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IoT-Based Solar Dehydration System with Energy Storage Material for Agricultural Products

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ABSTRACT

This review explores the integration of Internet of Things (IoT) technology and energy storage materials in solar dehydration systems for agricultural products. Solar drying is a sustainable method to reduce post-harvest losses, but traditional systems are limited by weather dependency and lack of process control. The inclusion of IoT enables real-time monitoring and automation, while phase change materials (PCMs) such as paraffin wax provide thermal energy storage for continuous operation. This paper reviews system architectures, performance outcomes, challenges, and future prospects of IoT-based solar dehydration systems with energy storage, highlighting their potential to improve efficiency, product quality, and farmer livelihoods.

KEYWORDS: *Solar Drying, IoT, Energy Storage, Phase Change Materials, Agricultural Products, Smart Dryer, Renewable Energy*

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1. INTRODUCTION

Post-harvest losses remain a significant challenge in agriculture-based economies, largely due to inadequate preservation techniques. Dehydration or drying is one of the most commonly employed methods for extending the shelf life of fruits, vegetables, and herbs. However, traditional sun drying practices are often inefficient, labor-intensive, and post hygiene concerns. Solar dryers provide a more effective and sustainable alternative, yet their performance is hindered by fluctuations in the solar radiation.

The Recent trends and advancements in Internet of Things (IoT) technologies and thermal energy storage (TES) have facilitated the emergence of smart solar drying systems. These systems enable real-time monitoring and control of drying parameters and utilize stored thermal energy to maintain optimal drying conditions during periods of low solar availability. This review paper discusses the principles, system designs, advantages, and challenges of IoT-based solar dehydration systems with energy storage for agricultural applications.

2. SOLAR DEHYDRATION SYSTEMS:

Solar dehydration systems utilize solar energy to remove moisture from agricultural products, preserving their nutritional value and extending shelf life. These systems can be classified into direct, indirect, and hybrid types, each with unique advantages and limitations. Traditional systems often lack precise control over temperature and humidity, resulting in variable drying rates and product quality. There are three types of Solar Dryers namely direct contact dryers, indirect contact dryers and mixed contact dryers. Direct Solar Dryers: Products are exposed directly to sunlight inside an enclosed chamber. Indirect Solar Dryers: A separate solar collector heats air, which is then directed into the drying chamber. Mixed-Mode Solar Dryers: Combine features of both direct and indirect systems.

2.1. IOT INTEGRATION:

IoT integration in solar drying technology enhances the efficiency and monitoring of drying processes for agricultural products. By utilizing sensors and remote management systems, users can optimize drying conditions and track performance in real-time, leading to improved quality and Reduced energy consumption. IoT-based systems improve drying efficiency, reduce labor, and enable data-driven decision-making for quality assurance. The integration of IoT technologies transforms conventional solar dryers into smart systems capable of:

- Monitoring temperature, humidity, and airflow using sensors and microcontrollers.
- Remote data access and control via web or mobile applications.
- Automated alerts for process optimization and maintenance.

3. ENERGY STORAGE MATERIALS:

Energy storage materials, especially phase change materials (PCMs) like paraffin wax, are incorporated to address the intermittent nature of solar energy. PCMs absorb excess heat during peak sunlight and release it during periods of low or no sunlight, maintaining optimal drying conditions. This ensures continuous operation and consistent product quality, even during cloudy weather or nighttime.

3.1. Thermal Energy Storage (TES):

Thermal Energy Storage (TES) refers to a range of technologies that capture and store thermal energy—either as heat or cold—for later use. This enables the decoupling of energy generation from energy demand, which is particularly valuable for balancing intermittent renewable energy sources such as solar and wind, as well as for improving the efficiency of heating and cooling systems in buildings and industrial processes. TES materials store excess thermal energy during peak sunlight hours and release it during cloudy conditions or nighttime, ensuring continuous drying. TES technologies are generally categorized into three main types, based on the storage mechanism and materials used:

3.1.1. Sensible Heat Storage (SHS):

Sensible Heat Storage is the most straightforward and widely adopted method of thermal energy storage. It works by raising or lowering the temperature of a storage medium—commonly water, sand, molten salts, or rocks—without changing its phase. The amount of energy stored depends on the material's specific heat capacity, the mass of the medium, and the temperature change it undergoes. Water is especially popular due to its high heat capacity, low cost, and safety profile.

Mathematical Representation: The energy stored in a sensible heat storage system can be expressed as:

$$\mathbf{Q}=mc\Delta T$$

Q = is the heat energy stored (in joules),
m =is the mass of the storage medium (in kilograms),
c = is the specific heat capacity (in J/kg·K),
ΔT = is the change in temperature (in Kelvin).

3.1.2. Latent Heat Storage (LHS):

Uses phase-change materials that store or release large amounts of energy during melting or freezing, making them efficient for compact storage. Latent Heat Storage utilizes phase-change materials (PCMs) that absorb or release large amounts of energy during transitions between solid and liquid states (melting or freezing). Unlike SHS, where the temperature changes, LHS stores energy at an almost constant temperature during the phase transition, making it highly efficient for compact storage.

Mathematical Representation: The energy stored in a latent heat storage system can be expressed as:

$$\mathbf{Q}=m\mathrm{L}$$

Q = is the heat energy stored (in joules),
m =is the mass of the storage medium (in kilograms),
L = is the latent heat of fusion or vaporization (in J/kg).

3.1.3. Thermochemical Storage (TCS):

Thermochemical Storage is an advanced method that relies on reversible chemical reactions to store and release heat. During periods of surplus energy, an endothermic reaction absorbs heat, transforming reactants into products. These products can be stored at ambient temperature for extended periods. When energy is needed, the reverse (exothermic) reaction is triggered, releasing the stored heat. It employs reversible chemical reactions for even higher energy density and long-term storage, though this method is less commercially mature

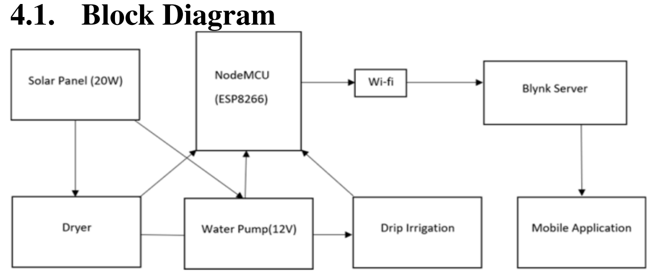
Mathematical Representation: The energy stored in a thermochemical storage system can be represented as:

$$\mathbf{Q}= n\Delta H$$

Q = is the heat energy stored (in joules),
n= is the number of moles of the reactants (in moles),
ΔH= is the enthalpy change of the reaction (in J/mol).

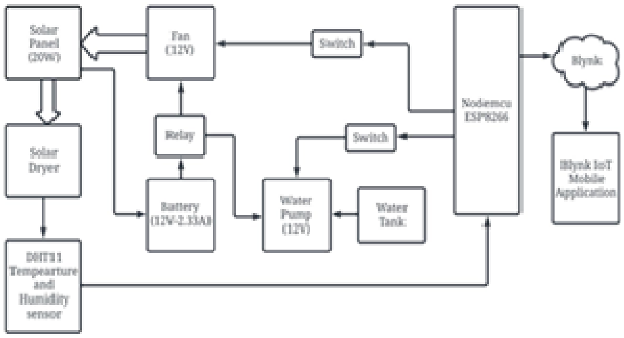
4. EXPERIMENTAL SETUP:

4.1. Block Diagram



The block diagram gives an overview of the system. The solar panel is connected to the dryer and the pump. The pump is further connected to an irrigation system. The dryer, pump and irrigation system are connected to the microcontroller. It is routed to the **YI IOT or Blynk server** using the microcontroller's internal Wi-Fi module. The mobile application (**YI IOT or Blynk IOT app**) gets the data.

4.2. System Architecture



The described system architecture integrates solar energy with automated control for efficient drying, leveraging several key components commonly found in modern solar dryer designs:

Solar Panel and Battery: The solar panel captures solar energy and charges the battery, providing a renewable power source for the system. This setup ensures continuous operation even during periods of low sunlight.

Relay-Controlled Exhaust Fan and Water Pump: The battery powers both the exhaust fan and the water pump through a relay, allowing for automated or remote switching. The relay acts as an electronic switch, enabling or disabling these devices based on control signals.

NodeMCU and YI IOT or Blynk IOT app Integration: The NodeMCU microcontroller connects to the Blynk app, allowing users to remotely control the water pump and exhaust fan via button controls on their smartphones. This adds IoT functionality, enabling real-time management and monitoring.

Airflow and Heat Transfer: The exhaust fan moves hot air from beneath the solar panel into the solar dryer chamber. This forced convection airflow is critical for efficient heat transfer and moisture removal, ensuring uniform drying and preventing spoilage.

Solar Dryer Chamber and DHT11 Sensor: The solar dryer houses a DHT11 sensor to monitor temperature and humidity, providing feedback for process optimization. The chamber is designed to retain heat and direct airflow over the products being dried, following best practices for solar dryer construction.

This architecture aligns with established solar dryer principles, which emphasize the conversion of solar energy to heat, the containment and direction of hot air, and the importance of controlled airflow for effective drying. The use of IoT controls via NodeMCU and Blynk app represents a modern enhancement, offering improved convenience and precision compared to traditional manual systems.

4.3. System Requirements

Hardware Requirements	Software Requirements
ESP 8266 microcontroller (NodeMcu) DHT11 Sensor 20W Solar Panel 12V Battery 12V Water Pump 12V Fan Wooden Enclosure Dryer box Connecting Wires Jumper Cables	Laptop Arduino IDE **YI IOT or Blynk IOT** app mobile application

4.4. Working principle:

The experimental setup for the IOT Based Solar Dehydration System with Energy Storage Material for Agricultural Products is shown in Fig. A 20 W solar panel is employed as the primary power source to generate electricity, which is stored in a 12 V, 2.33 Ah battery. This battery serves as the power supply for the 12 V DC water pump and 12 V DC exhaust fan. Both the water pump and fan are connected to the battery via a relay module, enabling automated or remote switching. The exhaust fan serves a dual function: it cools the solar panel to maintain optimal efficiency and pushes heated air through a pipe into the drying chamber.

Within the dryer, a DHT11 sensor continuously measures the temperature and humidity, ensuring proper monitoring of the drying environment. The solar panel is mounted within a wooden housing, while the drying chamber is constructed from cardboard. The drying chamber is the primary location for placing the food items for dehydration.

An IoT-based monitoring and control system is implemented using a NodeMCU ESP8266 microcontroller, which communicates via its built-in Wi-Fi module. The system is integrated with the Blynk IoT platform, allowing real-time data acquisition and remote control through a mobile application.

The DHT11 sensor readings can be monitored live, and the DC water pump and exhaust fan can be toggled on or off using virtual buttons within the Blynk app interface. This setup ensures energy-efficient operation, real-time monitoring, and remote control, making the system both user-friendly and suitable for off-grid applications.

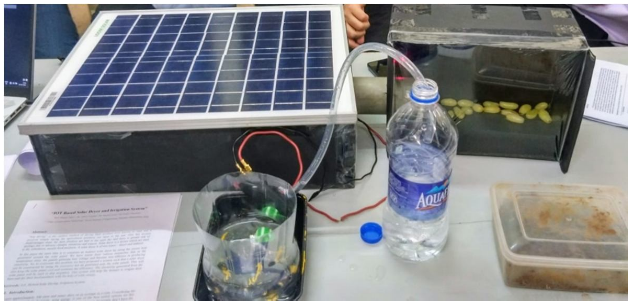


Fig: Experimental Setup of IOT Based Solar Dehydration System with Energy Storage Material for Agricultural products.

Figure 5: Blynk Application

The figure above shows the mobile application interface. The **Blynk IoT app** is utilized for **real-time monitoring and control** of the hybrid solar dryer system. Within the app interface, **two digital gauges** at the top display the **temperature and humidity** values received from the **DHT11 sensor**. Below these gauges, there are **two virtual buttons** dedicated to controlling the **DC water pump** and **DC fan**, allowing users to switch these components on or off remotely. This configuration enables intuitive interaction with the system and provides real-time feedback, enhancing the usability and efficiency of the drying process.

5. CONCLUSION

IoT-enabled solar dehydration systems integrated with energy storage materials present a robust and future-ready solution for agricultural drying. These systems enhance energy efficiency, minimize waste, and ensure consistent drying conditions. The integration of smart sensors, thermal energy storage, and cloud-based monitoring aligns well with sustainable agricultural practices.

Solar-powered systems offer significant long-term economic and environmental advantages over conventional energy sources. However, the performance of photovoltaic (PV) panels often declines due to heat accumulation. This article proposes an innovative approach that utilizes excess heat generated by solar panels in a solar dryer. By channeling the heat into the drying process, the system not only cools the PV panels to maintain optimal efficiency but also supports the preservation of crops and food products. This dual-functionality is particularly beneficial in agricultural applications.

The system features real-time monitoring and control through the Blynk IoT mobile application, enabling efficient, user-friendly operation. It is especially suited for deployment in rural areas where access to conventional energy sources is limited, providing farmers with a clean and sustainable alternative to traditional fuels.

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