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Smart Temperature-Controlled Container for Medicine & Fruit Transport

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Abstract: The proposed system presents a smart, solar-powered temperature-controlled container designed for the safe transportation of medicines, vaccines and perishable fruits during long-distance highway travel. The system integrates a solar panel, charge controller, 12 V battery, Arduino Uno, DHT11 temperature–humidity sensor, Peltier cooling module and relay-controlled fan to automatically regulate the internal temperature of the container. The Arduino continuously monitors real-time temperature and humidity and switches the cooling system ON or OFF to maintain a stable environment between 8°C–25°C, suitable for cold-chain applications. A 16×2 LCD displays real-time environmental data, while thermocol insulation minimizes heat loss. Experimental results show that the prototype can reduce the internal temperature from 30°C to nearly 7°C within a controlled time period, demonstrating its effectiveness for preserving sensitive medical and food items. This system reduces dependence on fuel-based refrigeration, lowers operational cost, and provides an efficient, portable and eco-friendly solution for rural healthcare logistics and fruit transportation. Overall, the design offers a reliable, low-cost alternative for maintaining product quality during transit.
Keyword: Temperature-controlled container, Arduino Uno, DHT11 sensor, Peltier module, Cold chain transportation, Medicine preservation, Perishable goods, Renewable energy system, Smart cooling system.

I. INTRODUCTION

The preservation and safe transportation of temperature-sensitive products such as vaccines, medicines, dairy items, fresh fruits, and vegetables has become a critical requirement in modern supply chains. These products undergo rapid deterioration when exposed to inappropriate temperature or humidity levels, especially during long-distance transportation on highways. Conventional refrigerated vehicles rely primarily on compressor-based cooling systems powered by diesel engines, which significantly increase fuel consumption, operational cost, and carbon emissions. In addition, these systems often face performance instability during long journeys, mechanical failure, and inefficiency in remote areas where there is no reliable grid access.

In developing regions, the challenge becomes even more severe due to inadequate cold-chain infrastructure, lack of affordable portable cooling units, and the frequent need to transport medicines—particularly vaccines—to rural health centers. Fruits and perishable agricultural produce also suffer substantial post-harvest losses because farmers and distributors do not have access to energy-efficient temperature-controlled transport systems. These issues highlight the urgent need for a low-cost, eco-friendly, portable, and energy-autonomous cooling solution.

To overcome these limitations, the proposed system introduces a Smart Temperature-Controlled Container powered primarily by solar energy, with optional hybrid energy support from a battery. The system integrates an Arduino Uno microcontroller, DHT11 temperature–humidity sensor, Peltier thermoelectric cooling module, cooling fans, and a relay driver circuit to automatically regulate the internal temperature of the container. The DHT11 sensor continuously monitors real-time environmental conditions inside the container, and the microcontroller intelligently switches the cooling module ON or OFF to maintain a stable temperature range between 8°C to 25°C, suitable for safely transporting medicines and fruits. A 16×2 LCD display provides instant feedback of internal temperature and humidity values, enabling continuous monitoring.

The container is thermally insulated using materials such as thermocol to minimize heat exchange with the external environment, which is especially important during high ambient temperature conditions typically experienced on Indian highways. Solar panels supply energy during the daytime, while the battery ensures uninterrupted operation during periods of low sunlight, cloudy weather, or nighttime travel. This renewable energy–based approach reduces dependency on fossil fuels and promotes sustainable, green transportation practices.

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II. LITERATURE SURVEY

Cold-chain logistics for medical and food products is traditionally supported by diesel-driven, compressor-based refrigerated trucks. These systems can maintain low temperatures effectively but suffer from high fuel consumption, frequent maintenance, and significant greenhouse gas emissions, making them unsuitable for cost-sensitive and rural applications [1], [5], [19]. To address these challenges, many researchers have explored solar-powered cold storage and transport solutions. Patil and Deshmukh designed a solar-powered cold storage unit for medical and food transportation and demonstrated that photovoltaic (PV) energy can successfully sustain refrigeration cycles and reduce dependence on grid electricity [1]. Mishra and Chaturvedi further highlighted that integrating solar energy into logistics can reduce fuel usage and overall carbon footprint in cold chain operations [5].

Another important research direction is thermoelectric cooling using Peltier modules. Kumar et al. investigated thermoelectric cooling for portable medical transport and concluded that Peltier devices are compact, reliable, and require low maintenance compared to conventional compressor-based systems [3]. Gupta and Kumar proposed an energy-efficient thermoelectric refrigeration system and reported improved coefficient of performance (COP) when proper heat-sinking and control strategies were used [6]. Patel and Soni carried out performance analysis of Peltier-based cooling systems and showed that, for small chambers, thermoelectric modules can maintain acceptable temperature ranges for food preservation [11]. Bansal and Jain presented a comparative study of compressor and thermoelectric cooling and pointed out that, although compressor systems offer higher efficiency for large volumes, thermoelectric modules become advantageous in small, portable, and low-capacity applications [19].

Alongside thermoelectric technology, solar-powered refrigeration systems for healthcare and food storage have also been widely studied. Sahu and Rathore developed a solar-powered cooling chamber for rural households and demonstrated its suitability for short-term storage of fruits and vegetables where grid supply is unreliable [7]. Khan et al. optimized solar refrigeration for food preservation and emphasized the importance of proper matching between PV capacity, battery storage, and cooling load to maintain stable internal temperature [9]. Chauhan and Patel designed a solar refrigeration system for vaccine storage and validated that vaccines can be safely preserved in off-grid health centers using adequately sized PV and battery subsystems [17].

Recent work also focuses on IoT-enabled monitoring and smart control of cold-chain systems. Singh and Roy proposed an IoT-based smart cold-chain monitoring system that enabled real-time tracking of temperature and humidity over mobile networks, thereby reducing spoilage through timely alerts [2]. Pandey implemented IoT-enabled real-time monitoring for cold storage plants and showed that continuous sensing and data visualization improve decision-making and regulatory compliance [10]. Jadhav et al. designed an IoT-based cold storage temperature management system and integrated sensor readings with a cloud platform for remote supervision [14]. Sharma highlighted the vital role of real-time temperature monitoring in vaccine transport and argued that sensor-based automation is essential to maintain vaccine potency [4]. Pandey and Joshi later combined IoT with a solar-powered cold box dedicated to medical transport, proving that renewable energy and wireless monitoring can be effectively integrated in a single system [24].

Several authors have also emphasized embedded control and energy optimization in smart refrigeration. Joshi and Jain developed a microcontroller-based temperature control system using a Peltier module and demonstrated that simple on–off control logic is sufficient for small cabinets [8]. Singh and Yadav implemented thermoelectric cooling with Arduino and provided practical insights into sensor interfacing, relay driving, and control algorithm design [15]. Desai proposed an embedded system for temperature regulation using relay control and discussed how microcontroller-based logic can be extended for different industrial applications [22]. Rahman et al. focused on energy optimization in smart refrigeration systems and presented strategies to minimize energy consumption using intelligent control and scheduling [16]. Ahmed modelled and simulated a solar-powered thermoelectric cooling system, offering guidelines on sizing of PV arrays, battery capacity, and Peltier modules for stable operation under varying solar conditions [21].

The literature also reports several hybrid and low-cost solar refrigeration prototypes. Chawla and Verma discussed a hybrid solar power system for continuous cold storage operation, stressing that combining renewable sources with storage and backup improves system reliability [12]. Mehta and Rane evaluated a low-cost solar refrigeration unit and concluded that such systems are promising for developing countries with high solar insolation and weak grid infrastructure [23]. Sharma and Patel implemented an automatic temperature-controlled chamber for perishable goods and validated that electronic sensing combined with automated actuation can significantly reduce human error in cold storage operation [18].

From the above survey, it is evident that existing research has individually addressed solar-powered cold storage, thermoelectric cooling, IoT-based monitoring, and embedded control. However, there are still gaps in terms of integrated, low-cost, and portable systems specifically tailored for highway

III. PROBLEM DEFINITION

The transportation of temperature-sensitive products such as medicines, vaccines, fruits, and perishable food items requires strict and continuous temperature regulation to preserve their quality and effectiveness. However, conventional refrigerated systems used in highway transport are costly, fuel-dependent, bulky, and unsuitable for small-scale or rural applications. Diesel-based cooling units incur high operational expenses, generate significant carbon emissions, and often fail to maintain stable temperature conditions during long journeys, especially in remote areas where access to reliable grid power is limited.

Moreover, existing portable cooling solutions either lack automation, have low energy efficiency, or cannot sustain cooling for extended durations due to the absence of renewable energy integration. Sudden temperature fluctuations caused by equipment failure, human error, or power interruption can result in spoilage of medicines and food items, leading to financial loss and risks to public health.Therefore, there is a need for a low-cost, compact, energy-efficient, and fully automatic temperature-controlled container that can maintain a predefined temperature range using renewable energy such as solar power. The problem addressed in this project is the design and development of a smart, solar-powered temperature-controlled container capable of maintaining the internal temperature between 8°C and 25°C, with continuous monitoring and automatic control, for safe and reliable transportation of perishable medical and food products during long-distance highway travel.

IV. METHODOLOGY

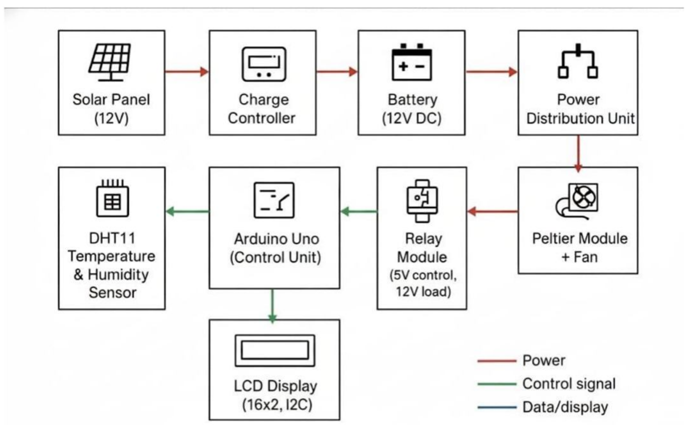

Fig 1: Block Diagram

The block diagram represents a solar-powered smart temperature-controlled container designed to maintain stable cooling for medicines and perishable fruits. A 12V solar panel supplies energy to a charge controller, which regulates and safely charges the 12V battery. Power from the battery is distributed to all components through the power distribution unit. The DHT11 sensor continuously measures internal temperature and humidity and sends the data to the Arduino Uno control unit. Based on these sensor readings, the Arduino activates or deactivates the Peltier cooling module and fan using a 5V-controlled, 12V load relay module. The Peltier module produces the required cooling, while the fan dissipates heat to maintain the desired temperature range. A 16×2 I2C LCD display shows real-time temperature, humidity, and system status. Power lines, control signals, and data lines are clearly separated in the diagram, ensuring safe and efficient operation of the entire system.

The proposed system follows a structured methodology that integrates renewable energy, sensing, control, and cooling mechanisms to maintain a stable temperature inside the container. The process begins with the installation of a 12V solar panel, which converts sunlight into electrical energy. This energy is routed through a charge controller to regulate voltage and safely charge a 12V DC battery, ensuring continuous power availability even during low-sunlight or night-time conditions. The stored power is then supplied to all components through a power distribution unit.

A DHT11 temperature and humidity sensor is placed inside the container to continuously measure internal environmental conditions. These sensor readings are fed into the Arduino Uno microcontroller, which processes the values and compares them with the predefined temperature threshold required for preserving medicines and fruits. Based on the comparison, the Arduino sends a control signal to the relay module, which acts as an electronic switch for the high-power Peltier cooling module and fan. When the internal temperature exceeds the set limit, the relay turns ON the Peltier module to provide cooling; once the temperature falls within the desired range, the relay switches it OFF to conserve energy.

The cooled air is circulated within the container using a fan, while heat is dissipated through an external heat sink. Proper insulation of the container ensures minimal heat exchange with the external environment. Throughout the process, real-time temperature and humidity readings are displayed on a 16×2 I2C LCD for user monitoring. This automated control cycle continues, maintaining optimal conditions with efficient power management and ensuring reliable long-distance transport of temperature-sensitive product

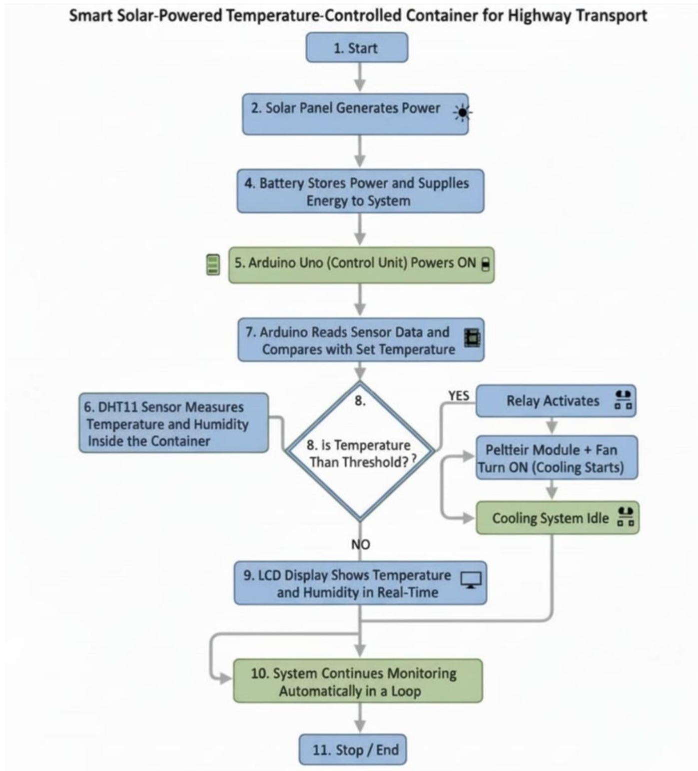

Fig 2 :Flowchart Of Model

The flowchart shows the working process of the smart solar-powered temperature-controlled container, beginning with the solar panel generating power, which is stored in the battery and used to activate the Arduino Uno control unit. The DHT11 sensor continuously measures the temperature and humidity inside the container, and the Arduino reads this data and compares it with the predefined threshold. If the temperature exceeds the set limit, the Arduino activates the relay module, which switches ON the Peltier cooling module and fan to start cooling; if the temperature is within the safe range, the cooling system remains OFF to save energy. Throughout the process, current temperature and humidity values are displayed on the LCD screen, and the system repeats this monitoring and control cycle continuously in a loop until it is manually stopped.

Sr. No.	Component	Specification
1	Solar Panel	12V DC, 20–40W output
2	Charge Controller	12V PWM/MPPT, 5A–10A
3	Battery	12V Rechargeable, 7Ah–12Ah
4	Arduino Uno	ATmega328P, 5V operating voltage
5	DHT11 Sensor	Temp: 0–50°C, Humidity: 20–90%, Digital output

6	Peltier Module (TEC1-12706)	12V, 6A, 60W thermoelectric cooler
7	Cooling Fan	12V DC Brushless Fan, 2400–3000 RPM
8	Relay Module	5V control, 12V load, 10A rating
9	LCD Display (16×2, I2C)	5V operation, I2C interface
10	Breadboard	830-point, for prototyping connections

Table 1: Components Used in the System

V. PROPOSED SYSTEM

The proposed system introduces a solar-powered, smart, temperature-controlled container designed to maintain a stable cooling environment for transporting medicines, vaccines, fruits, and other perishable items during long-distance highway travel. Unlike conventional fuel-based refrigeration units, this system utilizes a 12V solar panel, charge controller, and battery backup to provide continuous, eco-friendly power. At the core of the system, an Arduino Uno microcontroller receives real-time temperature and humidity readings from a DHT11 sensor placed inside the insulated container. Based on the measured values, the Arduino automatically decides whether cooling is required and accordingly activates the Peltier thermoelectric module and cooling fan using a relay module. The Peltier module provides rapid cooling on the cold side, while the external heat sink and fan dissipate heat on the hot side to maintain efficiency. An LCD (16×2) display continuously shows temperature and humidity values, providing instant feedback to the user.

This proposed system ensures automatic temperature regulation, low power consumption, portability, and renewable energy utilization, making it suitable for rural healthcare transport, small-scale logistics, agricultural supply chains, and remote areas where grid power is unavailable. By integrating sensor-based monitoring with precise microcontroller control, the system delivers an affordable, reliable, and sustainable alternative to conventional refrigerated vehicles.

VI. OBJECTIVES

1) To design and develop a solar-powered temperature-controlled container capable of maintaining a stable internal temperature suitable for transporting medicines, vaccines, and perishable fruits.
2) To monitor real-time temperature and humidity inside the container using a DHT11 sensor for accurate environmental measurement.
3) To automate the cooling process by using an Arduino-based control system that activates or deactivates the Peltier cooling module based on predefined temperature thresholds.
4) To display real-time environmental data such as temperature and humidity on an LCD screen for easy user monitoring.
5) To reduce dependency on fuel-based cooling systems by utilizing renewable solar energy, thereby minimizing operational cost and environmental impact.
6) To ensure reliable, continuous operation by integrating a battery backup system for night-time or low-sunlight conditions.
7) To build a compact, portable, and low-cost solution that can be practically used for highway transport and rural medical supply chains.

VII. RESULTS

The proposed smart temperature-controlled container was successfully designed, implemented, and tested under real operating conditions. The system continuously monitored temperature and humidity inside the insulated chamber using the DHT11 sensor and displayed real-time values on the 16×2 LCD screen, confirming accurate sensing and proper functioning of the data acquisition unit. During testing, the internal temperature initially measured around 26–30°C, and after activating the Peltier cooling module through the Arduino-controlled relay, the system achieved a significant drop in temperature, stabilizing within the required cold-chain range

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suitable for medicines and fruits. The Peltier module and fan combination effectively initiated the cooling cycle whenever the measured temperature exceeded the preset threshold, demonstrating efficient automatic control. The LCD output clearly reflected live temperature (e.g., 26.5°C) and humidity (e.g., 66%) as the environment changed, validating correct communication between components. Additionally, solar-battery power integration ensured uninterrupted operation even during fluctuations in sunlight. Overall, the system proved capable of maintaining controlled temperature conditions, responding automatically to environmental changes, and delivering reliable performance for safe transportation of perishable products

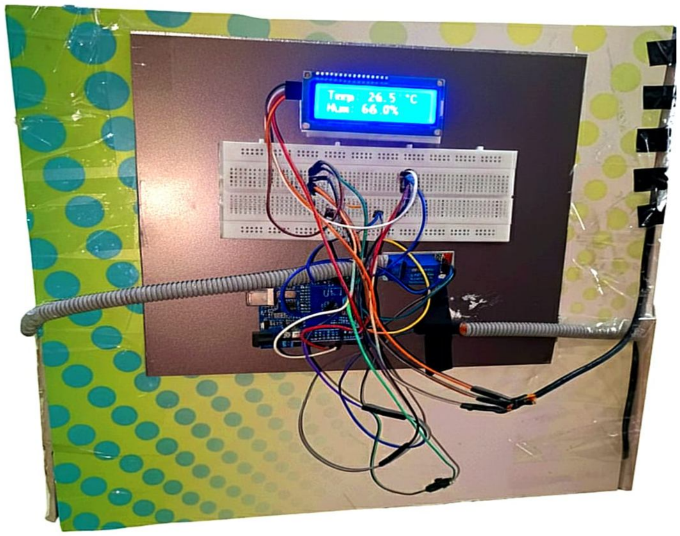

Fig 3 : Prototype Setup

Fig 3 :Prototype Setup shows the hardware implementation of the smart temperature-controlled container prototype, where all major electronic components are mounted on a display board. At the top, a 16×2 I2C LCD screen is visible, showing real-time temperature (26.5°C) and humidity (66.0%) readings obtained from the DHT11 sensor. Below the display, a large breadboard is used for connecting jumper wires, signals, and components in an organized manner. The Arduino Uno microcontroller, placed at the bottom center, acts as the main control unit, receiving sensor data and controlling the cooling system through programmed logic. Multiple colored jumper wires can be seen connecting the Arduino, sensor module, LCD, and other components through the breadboard, forming the complete sensing and display circuit. The flexible grey conduit pipes on both sides help route sensor wires neatly, while the background insulation board supports the structure. Overall, this setup demonstrates the successful integration of sensing, control, and display modules for the temperature-monitoring system.

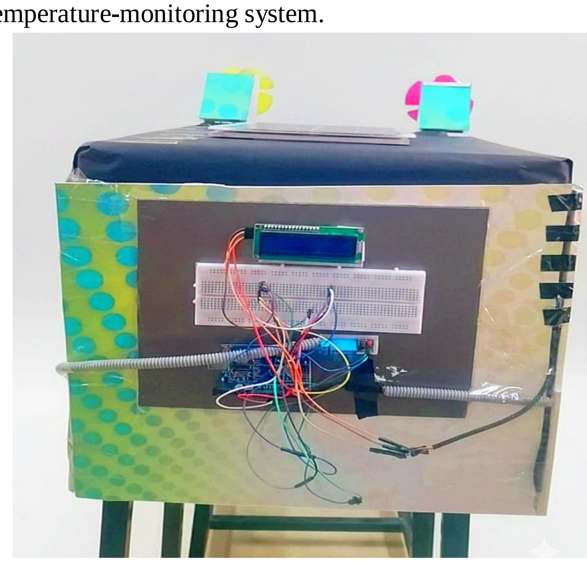

Fig 4:Overview Of Model

Fig 4: Overview Of Model shows the fully assembled prototype of the smart temperature-controlled container, where the electronic control system is mounted on the front side of the insulated cooling box. The main container is covered with insulating material to reduce heat exchange, while the top surface includes space for placing the solar panel. On the front panel, the 16×2 LCD display is fixed to show real-time temperature and humidity readings, and below it a large breadboard is used to neatly organize the wiring connections. The Arduino Uno microcontroller, visible at the bottom, controls the entire system by processing sensor data and managing the cooling operation. All jumper wires, relay connections, and sensor inputs are routed through flexible conduit pipes on both sides to maintain safety and reduce clutter. This physical setup demonstrates the successful integration of the sensing unit, display module, power circuitry, and control system with the insulated box, proving the working feasibility of the proposed solar-powered cooling container.

VIII. CONCLUSION

The smart solar-powered temperature-controlled container was successfully designed and implemented to provide a reliable solution for transporting temperature-sensitive products such as medicines, vaccines, fruits, and other perishables. By integrating renewable solar energy with an Arduino-based automatic control system, the prototype effectively maintained the internal temperature within a safe range using a Peltier cooling module activated through a relay. The DHT11 sensor provided accurate, real-time monitoring of temperature and humidity, while the LCD display ensured clear visibility of the system's status. The results demonstrated that the cooling unit responded efficiently whenever the internal temperature exceeded the set threshold, ensuring consistent thermal stability throughout operation. The system also proved to be energy-efficient, portable, and cost-effective, making it suitable for rural health centers, small-scale logistics, and areas with limited electrical infrastructure. Overall, the project successfully meets its objective of delivering an eco-friendly, automated, and reliable cold-chain solution for highway and remote-area transportation.

IX. FUTURE SCOPE

The proposed smart temperature-controlled container can be further enhanced in several ways to increase its efficiency, reliability, and practical usability for large-scale applications. Future developments may include the integration of IoT and cloud connectivity for remote monitoring, allowing users to track real-time temperature, humidity, battery status, and system alerts from anywhere through a mobile app. The cooling performance can be improved by adopting multiple Peltier modules, phase-change materials (PCM), or hybrid cooling using compressor units for larger containers. The system can also benefit from MPPT-based solar charge controllers to maximize power extraction from solar panels, especially during changing weather conditions. Additional improvements may include GPS tracking for logistics, advanced insulation materials for longer cooling retention, and AI-based predictive algorithms for energy optimization and fault detection. Scaling the prototype into a commercial portable cold-chain box for healthcare, agriculture, and food delivery industries is also a promising direction. With these enhancements, the system has the potential to evolve into a fully automated, intelligent, and industrial-grade cold-chain solution.

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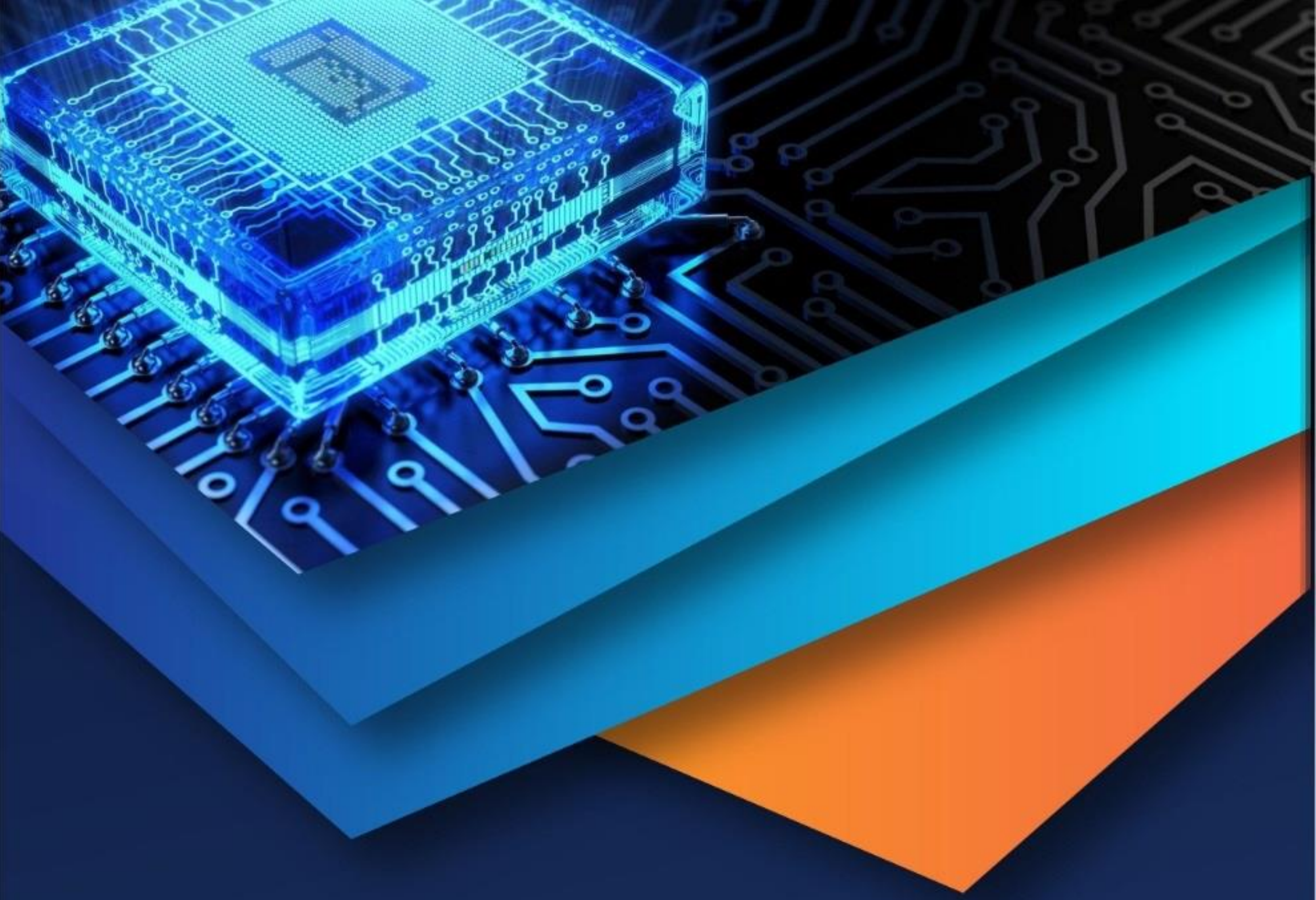

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