C. Increasing the thermal load reduced the temperature gradient across the Peltier modules, slightly lowering performance, but temperature stability remained within acceptable limits. The TRIAC-based ATS ensured continuous operation by automatically transferring the load to a secondary power source during supply interruptions. Results confirm the system's suitability for reliable insulin storage in areas with unstable power availability.

Keywords*:* cooling system, insulin storage box, Peltier module, thermoelectric, TRIAC-based Automatic Transfer Switch

1. Introduction

Diabetes mellitus remains a pervasive global health challenge, affecting an estimated 537 million adults aged 20–79 years worldwide, a figure projected to increase to 783 million by 2045 (IDF Diabetes Atlas, 2021). In the

Philippines, diabetes prevalence has significant health impacts, contributing to mortality and morbidity, particularly among overweight and obese adults (Cudis, 2021). Insulin is essential for glycemic control, but its therapeutic efficacy is highly sensitive to storage temperature; insulin stored outside recommended conditions can lose 14–18% of its potency due to denaturation at elevated temperatures (Khurana *et al*., 2019). Failure to maintain proper cold-chain storage, including common household refrigeration, has been documented and may lead to suboptimal insulin effectiveness and compromised clinical outcomes (Kaufmann *et al*., 2021). Power interruptions compound this challenge, as refrigeration systems may not sustain the 2–8°C range necessary for insulin preservation. In developing contexts like the Philippines, electricity supply disruptions remain frequent: average consumers experience multiple interruptions per year, with cumulative outage durations of several hours, underscoring the fragility of the continuous power supply (Francisco *et al*., 2021). These conditions elevate the risk of insulin degradation and jeopardize diabetes management, especially in areas with unreliable grid infrastructure.

Existing portable insulation and battery-powered solutions provide short-term cold storage but lack automated power switching to ensure uninterrupted operation during extended outages. Research on integrating automatic transfer switches into temperature-controlled storage systems to maintain recommended insulin storage conditions during power failures is limited. This study aims to develop and evaluate an insulin storage box with thermoelectric cooling and a TRIAC-based automatic transfer switch that maintains the required temperature range and automatically switches power sources during outages, addressing a critical gap in reliable insulin refrigeration technology.

Several studies have examined thermoelectric cooling systems for insulin storage, focusing on maintaining the recommended 2°C–8°C range through various heat-dissipation and power-supply strategies. Prior work has investigated forced-air convection, portable and solar-powered configurations, and low-cost cooling designs to improve thermal performance and portability. Other studies have addressed power-reliability concerns by developing automatic transfer switch (ATS) systems to ensure uninterrupted operation during power outages. Table 1 summarizes selected related literature, highlighting methodologies, key results, and research contributions of existing thermoelectric cooling and power-continuity solutions. This comparison establishes the research gap addressed by the proposed system, which integrates liquid-assisted thermoelectric cooling with a TRIAC-based

ATS to enhance thermal stability and power reliability for insulin storage applications.

Table 1. Comparative summary of selected related literature of thermoelectric cooling and power continuity solutions

Reference	Methodology	Key Results	Research Focus and Contribution
Hassaan-Younis and Ur-Rashid (2018)	Thermoelectric cooling with forced air convection	Achieved a minimum temperature of 2°C	Addressed heat dissipation on the hot side of the thermoelectric module by strategically positioning a blower fan on the heat sink to enhance airflow through the fins, improving cooling efficiency.
Vempati *et al.* (2019)	Thermoelectric cooling using forced air convection	Achieved a minimum temperature of 5°C	Focused on improving thermoelectric cooling performance through forced air convection as the primary heat removal mechanism.
Nohay *et al.* (2020)	Solar-powered thermoelectric cooling system	Maintained temperature within 2°C–8°C	Developed a portable, battery-powered thermoelectric refrigerator for insulin storage, emphasizing off-grid operation using renewable energy.
Daou *et al.* (2021)	Thermoelectric cooling with digital monitoring	Maintained insulin storage temperature within 2°C–8°C	Designed a smart medical storage box with temperature control and mobile application integration to preserve both used and unused insulin pens.
Rahman *et al.* (2022)	Low-cost thermoelectric cooling system	Observed temperature variation between empty and loaded storage conditions	Investigated the thermal performance of a low-cost thermoelectric cooling box intended for portable and travel-based applications.
Alembong (2021)	TRIAC-based Automatic Transfer Switch (ATS)	Successfully enabled automatic switching during power failure	Designed and simulated a TRIAC-based ATS using Proteus software to ensure power continuity during primary supply interruptions.
Proposed System	Thermoelectric cooling with liquid heat dissipation and TRIAC-based ATS	Maintained insulin storage temperature within 2°C–8°C under varying load conditions	Integrated liquid cooling to enhance heat dissipation on the hot side of the Peltier module and implemented a TRIAC-based ATS to ensure uninterrupted power supply by automatically switching from the main source to a secondary source during power failures.

It shows that the novelty of the proposed system is not merely the combination of thermoelectric cooling and an automatic transfer switch. Within the reviewed studies, prior insulin-storage systems focus on achieving the 2°C–8°C range through forced-air, solar-powered, battery-powered, or low-cost thermoelectric designs, while the TRIAC-based ATS study focuses on power-source switching as a standalone circuit. No reviewed work evaluates an insulin storage system in which liquid-assisted heat dissipation is used to improve the Peltier module’s thermal stability while a hardware-implemented TRIAC-based ATS actively preserves cooling operation during a power interruption. The proposed system therefore addresses the coupled cold-chain problem: maintaining safe insulin temperature not only during normal operation, but also across changing storage loads and loss of the primary power source. Its contribution is the design and experimental validation of this coordinated thermal-management and power-continuity system for insulin storage, rather than the independent use of either technology alone.

2. Methodology

2.1 Research Instrumentation and Procedure

This study used an experimental approach to develop and evaluate an insulin storage box designed to maintain the recommended storage temperature of 2°C to 8°C under varying power conditions. The independent variable was the storage temperature, and the dependent variable was insulin storage reliability, assessed by the system’s ability to sustain the prescribed temperature range over time. Temperature regulation was achieved using thermoelectric cooling modules, with ambient room conditions treated as external influences.

The system comprised thermoelectric coolers, a temperature sensor, and a microcontroller-based control unit. The cooling subsystem utilized a TEC1-12706 thermoelectric Peltier module (Hebei I.T. (Shanghai) Co., Ltd., Shanghai, China) as the primary active cooling device. The control algorithm was executed using an ATmega328P 8-bit AVR microcontroller or Arduino Uno (Microchip Technology Inc., Chandler, Arizona, USA). The monitoring and wireless communication subsystem was implemented using a 38-pin ESP32-WROOM-32 Wi-Fi development board (Espressif Systems, Shanghai, China).

Temperature data were continuously monitored and processed by the microcontroller to regulate the thermoelectric modules using a closed-loop control scheme. Sensor readings were validated against an external thermometer for accuracy. Firmware development and system programming were carried out in the Arduino Integrated Development Environment and then uploaded to an ESP32 microcontroller. Experimental testing was conducted at the researcher's residence in Cagayan de Oro City and at the Electronics Engineering Laboratory of the University of Science and Technology of Southern Philippines.

To mitigate temperature instability caused by power interruptions common in domestic refrigeration systems (Braune *et al*., 2019), the insulin storage box incorporated a TRIAC-based Automatic Transfer Switch (ATS). The ATS was controlled by an Arduino Uno, which monitored the availability of the primary and secondary power sources. When the primary supply was available, the corresponding TRIAC was activated to power the system. In the event of a primary supply failure, the system automatically switched to the secondary source by activating the appropriate TRIAC. If neither power source was available, both TRIACs remained inactive to ensure safe operation. The switching logic was fully governed by the programmed control algorithm to prevent simultaneous conduction and ensure reliable power transfer.

To sum it up, as shown in Figure 1, the whole thermoelectric refrigerator is powered from the main power outlet with a circuit breaker, followed by the switching circuit using a TRIAC-based Transfer Switch (ATS) that is powered by its power supply.

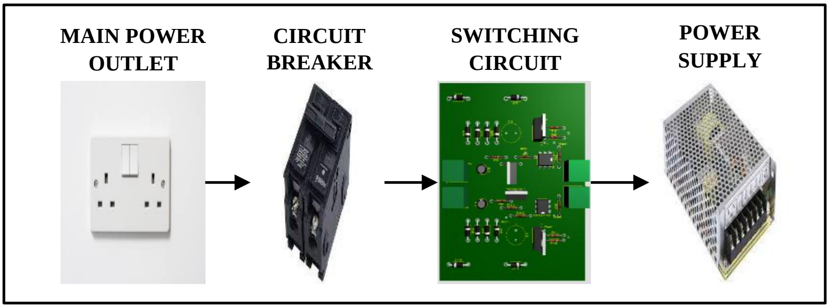

Figure 1. Source and switching architecture

2.2 Storage Box System and Architecture

As shown in Figure 2, the system is powered by a 12 V, 15 A DC supply that feeds both a boost and a buck converter to meet component voltage requirements. The boost converter provides regulated power to the thermoelectric cooling modules, cooling fans, and water pump, which collectively maintain the internal temperature of the insulin storage box within the recommended range. The buck converter steps down the 12 V input to a regulated 5 V output to power the ESP32 microcontroller and relay module. The ESP32 serves as the central control unit, processing temperature sensor data and actuating the relay to control the thermoelectric modules, fans, and water pump.

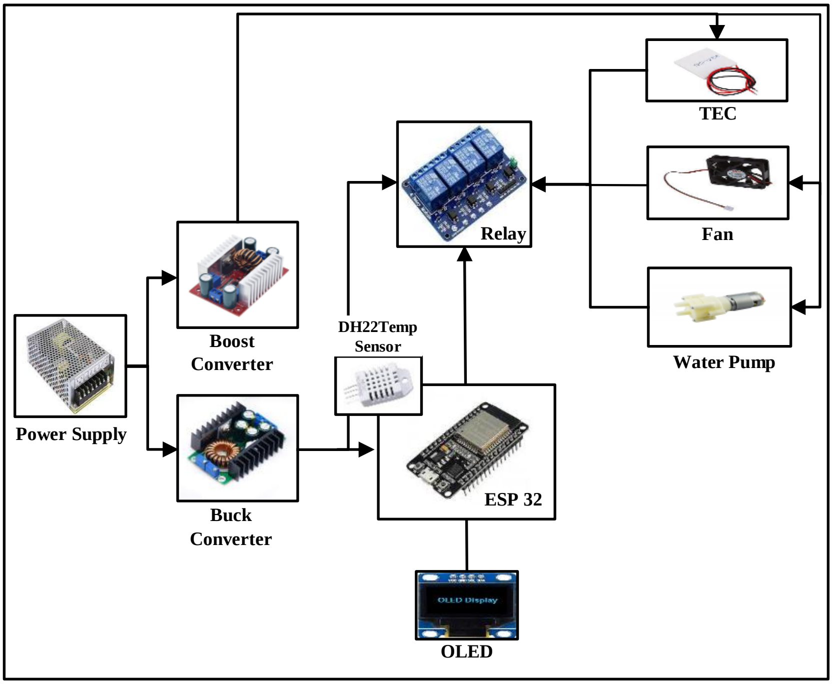

Figure 2. Storage box system architecture

Figure 3 shows the flowchart for the algorithm the ESP32 microcontroller uses to regulate the temperature inside the insulin storage box. According to this algorithm, if the temperature reaches or exceeds 8°C, the microcontroller activates the Peltier modules, the water pump, and the interior fans. Conversely, if the temperature drops to 2°C or below, it deactivates these components. The exterior fans remain on continuously to help cool the liquid in the water storage system and maintain the desired temperature differential.

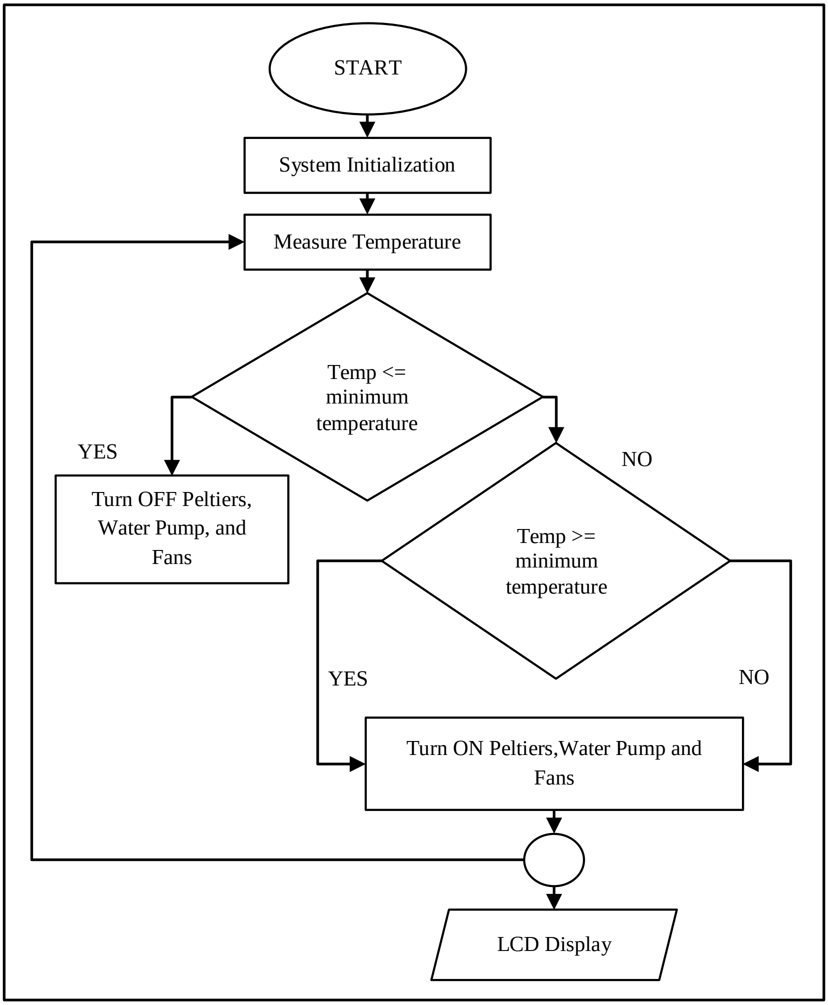

Figure 3. Temperature regulation of the Insulin Storage Box

2.3 Calculation of Heat Removal from the Storage Box

The heat absorbing load required for the Peltier cooling system to achieve the target temperature range in a 7.1 L insulin storage box was determined using the sensible heat equation (Equation 1):

$$Q_c = M * C_p * (T_f - T_i) \quad (1)$$

where Q_c is the heat absorbed (kJ), M is the mass (kg), Cp is the specific heat capacity (kJ•kg^{-1}•°C^{-1}), and T_i and T_f are the initial and final temperatures (°C), respectively.

The mass of insulin was estimated using Equation 2:

$$M = V * C * p \tag{2}$$

where V is the vial volume (10 mL), C is the insulin concentration (100 units·mL^{-1}), and p is the density (1.3 g•mL^{-1}), yielding a total mass of 1.3 kg. Substituting into (1) with C_p = 2.5 kJ•kg^{-1}•°C^{-1} and a temperature change from 26°C to 8°C gives Q_c = -58.5 kJ, indicating heat removal.

Converting this value to power yields 16.25 Wh, corresponding to a required cooling power of approximately 110 W over 0.15 h. Using two Peltier modules, each module is required to absorb approximately 55 W.

2.4 Calculation of Heat Rejection Load

The heat rejection load was estimated using Equation 3:

$$Q_h = h\,A\,(T_f - T_i) \tag{3}$$

where Q_h is the heat rejected (W), h is the heat transfer coefficient of aluminum (239 W•m^{-2}•K^{-1}), and A is the effective surface area (0.05 m^2). The calculated heat rejection per external fan was approximately 0.24 Wh, with an initial temperature of 34.7 °C and a final temperature of 29.2 °C. The heat transfer coefficient (h) used is aluminum. Each fan operates at 12 V and 0.3 A, resulting in a total fan power consumption of 7.2 W for two Peltier modules.

The total system power requirement was therefore determined to be 117.2 W, including the power needed to remove heat using Equation 1 (110 W), sufficient to maintain the insulin storage temperature within the recommended range of 2°C to 8°C.

2.5 Hardware Design of the TRIAC-based Automatic Transfer Switch

The operation of the implemented TRIAC-based Automatic Transfer Switch (ATS) is shown in Figure 4. The system has a primary and a secondary AC input, each independently monitored and controlled by an Arduino Uno microcontroller to ensure reliable power transfer.

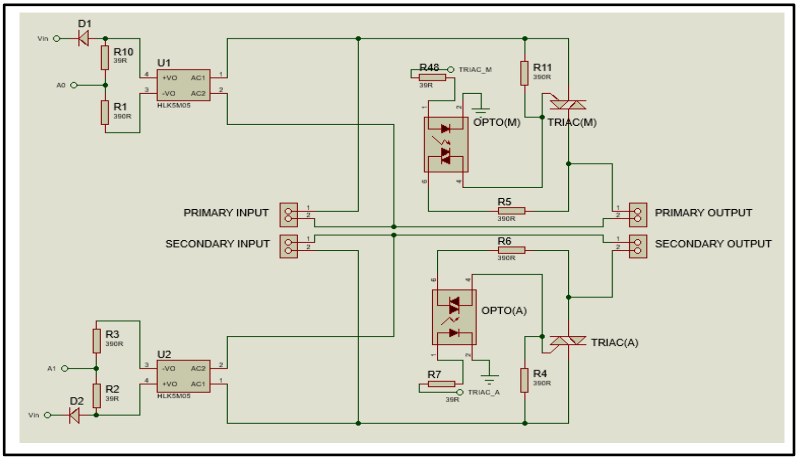

Figure 4. Implemented design of the TRIAC-Based Automatic Transfer Switch

The primary input is a 220 V AC supply from the main grid, converted to 5 V DC using a HiLink 5 V, 5 W power module (U1). The regulated 5 V output, routed through a diode, powers the Arduino Uno. A voltage divider composed of resistors R10 (39 Ω) and R1 (390 Ω) scales the sensed voltage to approximately 4.55 V at analog pin A0, ensuring safe operation within the microcontroller's input limits. Upon detecting this voltage, the Arduino Uno outputs a 5 V control signal at digital pin 4 to drive the main TRIAC (TRIAC(M)). A 39 Ω gate resistor (R48) supplies approximately 128.2 mA of gate current to the optocoupler (OPTO(M)) LED, exceeding the minimum activation requirement. The MOC3041 optocoupler provides electrical isolation between the low-voltage control circuitry and the high-voltage AC domain, triggering the main triac and delivering a 220 V AC output to the primary load.

The secondary input operates using an identical configuration. A separate 220 V AC source is converted to 5 V DC by a second HiLink module (U2), which also supplies the Arduino Uno. A voltage divider consisting of resistors R2 (39 Ω) and R3 (390 Ω) maintains a 4.55 V signal at analog pin A1. When this condition is detected, the microcontroller outputs a 5 V signal at digital pin 2 to activate the secondary TRIAC (TRIAC(A)) via optocoupler OPTO(A) and gate resistor R7. This configuration ensures safe, isolated, and automatic switching between the primary and secondary power sources.

2.6 Material Selection

The researchers purchased the materials and electronic components used in developing the prototype. The materials to be used are divided into two sections: TRIAC-based Automatic Transfer Switch in Table 2 and Insulin Storage Box in Table 3.

Table 2. Materials for TRIAC-based Automatic Transfer Switch

Quantity	Material	Purpose
1pc.	Arduino Uno	Microcontroller
2pcs.	MOC3041 Optocoupler	To provide electrical isolation between the input and output of the circuit
2pcs.	BTA24 TRIAC	Semiconductor device used for switching AC power.
4pcs.	Resistor (39Ω)	Used to resist or reduce the flow of
6pcs.	Resistor (390Ω)	electrical current in a circuit.
2pcs.	HLK-5m05	Convert AC voltage from a mains power source (100-240V AC) into a stable DC voltage output (5V DC)
4pcs.	2 pin Screw Terminal Block	An electrical connector
2pcs.	Circuit Breaker	to assume power outage
5 meters	Stranded and Solid Wires	Used to create connections between components
1pc.	Copper Board (4x3)	To provide a reliable and organized platform for mounting and Interconnecting electronic components

Table 3. Materials for Insulin Storage Box

Quantity	Material	Purpose
1pc.	ESP32	Microcontroller
1pc.	DHT22 Module	Temperature and Humidity Sensor
2pcs.	TEC1-12706 Peltier Module	To cool the Storage Box
1pc.	Radiator	to increase heat rejection effect at the hot side of the peltier
2pcs.	Aluminum Liquid Cold Plate	For heat rejection
2pcs.	Mini Exhaust Fans	cold air circulation inside the box

Table 3 continued.

2pcs.	External Fan	For better Heat Rejection
1pc.	SSD1306 0.9 in. OLED Module	For display
1pc.	12 V 4 Channel Relay Module	For peltier modules, and fans switching
1pc.	DC-CC 9 A 300 W Step Down Buck Converter 5-40 V to 1.2-3.5 V Power Module	To provide regulated 5V 1A to the ESP32 and relay
1pc.	DC-DC 400 W 15 A Module Boost Converter Constant Current Power Supply LED Driver 8.5-50 V to 10-60V	To provide regulated 12 V to the peltier module
1pc.	Styro Ice Box	For thermal insulation
1pc.	Insulation Foam	For additional insulation
1pc.	Mini LCD digital Thermometer	Temperature measurement
1pc.	Power Supply	To convert AC to DC
4pc.	Pro 99 Long Life Coolant	Liquid used for cooling hot side of peltier

2.7 Hardware and Software Assembly

As shown in Figure 5, the insulin storage box integrates the cooling, power-management, sensing, and monitoring subsystems of the proposed system. A 12 V, 15 A power supply provides power to the major loads, while an XL4015 step-down buck converter supplies regulated voltage to the ESP32 microcontroller and other low-voltage devices (XLSEMI, n.d.). The ESP32 serves as the main controller because it provides programmable GPIO, sensing interfaces, and wireless connectivity suitable for monitoring applications (Espressif Systems, 2026). The water pump, interior fan, Peltier module, aluminum heat sink, and liquid-cooling plate work together to remove heat and maintain the required insulin-storage temperature. Figure 5 also shows the physical arrangement of these components within the prototype enclosure.

As shown in Figure 6, the Automatic Transfer Switch (ATS) system consists of an Arduino Uno, SSD1306 OLED display, MOC3041 optocouplers, BTA24 TRIACs, a Hi-Link 5 V AC–DC power module, and a circuit breaker. The Arduino Uno serves as the controller for monitoring source availability and commanding the switching circuit (Arduino, 2026). The SSD1306 is a 128 × 64 monochrome OLED display driver used to present the status of the power sources and load (Solomon Systech, n.d.). The MOC3041 provides optically isolated TRIAC-driver functionality between the low-voltage control circuitry and the AC switching stage (Onsemi, n.d.), while the BTA24 TRIAC is designed for general-purpose AC switching applications (STMicroelectronics, 2024). The Hi-Link module supplies regulated 5 V DC power to the control components, and the circuit breaker provides manual isolation and protection.

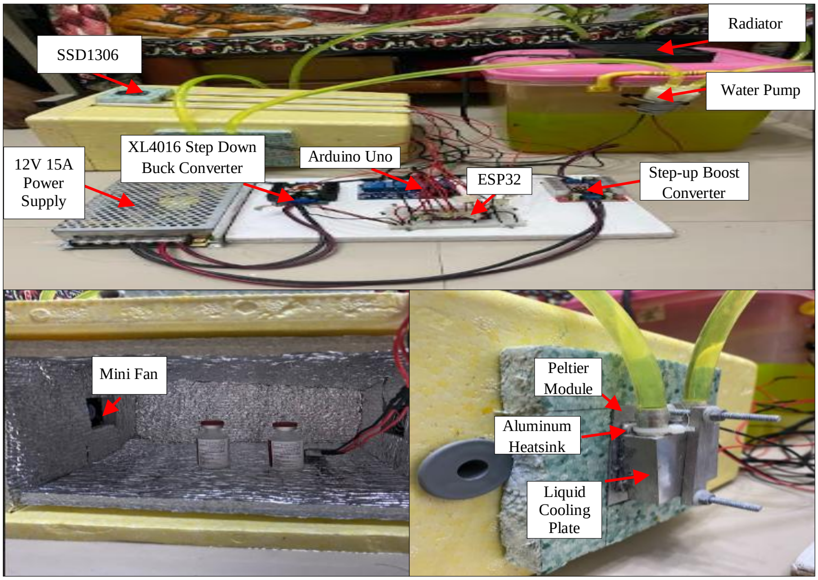

Figure 5. Automatic Transfer Switch and its component

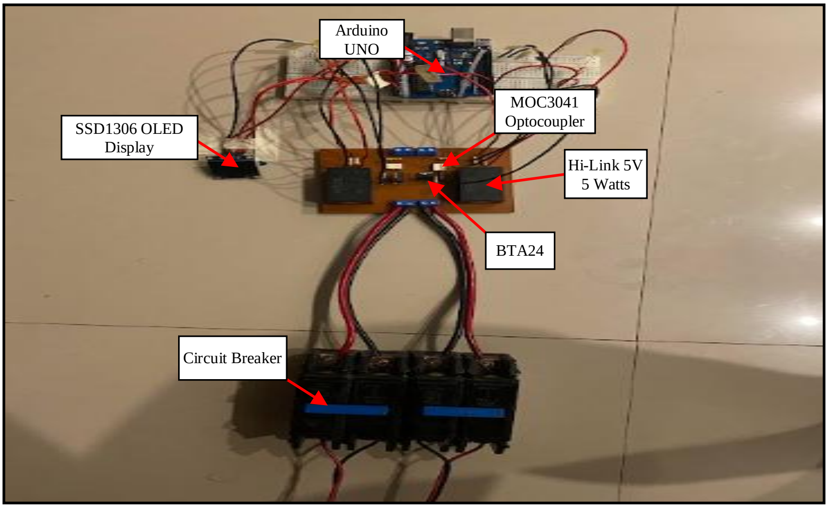

Figure 6. Insulin Storage Box and its components

2.8 Testing and Troubleshooting the System

After prototype development, a series of experimental tests were conducted to evaluate system performance. During testing, both a digital thermometer and a DHT22 temperature and humidity sensor were initially used for temperature measurement. However, due to noticeable discrepancies between the readings, the DHT22 sensor was selected as the primary measurement device because of its acceptable accuracy of ±0.5°C. Nevertheless, there was no calibration done nor reported during experimentation. Temperature and relative humidity inside the storage chamber were monitored using a DHT22 (AM2302) digital temperature and humidity sensor (Aosong Electronics Co., Ltd., Guangzhou, China).

The first experiment evaluated the ability of the storage box to achieve and maintain the recommended temperature range of 2°C to 8°C, both with and without insulin vials present. The second experiment verified the proper operation of the DHT22 sensor by confirming its ability to accurately measure the internal temperature of the storage box. The third experiment assessed the reliability of remote data acquisition, determining whether temperature data collected by the DHT22 sensor could be transmitted via the internet using the If This Then That (IFTTT) platform. Results confirmed that the data were successfully transmitted and stored in a Google spreadsheet. The final experiment evaluated the performance of the TRIAC-based Automatic Transfer Switch, confirming that the system automatically switched between the primary and secondary power sources when the main supply became unavailable.

2.9 Gathering and Analysis of Data

The experimental evaluation aimed to determine whether the developed insulin storage box could consistently achieve and maintain the target temperature range of 2°C to 8°C, which is critical for preserving insulin potency. A performance analysis of the system was conducted over an eight-hour period, during which electrical parameters (current and voltage), internal box temperature, and the time required to reach specific temperature levels were monitored and recorded at one-minute intervals. The effectiveness of different cooling fluids, namely Pro 99 Life Long Coolant and pure water, was assessed by comparing the time required to reach the recommended temperature range. This comparison was used to identify the cooling medium that provided superior thermal performance. Data acquisition and monitoring were facilitated using a personal computer with Proteus for simulation and the

Arduino IDE Serial Monitor for real-time observation. The ESP32 microcontroller was programmed to read temperature data from the DHT22 sensor and transmit the measurements at one-minute intervals to a cloud-based Google spreadsheet via the If This Then That (IFTTT) platform. Data transmission was accomplished using an HTTP GET request triggered by predefined event and key parameters. Successful data transfers were confirmed through responses displayed on the Serial Monitor. The collected data were subsequently analyzed to determine temperature stability and cooling efficiency under each test condition.

2.10 Pseudocodes of the Automatic Transfer Switch of the TRIAC-based Insulin Storage Box

2.10.1 Automatic Transfer Switch (Serial and Display Function)

This is the pseudocode for the Serial and Display Function for the Automatic Transfer Switch:

```
INITIALIZE OLED Display

INIITIALIZE serial communication
SET main source analog pin
SET auxiliary analog pin
DEFINE minimum allowable voltage = 110 V
DEFINE maximum allowable voltage = 230 V
FUNCTION isVoltageinRange(voltage):
        RETURN true if voltage is between min and max
        ELSE return false
        DISPLAY startup message on OLED
LOOP FOREVER:
        READ analog voltage from main source
        CONVERT analog voltage value to actual voltage
        SCALE voltage to display value
        IF main voltage is valid AND auxiliary voltage is valid:
                SELECT main source
                TURN ON main TRIAC
                TURN OFF auxiliary TRIAC
                TURN ON green LED
                DISPLAY “Powered by Main Source”
        ELSE IF main voltage is valid AND auxiliary voltage is invalid:
                SELECT main source
                TURN ON main TRIAC
                TURN OFF auxiliary TRIAC
```

```
            TURN ON green LED
            DISPLAY "Powered by Main Source"
      ELSE IF main voltage is invalid AND auxiliary voltage is valid;
            SELECT secondary source
            TURN OFF main TRIAC
            TURN ON auxiliary TRIAC
            TURN ON green LED
            TURN OFF red LED
            DISPLAY "Powered by Secondary Source"
      ELSE IF both voltages are invalid:
            TURN OFF both TRIAC
            TURN ON red LED
            DISPLAY "No Valid Power Source"
UPDATE OLED display with voltage readings
WAIT for stabilization delay
END
```

This pseudocode implements a TRIAC-based Automatic Transfer Switch (ATS) using a microcontroller interfaced with two power sources and an OLED display. The system continuously senses the voltages of the main power source (MPS) and the secondary power source (SPS) through analog inputs, with the measured values scaled to represent actual AC voltage levels. A predefined acceptable voltage range of 110–230 V is used to determine the availability and validity of each source. Based on real-time voltage conditions, the controller automatically selects the appropriate power source by activating the corresponding TRIAC. When the main source is within range, the load is supplied by the MPS. If the main source fails but the auxiliary source remains valid, the load is transferred to the SPS. When both sources are outside the allowable range, the load is disconnected to ensure protection. If only the auxiliary source fails, the load continues to be supplied by the main source. System status and voltage readings are provided through LED indicators and the OLED display, ensuring safe and uninterrupted power delivery to critical loads.

2.10.2 Insulin Storage Box

This is the pseudocode for maintaining temperature inside the Insulin Storage Box:

```
INITIALIZE OLED display

INITIALIZE DHT22 temperature and humidity sensor

INITIALIZE WIFI connection
```

```
INITIALIZE output pins for: Peltiers, water pump and internal fans
SET minimum temperature = 2 °C
SET maximum temperature = 8 °C
CONNECT to WIFI network
DISPLAY startup message on OLED
LOOP FOREVER:
        READ humidity from DHT sensor
        READ temperature from DHT sensor
        IF sensor reading is invalid
                EXIT current loop iteration
        DISPLAY humidity and temperature on OLED
        IF temperature <= minimum temperature:
                TURN OFF Peltiers
                TURN OFF Internal fans
                TURN OFF water pump
        ELSEIF temperature >= maximum temperature:
                TURN ON Peltiers
                TURN ON Internal fans
                TURN ON water pump
        ELSE:
                TURN ON Peltiers
                TURN ON Internal fans
                TURN ON water pump
        UPDATE OLED display with device (ON/OFF)
END
```

This pseudocode controls an insulin storage box designed to maintain a safe temperature range of 2°C to 8°C using thermoelectric cooling. A DHT22 sensor continuously measures temperature and humidity inside the storage box. These values are displayed in real time on an OLED screen along with the operational status of the cooling components. When the measured temperature exceeds 8°C, the system activates both Peltier modules, internal fans, and the water pump to increase cooling. If the temperature falls below 2°C, the Peltiers and fans are turned off to prevent overcooling, while the water pump remains active to stabilize thermal conditions. For temperatures within the acceptable range, all cooling components remain operational to maintain stability. The system connects to a WiFi network and transmits temperature and humidity data to an online Google Sheet via the IFTTT platform at one-minute intervals. This enables remote monitoring and data logging, ensuring reliable temperature control and traceability for insulin storage.

3. Results and Discussion

3.1 Simulation Testing of the TRIAC-based Automation Transfer Switch

A simulation study of the proposed TRIAC-based Automatic Transfer Switch (ATS) was first conducted using Proteus software to validate the switching logic prior to hardware implementation. The simulated circuit, shown in Figure 7, consisted of an Arduino Uno, OLED display, optocoupler, indicator lamp, and triac-based switching elements. In the absence of a Hi-Link 5 V, 1 W module in the Proteus library, an equivalent AC–DC conversion stage using a transformer, bridge rectifier, voltage regulator, and filter capacitor was implemented to provide a regulated 5 V DC supply from the 220 V AC input. The simulation evaluated four operating scenarios by monitoring the availability of the main and secondary power sources and the corresponding load status displayed on the OLED module. Results confirmed that the Arduino-controlled TRIACs responded correctly to changes in power availability, ensuring proper source selection and continuous load operation.

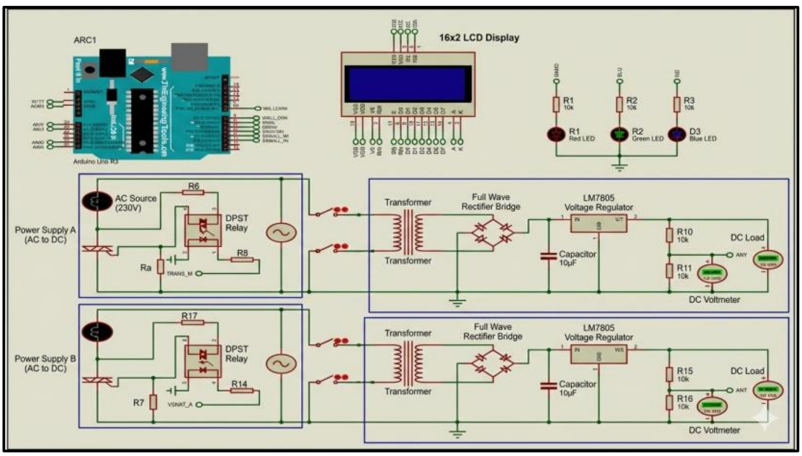

Figure 7. TRIAC-based Automatic Transfer Switch in Proteus™
(Google Gemini, photo enhancement, 2026)

To validate the simulation results, an experimental prototype of the ATS was constructed and tested under the same operating conditions. The hardware implementation demonstrated behavior consistent with the simulated model, with automatic and seamless switching between the primary and secondary power sources during power interruptions. The OLED display accurately reflected the real-time status of each power source and the load. No observable delay or malfunction was recorded during repeated switching events, confirming the reliability of the proposed ATS design for practical application in the insulin storage system.

3.2 Performance Evaluation of the ATS

The operational behavior of the triac-based Automatic Transfer Switch (ATS) was evaluated under four power availability conditions, as illustrated in Figures 8–11. When both the Main Power Source (MPS) and Secondary Power Source (SPS) were available, the OLED display indicated nominal voltage levels for both inputs. In this condition, the Arduino Uno activated the main TRIAC by setting the corresponding digital output pin to a HIGH (5 V) state, thereby triggering the optocoupler and supplying the load from the MPS.

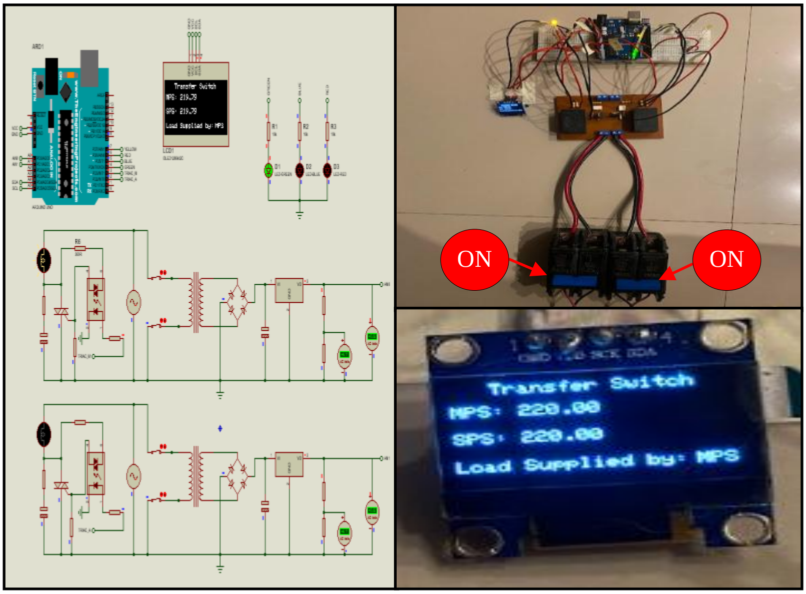

Figure 8. First case

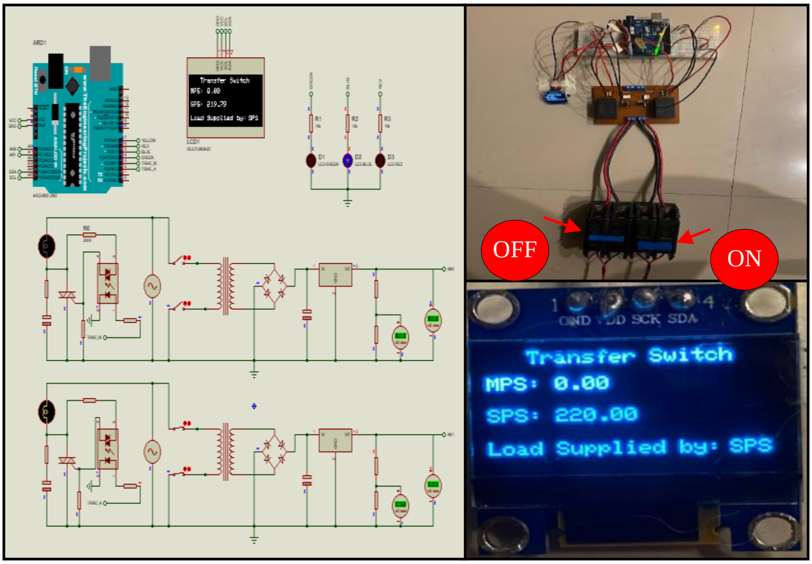

Figure 9. Second case

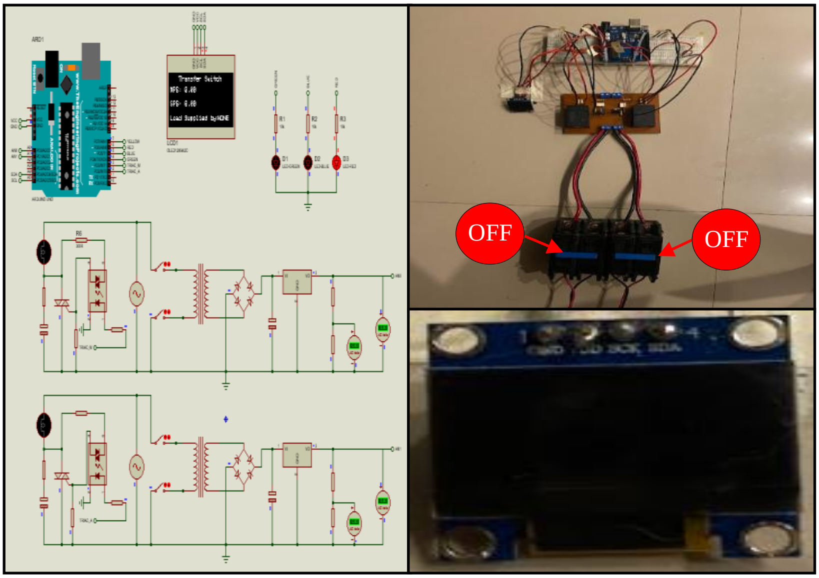

Figure 10. Third case

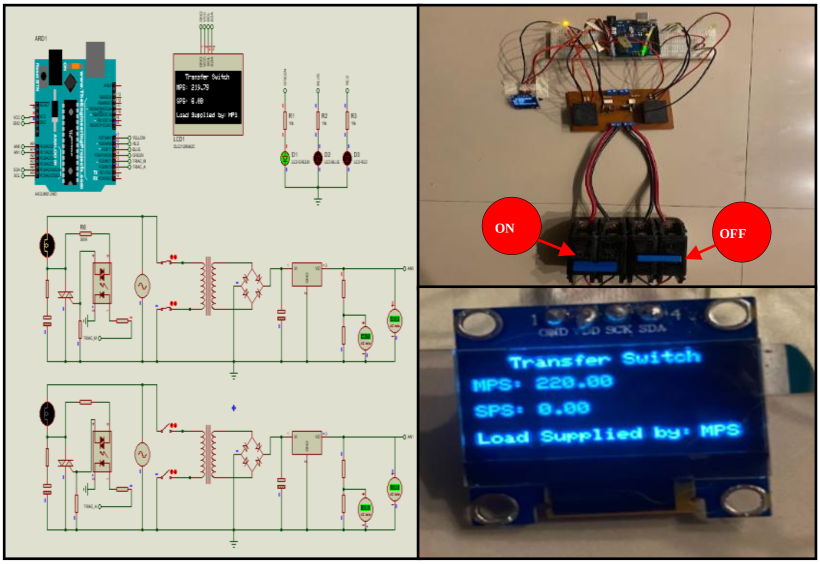

Figure 11. Fourth case

Table 4 summarized the operating principle of the proposed TRIAC-based Automatic Transfer Switch (ATS) under four distinct power availability scenarios. The table presented the corresponding system responses, including source detection, TRIAC activation, and load supply status. This representation provided a clear and systematic description of how the ATS manages power transfer between the main and secondary sources under varying conditions, thereby facilitating evaluation of its switching logic and operational reliability.

Table 4. Summary of the working principle of an Automatic Transfer Switch

	Main Source	Secondary Source	TRIAC	LED	Load Supplied By
1st State	On	On	Main	Green	MPS
2nd State	Off	On	Secondary	Blue	SPS
3rd State	Off	Off	Both	Red	None
4th State	On	Off	Main	Green	MPS

3.3 Operations of the Insulin Storage Box

Figure 12 illustrated the fully assembled insulin storage box and confirmed the proper operation of the proposed system. The figure served as visual validation that the cooling, power management, and monitoring subsystems function as designed.

Table 5 summarized the measured voltage and current consumption of the major system components, including the thermoelectric (Peltier) modules, water pump, and cooling fans. Electrical measurements were obtained using a calibrated digital multimeter. The total current drawn by the system was calculated as 9.8 A, consisting of 8.72 A for two Peltier modules, 0.40 A for the water pump, 0.22 A for two interior fans, and 0.46 A for two exterior heat sink fans.

The total power consumption was determined using Equation 4:

$$P = V * I \tag{4}$$

where V = 12 V and I = 9.8 A, yielding a total power of 117.6 W. This measured value closely matches the theoretical requirement of 117.2 W needed to achieve and maintain the recommended storage temperature of 2°C–8°C within the storage box, validating the accuracy of the system design.

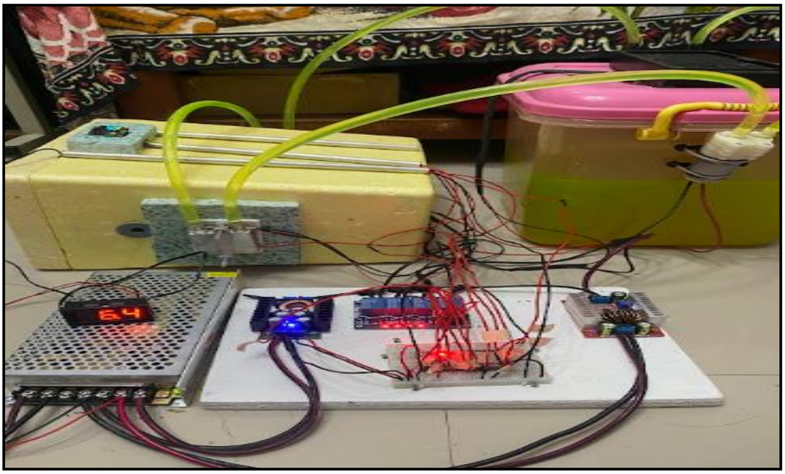

Figure 12. Insulin Storage Box functionality

Table 5. Actual load calculations of the critical components

Load	Current	Voltage
Peltier Module	4.36 A	12 V
Water Pump	0.40 A	12 V
Mini-Fans (Interior)	0.11 A	12 V
Heatsink Fans (Exterior)	0.23 A	12 V

3.4 Performance Evaluation of the Insulin Storage Box

3.4.1 Using Water as Coolant

Figures 13–15 present the measured temperature response of the insulin storage box under three loading conditions using water as the liquid coolant. For the no-load condition (Figure 13), the system achieved the target temperature range within approximately 18 min, reaching a minimum temperature of 2.3°C. Throughout the 3 h test duration, the temperature remained stable within 2.0°C–4.0°C, corresponding to a maximum deviation of ±1.0°C from the set range midpoint. With half-filled insulin vials (Figure 14), the cooling time increased to approximately 32 min. The steady-state temperature ranged from 3.1°C to 5.6°C over the 3 h operating period, remaining fully within the recommended storage range of 2°C–8°C. The observed temperature rise rate during steady operation was less than 0.02°C•min^{-1}. For the fully loaded condition (Figure 15), the system required more than 3 h to approach the target range and failed to reach it within 6 h. The lowest recorded temperature was 8.2°C, exceeding the upper storage limit. This corresponds to a cooling deficit of approximately 0.2°C, indicating that water-based liquid cooling is insufficient under maximum thermal load and prolonged operation, consistent with findings in thermoelectric cooling studies (Sitorus *et al.*, 2020).

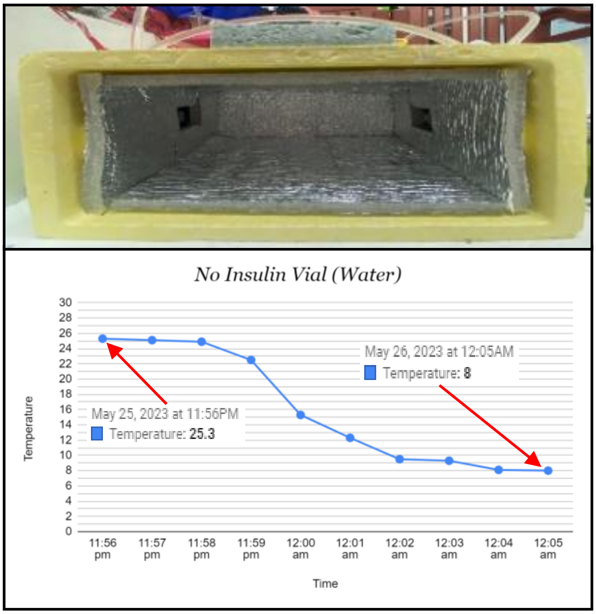

Figure 13. Empty capacity of storage box over time

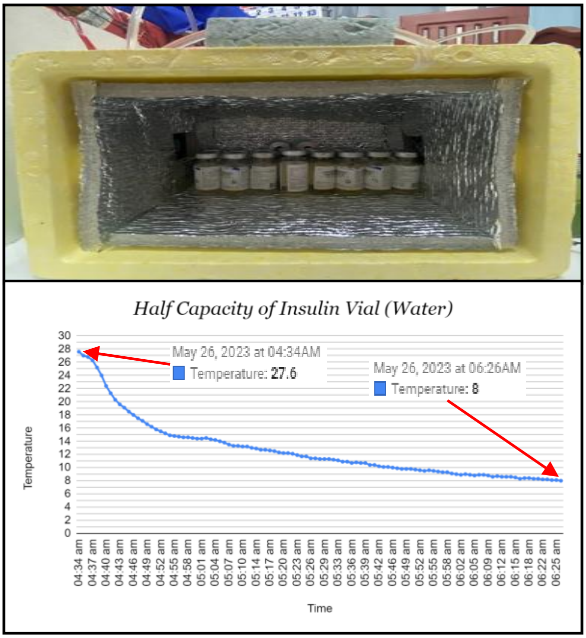

Figure 14. Half capacity of storage box over time

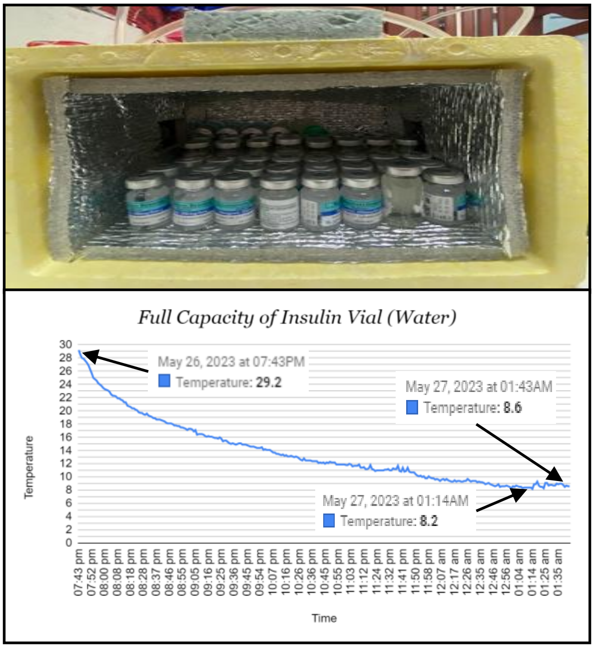

Figure 15. Full capacity of Storage Box over time

3.4.2 Using Pro 99 Long Life™ Coolant as Coolant

Figures 16–18 present the temperature profiles of the insulin storage box using Pro 99 Long Life™ coolant to dissipate heat from the hot side of the Peltier modules under three loading conditions: empty, half-filled, and fully loaded. In the no-load condition (Figure 16), the initial temperature of 26.4°C was reduced to 7.5°C within 8 min, which is 1 min faster than the cooling time achieved using water. The system remained within the recommended insulin storage range of 2°C–8°C thereafter. For the half-filled condition (Figure 17), the temperature decreased from 25.3°C to 8.0°C in 64 min. This represents a 48 min reduction in cooling time compared with water-based cooling. In the fully loaded condition (Figure 18), the temperature was reduced from 27.3°C to 8.0°C in 183 min and was subsequently maintained within the recommended range for the remainder of the test. By contrast, water-based cooling under full load reached only a minimum temperature of 8.2°C. These results demonstrate the superior cooling performance of the coolant relative to water. Table 6 summarizes the minimum temperatures achieved and the corresponding cooling times for all loading conditions.

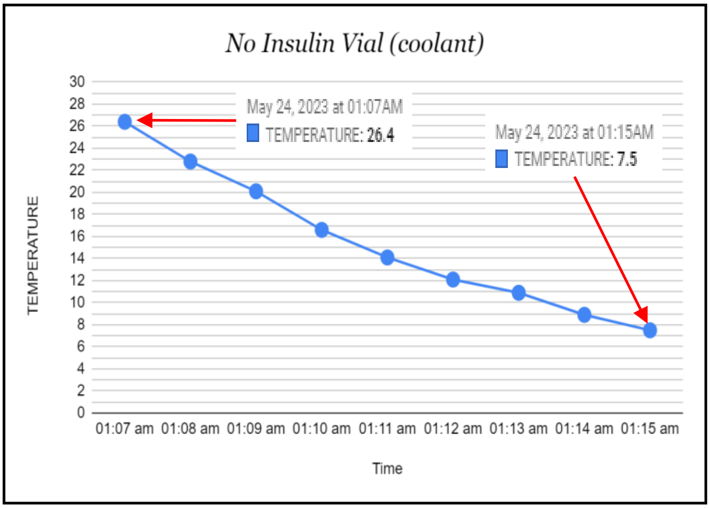

Figure 16. Empty capacity of Storage Box over time

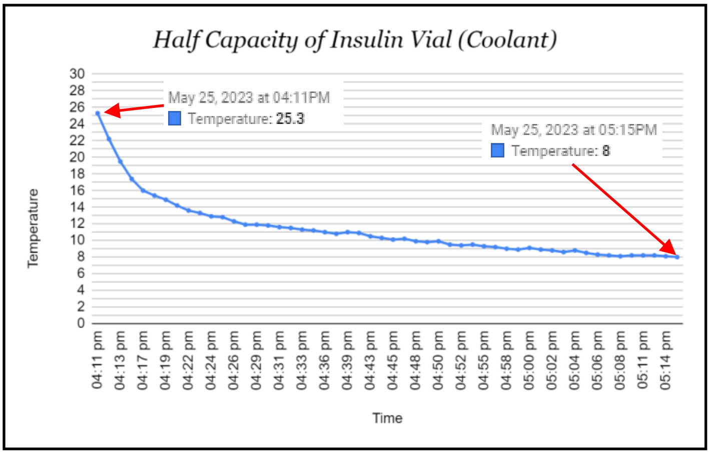

Figure 17. Half capacity of Storage Box over time

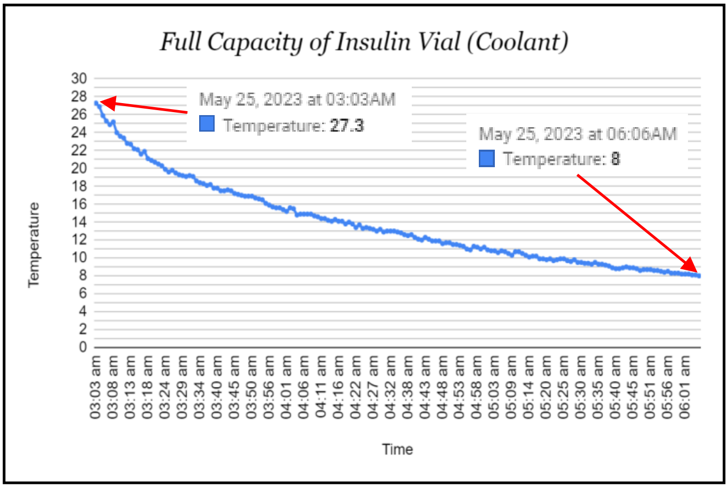

Figure 18. Full capacity of Storage Box over time

Table 6. Summary of the results from various insulin storage box capacity

Cases	Water		Coolant	
	Temperature (°C)	Time (minutes)	Temperature (°C)	Time (minutes)
Empty Capacity	2.1	9	2.2	8
Half Capacity	6.1	112	3.3	64
Full Capacity	8.2	Have not attained the insulin vial temperature range	5.2	183

The cooling-performance experiments under the empty, half-loaded, and fully loaded conditions were conducted only once for each condition. Likewise, the comparison between water and Pro 99 Life Long Coolant was based on a single trial per coolant type. Therefore, the reported temperatures represent actual observed values from the conducted tests rather than mean values from repeated experiments. No measures of variability, such as standard deviation, range, or confidence interval, were calculated. Although on both setup, the minimum temperature recorded was around 2 0C. The findings should consequently be interpreted as preliminary prototype-performance results.

3.5 Coefficient of Performance (COP) of Thermoelectric Cooling System

The coefficient of performance (COP) was used to evaluate the efficiency of the TEC1-127-06L thermoelectric cooling module. COP quantifies the ratio of heat absorbed at the cold side to the electrical power supplied and was computed following the formulation reported by Patel *et al*. (2016). The COP is expressed as Equation 5:

$$COP = \frac{Q_L}{Energysupplied(W)} \tag{5}$$

where the heat absorbed at the cold side Q_L and the heat rejected at the hot side Q_H are given by Equations 6 and 7:

$$Q_L = -[SIT_c - \frac{1}{2}I^2R - k(T_h - T_c)] \tag{6}$$

$$Q_H = SIT_h + \frac{1}{2}I^2R - k(T_h - T_c) \tag{7}$$

The electrical input power is obtained from Equation 8:

where *I* is the operating current, *S* is the Seebeck coefficient, *R* is the electrical resistance, and k is the thermal conductance of the module. The hot-side temperature was maintained at 50°C using liquid cooling.

For the empty, half-filled, and fully loaded storage box conditions, the measured cold-side temperatures were 2.2°C, 3.3°C, and 5.2°C, respectively. The corresponding COP values were 1.9778, 1.9767, and 1.9749. The slight reduction in COP with increasing thermal load is attributed to the decreasing temperature gradient across the module. Overall, the results indicate stable and efficient thermoelectric performance, with COP values remaining close to 2 across all operating conditions.

The reported coefficient of performance (COP) values was not obtained from manufacturer specifications and were not measured directly from cooling-capacity and electrical-power measurements. Instead, they were calculated using the theoretical COP equation, with experimentally measured temperatures used as the input variables. Thus, the reported COP values represent temperature-based theoretical estimates of the thermoelectric cooling system’s performance. The small variation in COP values, from 1.9778 to 1.9749, is consistent with the minimal differences in the measured temperature conditions among the tested loading cases. The temperature values were converted to the required absolute-temperature scale before substitution into the COP equation.

4. Conclusion and Recommendation

The authors acknowledge that the present study evaluated only one prototype over a limited testing duration. Consequently, the long-term reliability, durability, and consistency of the proposed system were not assessed. In addition, the evaluation focused on the temperature within the storage chamber; actual insulin potency was not chemically analyzed. Therefore, although the results indicate that the prototype can maintain the recommended storage-temperature range under the tested conditions, they do not establish the long-term preservation of insulin quality. Future studies should evaluate multiple prototype units over extended operating periods, assess performance under repeated power interruptions and varying environmental conditions, and conduct laboratory-based chemical assays to determine whether insulin potency is retained during storage. Also, conduct repeated trials for every loading condition and coolant type, report mean temperature values with appropriate measures of variability, and apply statistical analysis to determine whether the observed differences between water and Pro 99 Life Long Coolant are reliable and significant.

This study successfully designed, implemented, and experimentally validated an insulin storage box integrated with a TRIAC-based Automatic Transfer Switch (ATS). The thermoelectric cooling system consistently maintained the recommended insulin storage temperature range of 2°C–8°C under empty, half-filled, and fully loaded conditions. A minimum internal temperature of 2 °C was achieved, confirming the system's capability to preserve insulin potency under varying storage capacities. The use of liquid cooling, particularly coolant, further enhanced thermal performance and reduced cooling time compared with water.

The TRIAC-based ATS demonstrated reliable and seamless power source switching, ensuring uninterrupted operation during primary power interruptions. This feature is critical for maintaining continuous temperature control, especially in locations with unstable electricity supply. Experimental results also indicated that increasing storage capacity reduced the temperature gradient across the thermoelectric modules, resulting in a marginal decrease in the coefficient of performance (COP), consistent with thermoelectric cooling theory.

For future work, system reliability may be further improved through better cable management, enhanced electromagnetic interference shielding, and the use of a contactor or double-pole double-throw relay to provide improved electrical isolation and long-term operational robustness.

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