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Design and Development of a Smart Temperature Controlled Sustainable Packaging System from Agriculture Waste

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Abstract- The design and development of a smart temperature-controlled sustainable packaging system fabricated from agricultural waste materials. Banana fiber, sugarcane bagasse, rice husk and coconut coir are utilized to form a biodegradable composite structure bonded using a starch-based adhesive. Phase change material (PCM) is integrated to provide passive thermal energy storage and temperature stabilization during transit. An embedded smart control unit comprising an ESP32 microcontroller and a DS18B20 temperature sensor enables continuous monitoring of internal temperature. A E27 Infrared heat bulb is automatically activated when the temperature falls below a predefined threshold, ensuring controlled thermal regulation. The proposed system offers an eco-friendly, cost-effective and energy-efficient solution for transporting temperature-sensitive goods.

Keywords: PCM, PLA, ESP32, DS18B20, IR Bulb, Sustainable packaging.

I. INTRODUCTION

Transportation of temperature-sensitive goods such as food products and pharmaceuticals is often affected by temperature fluctuations, leading to quality degradation and safety risks. Conventional packaging relies on non-biodegradable materials and energy-intensive systems, increasing cost and environmental impact. This project presents a smart temperature-controlled sustainable packaging system using agricultural waste materials and phase change material (PCM) for passive thermal stabilization. An ESP32 microcontroller with a DS18B20 sensor continuously monitors temperature and automatically controls an infrared heat bulb to maintain desired conditions. The biodegradable composite structure made from banana fiber, sugarcane bagasse, rice husk and coconut coir provides an eco-friendly, cost-effective and energy-efficient solution for green logistics.

II. LITERATURE REVIEW

Abdel-Rahman et al. (2021) reviewed lactic acid production from lignocellulosic biomass using lactic acid bacteria. The study discussed pretreatment methods, fermentation challenges and process optimization strategies. The authors highlighted the potential of lignocellulosic feedstocks for large-scale lactic acid and production.

Benavides et al. (2018) explored the comparative energy consumption and environmental impacts of virgin, recycled and bio-derived PET bottles through life cycle assessment. The findings revealed that bio-derived polymers significantly reduce fossil fuel usage and greenhouse gas emissions compared to virgin petroleum-based plastics. The study highlighted that adopting bio-based alternatives such as PLA can contribute to sustainable packaging systems when combined with efficient recycling and waste management practices.

Ciriminna et al., (2020) critically examined the global adoption of biodegradable and compostable plastics. The study addressed both the environmental benefits and limitations of bioplastics, highlighting challenges related to improper disposal and lack of industrial composting facilities. The authors stressed the importance of standardized regulations, clear labelling and public awareness to ensure environmental pollution.

Dorgan et al. (2019) examined the thermal and rheological properties of commercial-grade PLA to assess its processability. The results indicated that PLA exhibits favorable melt flow behavior but limited thermal stability at elevated temperatures. The study suggested that additives and polymer blending can improve PLA's processing window and mechanical performance.

Esmaeely Neisiany et al. (2020) provided an extensive review of recent advancements in functionalized nanocomposite hydrogels. The study discussed the integration of biodegradable polymers with nanomaterials to enhance mechanical strength, thermal stability and functional performance. The authors highlighted that such nanocomposites have gained attention due to their environmental compatibility and versatility in applications such as biomedical devices, smart materials and sustainable packaging. The review emphasized the growing importance of eco-friendly polymers in advanced material engineering.

John et al. (2025) examined lactic acid production from agricultural waste using solid-state fermentation techniques. The study reported high lactic acid yields using Lactobacillus delbrueckii, demonstrating the feasibility of converting agro-waste into valuable biopolymer precursors. This research supports sustainable and cost-effective PLA production.

Lazim et al. (2021) investigated cellulose nanofiber-reinforced PLA bio composites for packaging applications. The results showed enhanced tensile strength, thermal stability and barrier properties compared to neat PLA.

III. DESCRIPTION OF EXISTING SYSTEM

The existing system for transporting temperature-sensitive goods mainly uses conventional packaging materials such as plastic, thermocol and synthetic insulating foams. Temperature control is achieved through refrigerated transport, ice packs, or electrically powered cooling systems. These methods require high energy consumption and increase operational costs. Most packaging materials used are non-biodegradable, causing environmental pollution. Additionally, real-time temperature monitoring is often absent, leading to unnoticed temperature fluctuations. As a result, product quality and safety may be compromised during transit.

Fig.1.Plastic food packaging System

IV. PROPOSED WORK EXPLANATION

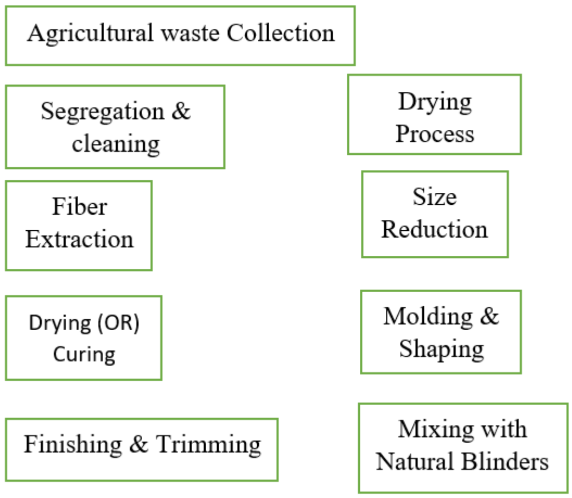
The proposed system is a smart temperature-controlled sustainable packaging solution for transporting temperature-sensitive goods such as food and pharmaceuticals. The structure is made from agricultural waste materials bonded with starch-based adhesive for biodegradability. Phase Change Material (PCM) provides passive thermal storage to reduce temperature fluctuations. An ESP32 microcontroller with a DS18B20 sensor monitors temperature and automatically controls an infrared heat bulb when required. The system ensures reliable thermal regulation with low energy consumption, offering an eco-friendly and cost-effective alternative to conventional packaging.

4.1 Material Preparation and Drying Process

Agricultural wastes such as banana fiber, sugarcane bagasse, rice husk and coconut coir are collected and cleaned. The materials are dried at 50°C–80°C to reduce moisture content to about 8–12%. Proper drying improves fiber strength, prevents microbial growth and ensures effective bonding with starch-based resin during molding.

4.1.2 Flow Chart of Material Processing

The flow chart shows the sequence from agricultural waste collection to final biodegradable packaging. The fibers are cured at 65°C, mixed with natural binders, molded into shape and finally finished to obtain the packaging product.



4.1.1 Block Diagram:

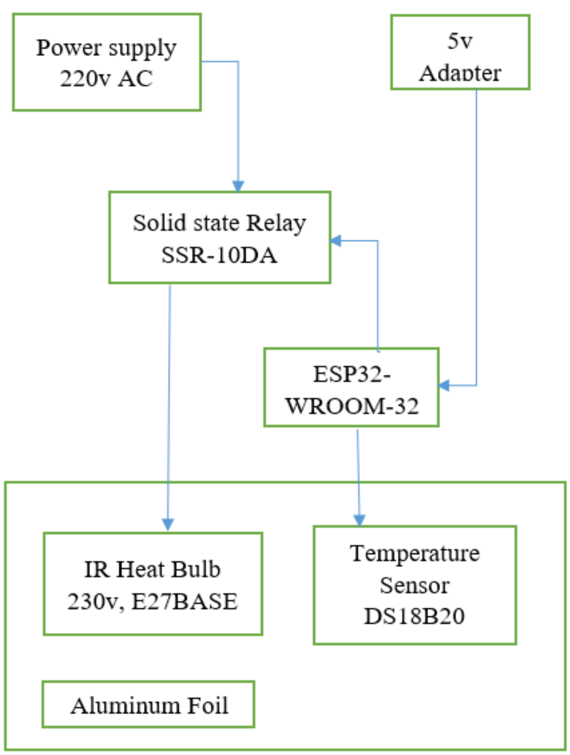


Fig.2. Block Diagram of Proposed System

4.1.2 Flow Chart:

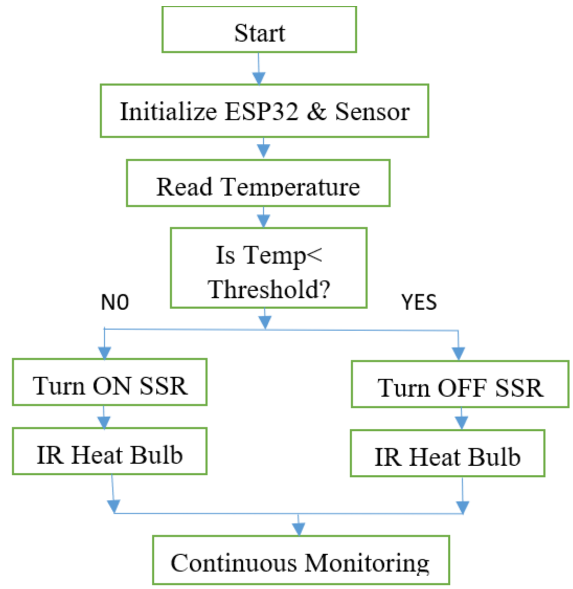


Fig.3. Flow Chart of Proposed System

4.1.1 Hardware Implementation:

A plywood heating chamber lined with aluminium foil to improve heat reflection and efficiency. An infrared heating lamp is mounted inside the box and controlled through a relay module. A temperature sensor continuously monitors the internal temperature and sends data to the microcontroller. The microcontroller automatically switches the heater ON or OFF to maintain the desired temperature.

Hardware Components:

(i) Solid State Relay: A Solid-State Relay (SSR) is an electronic switching device used to control high-voltage AC loads using low-voltage control signals. Unlike electromechanical relays, SSRs have no moving parts, which provides silent operation and high reliability. It enables fast and efficient switching with minimal power loss and improved safety.

Fig.4. Solid State Relay Module

(ii) Microcontroller (ESP32): The main microcontroller serves as the central control unit of the system. It processes sensor inputs and controls the exhaust fan and incandescent bulb accordingly enabling automated.


Fig.5. Microcontroller (ESP32)

(iii) DS18B20 Sensor: The DS18B20 is a digital temperature sensor used to measure the internal temperature of the packaging system. It provides accurate temperature readings with a wide operating range and communicates using a single-wire interface, reducing wiring complexity.


Fig.6. DS18B20 Sensor

(iv) The infrared (IR) heat bulb: It is used as a heating element to maintain the required temperature inside the packaging system. It emits infrared radiation that provides uniform and efficient heat without direct contact. The E27 base allows easy installation with standard bulb holders and operation at 230 V AC.


Fig.7. 150W IR Bulb

(v) Specifications:

Solid State Relay	25A
Microcontroller	ESP32
Temperature	DS18B20
Bulb	150W

V. RESULTS AND DISCUSSION

The proposed smart temperature-controlled sustainable packaging system was successfully implemented and tested. The biodegradable composite structure provided effective thermal insulation, while the integrated phase change material (PCM) minimized temperature fluctuations during transit. The DS18B20 sensor accurately monitored temperature and the ESP32 reliably controlled the solid state relay to switch the infrared heat bulb whenever the temperature dropped below the set value. The system maintained the required temperature range with low energy consumption. Overall, the results demonstrate that the proposed solution is eco-friendly, cost-effective and suitable for transporting temperature-sensitive goods.

5.1 Preparation of Figures and Tables

The developed smart temperature-controlled sustainable packaging system is illustrated using clearly labelled figures and tables to enhance understanding of the design and performance. The structural composition fabricated from agricultural waste materials such as banana fiber, sugarcane bagasse, rice husk and coconut coir is presented through schematic and photographic figures, highlighting the biodegradable composite arrangement. Figures also depict the integration of phase change material (PCM), ESP32 microcontroller, DS18B20 temperature sensor, solid state relay and infrared heat bulb used for thermal regulation. Tables are used to summarize hardware components, specifications and operating parameters for clarity and comparison. As shown in the respective figures, the proposed system demonstrates an eco-friendly, low-cost and energy-efficient packaging solution suitable for transporting temperature-sensitive goods.

Fig.8.Hardware Implementation

VI. CONCLUSION

The design and development of the smart temperature-controlled sustainable packaging system successfully address the challenges associated with transporting temperature-sensitive goods. By utilizing agricultural waste materials such as banana fiber, sugarcane bagasse, rice husk and coconut coir, the proposed system significantly reduces dependence on non-biodegradable packaging materials and promotes environmental sustainability. The biodegradable composite structure provides adequate mechanical strength and thermal insulation while ensuring eco-friendly disposal.

The integration of phase change material (PCM) enhances thermal stability by reducing sudden temperature fluctuations during transit through passive thermal energy storage. The embedded IoT-based control unit comprising an ESP32 microcontroller and a DS18B20 temperature sensor enables continuous temperature monitoring and automatic regulation using an infrared heat bulb controlled via a solid-state relay. Experimental results demonstrate reliable temperature maintenance with minimal energy consumption.

Overall, the proposed system offers a cost-effective, energy-efficient and environmentally responsible alternative to conventional packaging solutions. It supports green logistics, minimizes product spoilage and has strong potential for real-world application in food, pharmaceutical and biological material transportation. With further optimization and large-scale implementation, this system can contribute significantly to sustainable supply chain management.

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