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Solar-Powered Crop Drying with Automated Temperature and Humidity Control: A Comprehensive Analysis

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ABSTRACT: This article presents the conceptualization and development of an automatic temperature and humidity-controlled solar-powered crop drying system based on an Arduino Uno microcontroller [1], [2]. The system uses solar energy for power and employs sensors and actuators in combination to provide the best drying conditions in a controlled atmosphere. The main aim is to improve the quality and uniformity of stored agricultural products by optimized drying. The article features a critical overview of existing literature on solar drying of crops, a step- by-step explanation of the proposed model, design parameters, and comparative analysis with other conventional drying processes. Emphasis is given to energy efficiency, operational viability, and cost-effectiveness. The system shows the potential of large-scale solar drying to minimize post-harvest losses with the benefits of reduced drying times, improved product quality, and lower operating expenses as compared to open-air or fuel-based drying.

Keywords: Solar Crop Dryer, Automated Control, Arduino Uno, Temperature and Humidity Sensors, Post-Harvest Preservation, Renewable Energy Solutions.

1. Introduction

Preserving agricultural produce after harvest is essential for ensuring food availability and supporting sustainable farming. One of the critical challenges faced globally—especially in developing countries—is the significant loss of crops due to improper post-harvest handling, which leads to both a decline in quality and quantity. These losses have severe economic and social consequences, particularly in regions lacking access to modern preservation techniques [3], [4].

Drying is one of the oldest and most reliable methods for preserving agricultural goods. By lowering the moisture content to safe levels, drying effectively prevents microbial growth, enzymatic spoilage, and physical degradation of produce. Properly dried crops not only last longer but also retain their nutritional value and are more marketable, thereby improving farmers' income and food security.

In recent years, solar energy has become a promising solution for making the drying process more sustainable. As a widely available and eco-friendly resource, solar energy offers a clean alternative to conventional drying techniques that typically rely on electricity or fossil fuels— both of which contribute to higher costs and environmental pollution. Solar dryers, when designed effectively, can minimize energy consumption, reduce greenhouse gas emissions, and support environmentally responsible agricultural practices. This research explores how solar-powered systems with automated controls can further enhance drying efficiency and reliability [4].

2. Literature Survey

2.1 Solar Crop Dryer with Thermal Energy Storage (2023)

This study presents a solar drying system that integrates thermal energy storage (TES) to serve as a backup heat source for sorghum drying. Flake salt is used within aluminum pipes as a medium to retain thermal energy. The system aims to address the shortcomings of traditional sun drying, particularly in sub-Saharan Africa, where grain is often left out in open conditions, making it vulnerable to pests, weather, and contamination. The paper highlights TES as an effective approach to improve energy utilization and maintain drying consistency [5].

2.2 Hybrid Solar-Biomass Dryer for Agricultural Applications (2023)

This work introduces a dual-source dryer combining solar and biomass energy to enhance the drying of food items. The design, tailored for Pune’s climate, includes a solar chamber with multiple trays and a biomass chamber. It overcomes typical problems in open sun drying, such as direct exposure, pest infestation, and process inconsistency. Materials like mild steel, glass, and aluminum were employed to balance durability and efficiency [6].

2.3 Overview of Solar Drying Technologies for Agriculture (2023)

A review focused on the evolution of solar drying systems for post-harvest produce. It classifies different types of dryers, discusses their principles, and compares them with conventional drying methods. The paper emphasizes the growing relevance of solar drying for small-scale farmers, particularly in regions with abundant sunlight, citing benefits such as energy efficiency, product quality preservation, and cost-effectiveness [7].

2.4 Progress in Solar Drying Technologies: A Review (2022)

This research highlights how modern solar dryers aim to address the limitations of open-air drying. It evaluates the use of TES and biomass alternatives to extend drying periods beyond daylight hours. The study supports solar drying as a sustainable method to improve agricultural productivity and reduce spoilage [8].

2.5 Review on Solar Dryer Innovations (2022)

The study examines the ongoing improvements in solar dryer systems designed to mitigate common drying issues like contamination and inconsistent results. It discusses how using clean energy from the sun, along with auxiliary systems like TES and biomass heating, can enhance the process's reliability, making solar dryers a viable option for reducing post- harvest waste and enhancing food security [9].

2.6 Advanced Analysis of Solar Drying Mechanisms (2025)

This paper critically analyzes the working mechanisms of solar dryers, including airflow dynamics, energy conversion, and heat transfer models. It also assesses the impact of TES and microcontroller-based control systems on drying performance. The study underlines the need for adaptive designs to handle diverse climatic conditions and crop types [10].

3. Methodology

The novelty in design for the crop drying system for use with the sun lies through a systematic, multi-level approach to effective, automated control over drying conditions. The central theme lies in leveraging clean solar energy, integrated sensing of the environmental parameters, and intelligent automation of control over the drying process. The first step is energy harvesting. Solar panels are used to harness sunlight and transform it into electrical energy by the photovoltaic effect. The energy obtained is controlled by a charge controller to charge the installed 12V battery efficiently and without overcharge and deep discharge hazards. The battery is a reserve power source, allowing system operation even on cloudy days and at night. For environmental sensing, the system consists of a DHT22 digital sensor, which can sense the temperature and humidity levels in the drying chamber accurately [12]. The data of the measurements are communicated to the Arduino Uno, which serves as the system controller [11], [12]. The microcontroller runs a control logic from pre-defined temperature and humidity levels to decide whether to turn on or off the fan and heater. The Arduino code can be programmed to set individual temperature and humidity thresholds, giving the system the ability to adapt to different crops and drying requirements. Real-time conditions inside the chamber are displayed on an LCD screen, allowing users to monitor performance at all times [11]. When the environmental conditions surpass the desired level— for example, when humidity is higher than or temperature lower than the optimal levels—the Arduino reacts by switching on the fan or heating device accordingly. The moment the optimal drying conditions are regained, the system automatically switches off these devices, saving unnecessary power consumption and maximizing energy efficiency. This closed-loop control system maintains the drying chamber in its ideal environment, yielding quicker drying, less energy wasted, and better crop conservation.

4. Proposed System

The suggested solar-powered crop drying system combines various constituents and control systems to develop a dependable, efficient, and self-sustaining drying system. The system is made to operate on solar energy without external interference and also dynamically adjust according to drying chamber ambient conditions [15].

Integrated into the system is solar energy harvesting. Solar irradiance is captured by photovoltaic (PV) panels and is converted to direct current (DC) power. The power is controlled by a charge controller, stabilizing voltage and current output to a 12V rechargeable battery. Reliability in power supply from the battery guarantees power supply even at low solar intensity or at night, making the system not dependent on external power supplies.

The system continuously monitors the internal conditions within the chamber using a DHT22 temperature and humidity sensor [12]. The sensor provides digital output that signifies the environmental conditions prevailing in the environment at present within the dryer. The data is processed using an Arduino Uno, which runs preloaded control programs. The Arduino, with the data from the sensor, determines whether to switch on or off devices such as fans and heating coils.

These pre-programmed thresholds—like humidity above 60% or below 30°C temperature— can be adjusted by users themselves via the Arduino code for flexibility for various crop types and for particular drying requirements [13].

An LCD module shows real-time information, e.g., temperature and humidity at the moment, to inform users of the drying process. The automation logic in the system provides the best conditions by turning the fan and heating element on or off as necessary. The closed-loop system not only enhances drying efficiency but also conserves power by turning devices off once optimal conditions are achieved. In essence, the solution combines solar power and intelligent automation to maximize the efficiency and sustainability of crop drying— minimizing human interference, energy expense, and post-harvest loss.

5. Design Overview

The solar-powered crop dryer system has been conceptualized to offer an efficient, automated, and eco-friendly solution for drying agricultural produce. It addresses the limitations of conventional drying methods by leveraging solar energy and intelligent control mechanisms. The system's design integrates multiple modules, each contributing to the overall performance and sustainability of the drying process.

5.1 Solar Energy Collection and Conversion

Photovoltaic (PV) Panels: The system uses an array of solar panels to convert sunlight into DC electricity through the photovoltaic effect.

Panel Design Considerations: Size & Number: Depends on energy demands, drying capacity, and local sunlight availability.

Orientation & Angle: Optimized for maximum daily and seasonal sunlight exposure.

Type: The panel type—monocrystalline, polycrystalline, or thin-film—is selected based on cost-efficiency, performance, and local climate conditions [15].

5.2 Energy Management and Storage

Charge Controller: Regulates energy flow from the solar panels to the battery.

MPPT (Maximum Power Point Tracking): Enhances energy conversion efficiency by adjusting to optimal voltage and current levels.

Battery Protection: Prevents overcharging or excessive discharge, thereby extending battery life.

Battery Bank: Stores energy for continuous operation during low-light conditions.

Selection Criteria: Battery technology (lead-acid or lithium-ion), storage capacity, cycle life, and cost.

5.3 Drying Chamber and Airflow Control

1. Drying Chamber:

Airflow Optimization: Chamber layout is designed to promote uniform airflow across crops.

Thermal Insulation: Minimizes heat loss to improve energy use.

Material Choice: Durable, food-safe, and corrosion-resistant materials are preferred. Ventilation System:

Fans: Generate airflow within the chamber.

Fan Selection: Based on desired airflow rate and system pressure.

Air Ducts and Vents: Strategically placed to guide airflow efficiently across the drying surface.

5.4 Environmental Monitoring and Control

1. Sensors:

DHT22: Continuously tracks chamber temperature and humidity with high precision [12].

Optional Add-ons: Sensors for airflow rate or crop moisture content may be included for enhanced control.

Control Unit: Arduino Uno Microcontroller: Reads sensor inputs and executes the control logic. Regulates the fan and heating element based on real-time data. Offers options for data logging or future integration with IoT systems [14].

Control Logic: Uses simple threshold or PID-based algorithms to maintain ideal drying conditions. Allows adjustment of temperature and humidity targets via Arduino code [11].

5.5 Auxiliary Heating (Optional)

Heating Element: Supplements solar heat during overcast days or when higher temperatures are required for certain crops. Controlled by the Arduino to maintain precise temperature levels.

5.6 User Interface and Display

LCD Display: Shows real-time data including chamber temperature and humidity. Helps users track system status and environmental conditions.

Optional Input Controls: Switches, buttons, or keypads may be included for user-defined settings like threshold values or manual overrides.

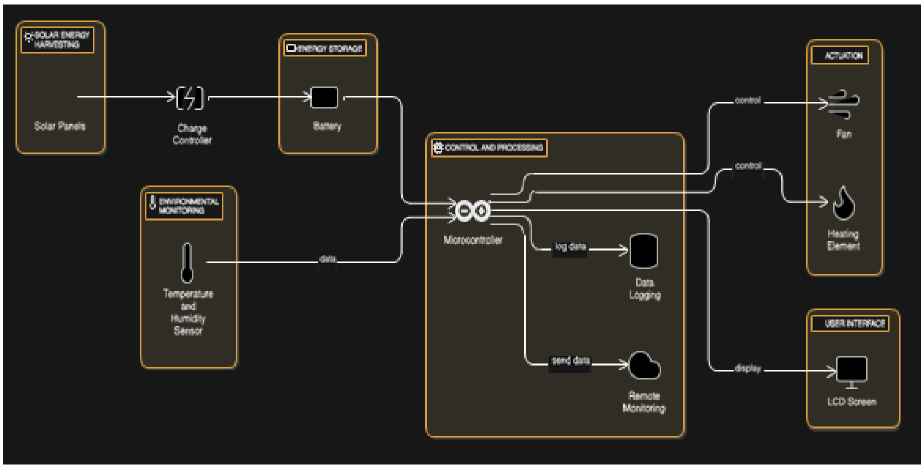

Figure 1: *Design Overview*

6. System Architecture

The solar-crop drying system is based on a modular design that integrates online monitoring, automated control, renewable energy harvesting, and user interface. The system has been engineered to dry farm produce in a controlled manner and efficiently, irrespective of the weather outside.

6.1 Solar Energy Subsystem

Solar Panels: Solar panels are the primary power source, which generates DC electricity from sunlight through the photovoltaic effect. The energy output is a function of the number and efficiency of the panels, their orientation, and the local solar irradiance.

Charge Controller: This regulates the movement of electricity from the panels into the battery. Its functions are:

- Prevention of overcharging the battery.
- Safeguarding against deep discharge.
- Highest charging efficiency, particularly if it has MPPT (Maximum Power Point Tracking) technology.

6.2 Energy Storage Subsystem

12V Battery: Acts as the storage component of the electrical energy. It ensures that the system can function day and night—even during nighttime or low sunlight hours. The battery capacity will dictate how long the dryer can be operated without solar power.

6.3 Environmental Monitoring Subsystem

DHT22 Sensor: Measures temperature and humidity inside the drying chamber. It gives digital signals proportional to the readings at that moment, which are processed using the control unit. Key features are:

- Quick response time and high precision.
- Proper communication with the microcontroller.

6.4 Control and Processing Subsystem

Arduino Uno: Acts as the system's central processing unit. It is accountable for:

- Reading sensor input data.
- Making decisions based on pre-programmed logic.
- Sending commands to actuators (fan and heater) for regulation of the desired environment.
- Showing system information on the LCD display and controlling user-defined thresholds [11] [16].

6.5 Actuation Subsystem

Fan: Provides effective air circulation throughout the drying chamber. Adequate airflow removes moisture from the surface of the crop and helps in uniform drying.

Heating Element: Triggers whenever the ambient temperature is below the threshold set. It helps in the drying process during low-sunlight periods or cold temperatures.

Both units are governed by the Arduino, depending on the environmental input of the DHT22 sensor.

6.6 User Interface Subsystem

LCD Display: Offers instant internal temperature and humidity feedback. Users can track drying conditions and system performance without having to monitor constantly manually [17].

Optional Controls: In more sophisticated versions, setpoints can be reset or overrides started manually through switches or buttons.

6.7 System Operation Flow

1. Energy Production: Solar panels harness sunlight and transfer it into electrical energy.
2. Power Regulation: The charge controller delivers this power to the battery in a secure way.
3. Sensor Input: The DHT22 is constantly taking environmental readings from within the drying chamber.
4. Control Execution: Sensor inputs are read by the Arduino and compared with predetermined thresholds.
5. Actuation: The heating element and fan are actuated according to the data to give the best drying conditions.
6. User Feedback: The LCD provides the user's current humidity and temperature levels to inform the user.

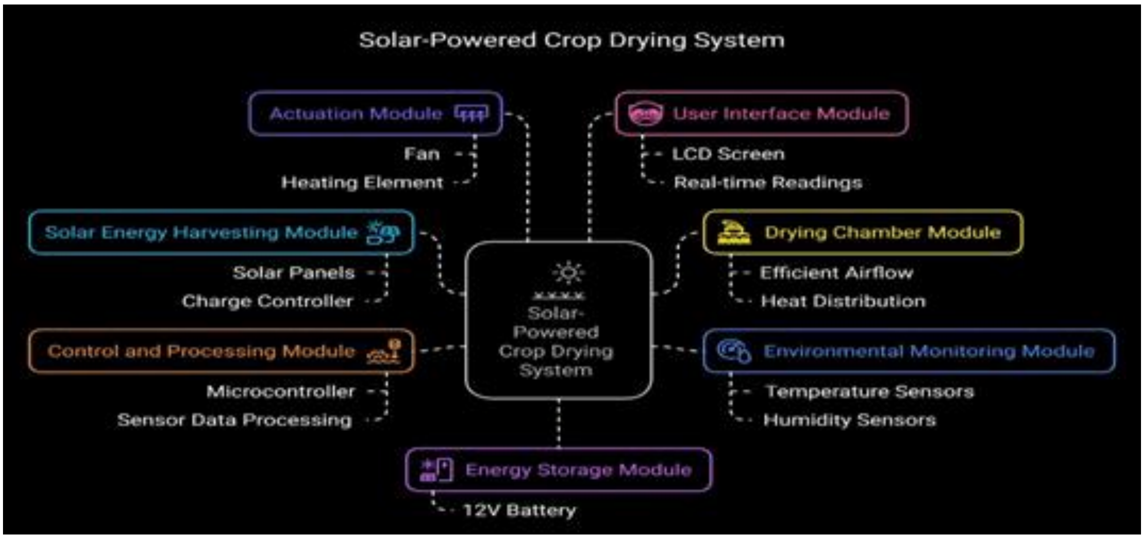

Figure 2: *System Architecture*

7. Requirements

The solar-powered crop drying system includes functional and non-functional specifications in order to execute proper performance, independence, and simple interaction. These specifications play a significant role in guaranteeing efficient and successful drying of the crops.

7.1 Functional Requirements

1. Solar Energy Generation- The system should use solar panels to capture electricity from the sun to energize all system parts.
2. Energy Storage- A 12V battery will be required to store the accumulated energy collected and supply energy in low sunlight or nighttime conditions.
3. Power Regulation- A charge controller will have to regulate the charging, preventing the battery from overcharging or complete discharge.
4. Temperature Monitoring- The system must constantly check temperature inside the drying chamber to ensure optimum conditions.
5. Humidity Monitoring- Real-time monitoring

of humidity is necessary for effective control of the drying process.

6. Sensor Integration- A DHT22 sensor is employed to sense temperature and humidity precisely.
7. Data Processing Unit- A microcontroller within an Arduino Uno processes sensor information and controls the system in accordance with pre-programmed rules.
8. Fan Activation (High Humidity)- When humidity is more than 60%, the system has to activate the fan to help in moisture removal.
9. Fan Deactivation (Optimal Humidity)- When humidity is at 60% or below, the fan must be switched off in order to save energy.
10. Heater Activation (Low Temperature)-,If the chamber temperature drops below 30°C, then the heating element must be activated to allow for optimal drying.
11. Heater Deactivation (Adequate Temperature)- If the ambient temperature is 30°C or more, the heating element should be turned off to save power.
12. LCD Display for Temperature- The system must display actual temperatures on an LCD display for the user's reference.
13. LCD Indicator of Humidity- The level of humidity must also be displayed to enable users to track changes around them.
14. User Monitoring Interface- The screen must enable users to view system status and drying conditions clearly.
15. Automatic Fan Control- The system must regulate the fan automatically based on current humidity levels [11], [17].
16. Automatic Heater Control- Equally, the heating coil must be automatically controlled by the prevailing temperature conditions.
17. Variable Thresholds- The temperature and humidity set points should be adjustable with adjustments to the Arduino programming if necessary to match the crop requirements.

Non-Functional Requirements-

18. Energy Conservation- The system should reduce unwanted power usage by shutting down components once the ideal conditions are reached.
19. Autonomous Operation- It should be autonomous, being powered by solar power and batteries, with minimal human intervention.
20. Drying Efficiency- The process should provide efficient moisture elimination without compromising crop quality [17].
21. Real-Time Monitoring- Users need to be able to track the system's performance via seemingly real-time, apparent data on the LCD display.
22. System Flexibility- The system would enable users to adjust drying parameters for various agricultural commodities or conditions.

8. Working

The solar-powered crop drying system is designed to create a controlled environment for effective moisture removal from agricultural produce. It relies on multiple interconnected subsystems that function together to maintain consistent drying conditions.

8.1 Solar Power Generation

The system starts by using solar panels to capture energy from sunlight. These panels convert solar radiation into direct current (DC) electricity through the photovoltaic process. The choice of panel type—monocrystalline, polycrystalline, or thin-film—is based on factors such as efficiency, cost, and environmental suitability.

8.2 Energy Regulation and Storage

A charge controller regulates the electrical energy coming from the solar panels. It ensures the connected 12V battery is charged safely, preventing overcharging or deep discharge, both of which could reduce battery life. The stored energy enables the system to operate continuously, including during periods of low sunlight or at night.

8.3 Environmental Monitoring

Inside the drying chamber, a DHT22 sensor constantly measures the current temperature and humidity. The sensor is chosen for its high accuracy and wide operating range. It transmits digital data to the control unit for further processing.

8.4 Automated Control Logic

The Arduino Uno acts as the central controller for the entire system. Based on the sensor data, it applies pre-defined logic to decide how to operate the fan and the heating element [11], [18].

- If humidity levels rise above 60%, the Arduino triggers the fan to circulate air and remove excess moisture.
- If the temperature drops below 30°C, it activates the heater to warm the drying chamber.
- When both values return to their ideal ranges, the fan and heater automatically shut off to preserve energy.

These thresholds can be adjusted by modifying the Arduino code, allowing users to tailor the system to specific crop requirements.

8.5 User Interface

A real-time LCD screen displays the current temperature and humidity readings from the drying chamber. This feature allows users to monitor internal conditions and system behavior without needing manual measurements.

8.6 Automatic Adjustments

The fan and heating coil operate in response to live sensor data, turning on and off as needed. This automatic adjustment ensures a consistent drying environment, maximizing energy efficiency and minimizing user intervention [13], [18].

Summary:

By integrating solar power with sensor-driven automation, the system ensures optimal drying conditions. It maintains consistent airflow and temperature, effectively reduces moisture, and minimizes energy consumption — making it a smart, sustainable solution for post-harvest processing.

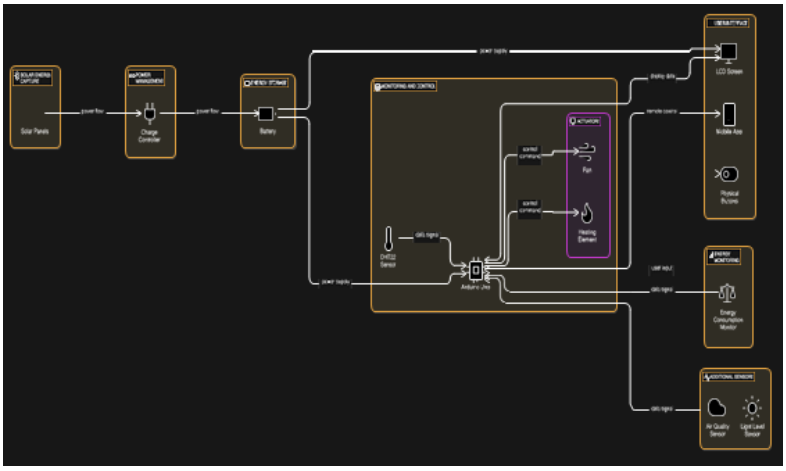

Figure 3: *Working*

9. Conclusion

This study underscores the significant advantages of solar-powered crop drying systems over traditional methods, particularly those reliant on open-air sun drying. The analysis highlights how indirect solar drying techniques can lead to faster drying rates, better moisture removal, and superior preservation of crop quality. These benefits contribute to reduced post-harvest losses, enhanced nutritional retention, and improved marketability of the final product.

The integration of automation through microcontrollers like the Arduino Uno plays a crucial role in elevating system efficiency and reliability. By maintaining optimal temperature and humidity levels, the system prevents issues like under- or over-drying, ensuring consistent and high-quality results [1], [9] ,[18].

The prototype developed in this research effectively combines key elements—renewable energy harvesting, sensor-based monitoring, and automated control—into a cohesive, sustainable drying solution. With solar power as its primary energy source and battery storage to support continuous operation, the system offers an eco-friendly and potentially cost-saving alternative to fuel-based methods.

Key innovations include the use of a DHT22 sensor for accurate environmental monitoring, programmable control logic via Arduino, and a user-friendly LCD display for real-time feedback. Collectively, these components create a smart system that adapts to changing conditions and specific crop needs.

Future research could focus on enhancing the system's performance further through the use of advanced solar technologies (like thin-film or concentrated photovoltaics), high-efficiency battery systems, and more intelligent control algorithms such as adaptive or predictive models. Incorporating thermal energy storage (TES) could also help extend drying capability beyond daylight hours. Comprehensive field trials across varied climates and crop types are recommended to fine-tune the system and establish its global scalability [10], [19].

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