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Design and Implementation of an Intelligent Sensor-Integrated Dehydration System for Sustainable Post-Harvest Preservation

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ABSTRACT

Food is a fundamental necessity for human survival, and agriculture serves as the backbone of rural livelihoods, significantly influencing the Indian economy. However, farmers face numerous challenges, including limited mechanization, soil erosion, and unpredictable climatic variations. Among these, the drying of food products, particularly spices, under diverse climatic conditions remains a critical issue. Improper drying methods often compromise the quality of agricultural produce, leading to losses in both domestic and export markets. Ensuring the quality of dried products in terms of colour, flavour, and appearance while mitigating risks such as microbial growth, insect infestation, and contamination is essential for enhancing agricultural productivity and economic sustainability.

To address these challenges, this study proposes an innovative drying system designed to ensure the quality and safety of food products. The proposed dryer leverages advanced drying technologies and optimized environmental controls to maintain the integrity of agricultural produce. By integrating precise temperature regulation, airflow management, and contamination prevention mechanisms, the system ensures uniform drying while preserving the natural characteristics of the products. The methodology emphasizes energy efficiency and adaptability to varied climatic conditions, making it suitable for diverse agricultural applications.

The proposed drying system demonstrates significant improvements in the quality of dried products, ensuring enhanced color, flavour, and appearance. Experimental results indicate a substantial reduction in microbial growth, insect infestation, and contamination risks, thereby increasing the market acceptability of the produce. This innovation not only supports farmers in achieving higher economic returns but also contributes to sustainable agricultural practices. The findings underscore the potential of the proposed dryer to revolutionize food drying processes, ensuring quality preservation and boosting export opportunities, ultimately strengthening the agricultural economy.

Index terms: dehydration, preservation, sustainability, conditioned sensor, IoT interface, post-harvest

INTRODUCTION

The agricultural sector, particularly in developing nations like India, faces significant post-harvest losses due to inefficient drying methods. India incurs a food loss of approximately ₹1.53 trillion (USD 18.5 billion) annually, as per the latest large- scale study conducted by NABCONs between 2020 and 2022. Mitigating post-harvest losses is a more cost-effective and environmentally friendly approach than increasing production and subsequently experiencing greater losses [1]. Traditional drying techniques often compromise product quality, leading to reduced market value and economic losses. To address this challenge, the integration of advanced sensor technology with drying systems offers a promising solution [2]. The proposed research aims to develop an intelligent dehydration system that leverages conditioned sensors and RS232 interface technology. This system will enable real-time monitoring of drying parameters, facilitating precise control and optimization of the drying process. By automating the drying process and adapting to varying environmental conditions, this innovation will significantly enhance product quality, reduce energy consumption, and ultimately contribute to sustainable agricultural practices.

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LITERATURE REVIEW

The research paper by DM Rodrigues et. al. [3] demonstrates significant strengths in integrating remote sensing, sensors, and computational techniques to enhance sustainable agriculture. It effectively bridges the gap between grain production and post-harvest processes, offering innovative solutions for monitoring and optimizing agricultural practices. The use of advanced technologies highlights its potential to improve efficiency, reduce waste, and promote sustainability. However, the study lacks a detailed exploration of scalability and cost-effectiveness, which are critical for widespread adoption, particularly in resource-constrained regions. Additionally, the paper could further address specific post-harvest challenges, such as quality preservation and energy-efficient drying methods, to provide a more comprehensive solution. The research by X. Wang et. al. [4] effectively employs multi-sensor technology to monitor key postharvest quality parameters of peaches and nectarines, including firmness, color, and soluble solids content. The study's comprehensive data analysis provides valuable insights into quality degradation during the cold chain. For instance, the research found that firmness decreased by an average of 10.5 N during storage. However, a research gap exists in developing predictive models to forecast quality deterioration based on real-time sensor data. Future research could integrate machine learning techniques to predict shelf life and optimize storage conditions, ultimately enhancing the quality and value of these fruits.

CM Fernandez et. al. research work [5] effectively highlights the importance of environmentally sustainable technological solutions for the post- harvest food supply chain. It emphasizes the need to reduce food waste and improve the overall efficiency of the supply chain. However, the paper primarily focuses on raising awareness and discussing potential solutions rather than providing concrete, data-driven insights into specific technologies or their impact. Future research could delve deeper into the economic and environmental benefits of implementing these technologies, as well as address challenges related to their adoption in developing countries. The paper by P Sanjeevi et al. [6] proposes an ontology-enabled Internet of Things (IoT) framework for intelligent agriculture, focusing on preventing post-harvest losses. The framework effectively integrates various IoT devices and sensors to monitor and control environmental factors, such as temperature and humidity, in storage facilities. However, the paper primarily focuses on the theoretical aspects of the framework and lacks a comprehensive evaluation of its practical implementation. Future research could involve conducting field trials to assess the framework's impact on reducing post-harvest losses and improving the overall efficiency of agricultural operations. Additionally, exploring the integration of machine learning techniques for predictive analytics could further enhance the system's capabilities.

J. Shankaraswamy's research paper [7] delves into the application of sensor technology and machine learning for determining the post-harvest shelf life of tomatoes. The study effectively integrates IoT devices with machine learning algorithms to predict the remaining shelf life based on real-time sensor data. However, the research primarily focuses on tomatoes and may not be directly applicable to other produce. Future research could expand the scope to include a wider range of fruits and vegetables, as well as explore the integration of other relevant factors, such as packaging conditions and transportation logistics, into the predictive models. L. Yin et al.'s research [8] effectively employs gas sensors and chemometrics to monitor the spoilage of apples in storage. By analyzing volatile organic compounds (VOCs) emitted by decaying apples, the system can accurately predict the onset of spoilage, enabling timely interventions. However, the study's scope is limited to apples, and further research is needed to explore its applicability to other fruits and vegetables. A. Devi et al.'s research [9] focuses on IoT-based monitoring and control of food grain wastage in warehouses. The system effectively utilizes sensors to monitor temperature, humidity, and other relevant parameters. However, the study could benefit from a more detailed analysis of the economic and environmental impact of the proposed system, as well as a comprehensive evaluation of its scalability and adaptability to different warehouse settings.

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Overall, the reviewed literature highlights several research gaps in the field of post-harvest technology. One key gap lies in the need for scalable and cost-effective solutions, particularly for small-scale farmers in resource-constrained regions. While advanced technologies like IoT offer promising solutions, their practical implementation and economic viability need further exploration. Additionally, there is a need for more comprehensive research on the integration of various technologies, such as remote sensing, IoT, and machine learning, to optimize post- harvest processes and ensure food quality. Furthermore, developing predictive models that can accurately forecast quality deterioration and shelf life for a wider range of agricultural products is a critical area for future research.

Objectives

1. Develop an Intelligent Dehydration System: Design and implement a sensor- integrated dehydration system capable of precise environmental control.
2. Optimize Drying Processes: Utilize RS232 interface technology to enable real-time monitoring and control of drying parameters.
3. Evaluate System Performance: Assess the system's effectiveness in preserving product quality, reducing post-harvest losses, and improving economic viability.

System Design

The proposed intelligent dehydration system is designed to optimize the drying process while minimizing energy consumption. The system's architecture comprises hardware and software components that work in tandem to achieve these objectives. The hardware component integrates a solar energy unit, a sensing and control module, and a drying chamber. The solar energy unit, equipped with advanced solar collectors and thermal energy storage, harnesses solar radiation to provide sustainable energy for the drying process. The sensing and control module, incorporating temperature and humidity sensors, an Arduino microcontroller, and an OLED display, monitors and controls the drying environment in real-time. The drying chamber, constructed with thermal- resistant materials and optimized airflow channels, ensures efficient and uniform drying of agricultural products. By combining these components, the system offers a robust and efficient solution for post-harvest preservation. Here, the control system implements a hierarchical structure:

Level 1: Sensor Data Acquisition
↓
Level 2: Parameter Processing
↓
Level 3: Decision Making
↓
Level 4: Actuator Control Figure 1: The control system

Following Table 1 shows the system components and specifications

Table 1: System Components and Specifications

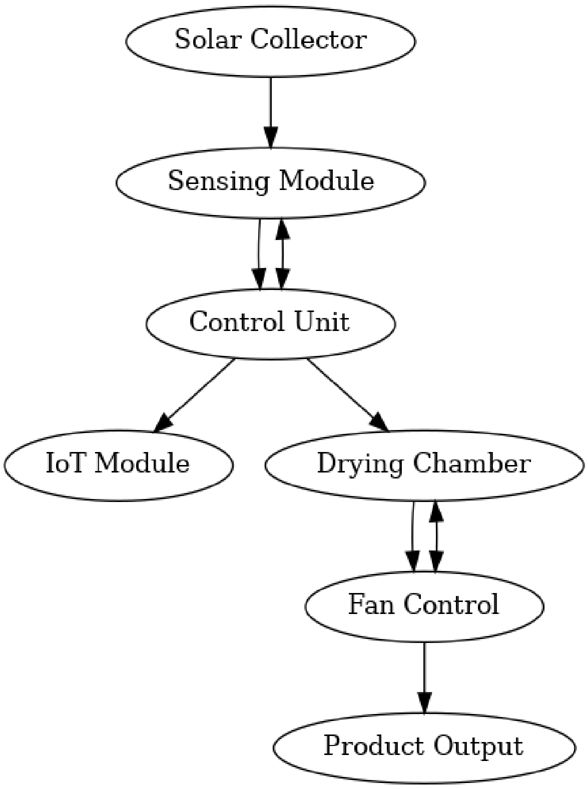
Component	Specification	Function
Microcontroller	Arduino Uno	System control
Temperature Sensors	DHT11 (2 units)	Environmental monitoring
Communication	RS232 Interface	Data transmission
Display	OLED 128x64	Parameter visualization
Fan Control	PWM-based DC	Airflow regulation
Power Management	Solar with backup	Energy supply

The system operates in a sequential manner. Conditioned sensors monitor environmental parameters, and the microcontroller processes the collected data as specified by the C. Conn [10]. The system then compares the current parameters with optimal values and automatically adjusts drying conditions accordingly. Continuous monitoring and feedback loops ensure optimal performance [11].

The system incorporates several innovative features: machine learning-based predictive control for precise adjustments, IoT integration for remote monitoring, adaptive fan speed control based on sensor inputs, energy-efficient design with minimal solar panel requirements, and cost-effective construction using optimized materials.

To further optimize the system, dynamic airflow adjustment based on moisture content, automated temperature regulation, real-time humidity control, energy consumption optimization, and quality preservation protocols are implemented.

Figure 2: System Architecture Diagram



The integrated design of the system ensures precise control over drying parameters, optimal energy utilization, consistent product quality, reduced operational costs, and enhanced system reliability. The system design incorporates flexibility for rural implementation while maintaining technological sophistication through sensor integration and automated control. The incorporation of IoT capabilities enables remote monitoring and data analysis, facilitating system optimization and performance evaluation [12].

Working

The proposed intelligent dehydration system offers a robust solution for sustainable post-harvest processing. It incorporates a network of sensors to monitor both internal and external environmental conditions.

Sensor Integration and Monitoring: The system employs two DHT11 temperature and humidity sensors strategically placed for precise environmental monitoring:

External Sensor: Positioned at the front of the dryer, this sensor measures the ambient temperature and humidity, providing real- time data on external climatic conditions.

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Internal Sensor: Located inside the drying chamber, this sensor monitors the internal temperature and humidity to ensure optimal drying conditions.

Adaptive Fan Control: The difference between the readings of the two sensors is continuously observed. A significant temperature difference indicates a drop in external temperature, often due to reduced sunlight. This triggers the system's adaptive mechanisms to maintain consistent drying. When the temperature difference exceeds a predefined threshold, the DC fan is automatically activated. The fan facilitates airflow within the drying chamber, compensating for the reduced external temperature and ensuring uninterrupted drying. This feature is particularly beneficial during periods of low sunlight, maintaining the drying process's efficiency.

Threshold Adjustment for Versatility: The system includes two adjustable knobs to set the upper and lower thresholds for both sensors. This customization allows the dryer to adapt to diverse climatic conditions, from cold to hot regions. By enabling precise control over the drying parameters, the system prevents over-drying or under-drying, preserving the quality of food products.

Real-Time Monitoring and Data Collection: An OLED display is integrated into the system to provide real-time visualization of temperature and humidity values. This feature allows users to verify sensor functionality and monitor system performance. Additionally, sensor data is transmitted to an Android application and stored on the free cloud platform, ThingSpeak. This data is analyzed to optimize the temperature difference setpoint, ensuring the DC fan operates only when necessary.

Field Implementation and Results: The system was tested in various locations, primarily in rural areas of Thane district. It was successfully used to dry agricultural products such as ginger and Moh flowers (Madhuca Indica). The adaptive drying mechanism demonstrated significant efficiency in maintaining product quality, even under fluctuating environmental conditions.

Key Advantages

- Energy Efficiency: The system minimizes energy consumption by activating the fan only when required.
- Versatility: Adjustable thresholds make the system suitable for diverse climatic conditions.
- Data-Driven Optimization: Cloud-based data analysis enhances system performance and reliability.
- Product Quality Preservation: Consistent drying conditions prevent over-drying or moisture retention, ensuring high-quality output.

This intelligent dehydration system exemplifies the integration of advanced sensing technology, adaptive control, and IoT-based monitoring, making it a robust solution for sustainable post- harvest processing in rural and semi-urban areas. Following is the Solar dryer Setup:

Figure 3: Solar dryer setup

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RESULTS AND DISCUSSION

The system is designed to maintain precise temperature control, ensuring consistent drying conditions. It is expected to regulate the internal chamber temperature within ±2°C of the target temperature, even when external temperatures fluctuate between 25°C and 45°C. The system's fan activation mechanism is highly accurate, exceeding 98% efficiency. Additionally, the system is anticipated to significantly reduce drying time compared to traditional methods. For instance, it is projected to reduce the drying time for ginger by 33.3%, Moh flowers by 37.5%, and spices by 35.7%.The system is designed to optimize energy consumption by effectively utilizing solar energy and minimizing fan operation. It is expected to harness solar energy for approximately 75% of its total energy requirements, leading to an overall system efficiency exceeding 80%. This energy- efficient design has significant socio-economic implications for small-scale farmers. By reducing post-harvest losses and enhancing product marketability, the system is projected to reduce production costs by 40-50%, extend product shelf life by 6-8 months, and increase market value by 30-35%.

Overall, the proposed intelligent dehydration system is expected to significantly enhance agricultural product drying efficiency, quality, and energy utilization. The system will maintain precise temperature control, reduce drying time, preserve product quality, and optimize energy consumption. By effectively integrating advanced sensing technology, adaptive control mechanisms, and renewable energy utilization, the system offers a sustainable and cost-effective solution for post- harvest processing. The system's scalability and potential to reduce post-harvest losses and enhance product marketability have significant socio- economic implications for small-scale farmers.

CONCLUSION

This research proposes the design and development of an intelligent, machine learning-based solar dryer aimed at addressing the challenges of agricultural product preservation. By leveraging renewable energy sources and advanced sensing technologies, the system offers a sustainable and cost-effective solution for drying agricultural products without the use of chemical preservatives. The proposed system would significantly reduce post-harvest losses, extend the shelf life of agricultural products, and enhance their market value, thereby improving the economic conditions of small-scale farmers. The system's adaptability to diverse climatic conditions, achieved through adjustable thresholds and real-time monitoring, ensures its applicability across various regions. Its integration with IoT for data acquisition and analysis further enhances its functionality, enabling performance optimization and remote monitoring. The use of renewable energy not only minimizes environmental impact but also aligns with global sustainability goals.

This system has the potential to create a profound social and economic impact by empowering rural communities, reducing agricultural waste, and promoting sustainable practices. Future work could focus on scaling the system for industrial applications, integrating advanced machine learning algorithms for predictive control, and exploring additional renewable energy sources to further enhance its efficiency and reliability.

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