International Journal of
DATA SCIENCE AND IOT MANAGEMENT SYSTEM
Peer Reviewed, Referred & Indexed Journal
ISSN: 3068-272X www.ijdim.com Original Research Paper

An Edge-Embedded Microcontroller Architecture for Grain Moisture State Estimation and Adaptive Drying Process Regulation

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ABSTRACT

Grain drying is a crucial post-harvest operation that significantly affects storage life, quality, and market value of agricultural produce. Traditional drying methods, mainly based on open sun exposure, are highly dependent on climatic conditions and require extensive manual effort, often resulting in uneven drying, contamination, and increased post-harvest losses. These limitations create the need for a more controlled, efficient, and reliable drying system. To address this issue, the proposed work presents an automated temperature-controlled harvester developed using the Raspberry Pi Pico microcontroller (RP2040-based microcontroller board). The system incorporates environmental monitoring through temperature and humidity sensors to continuously observe internal conditions within the drying chamber. Based on real-time data, the controller regulates heating and airflow mechanisms to maintain optimal drying parameters, ensuring uniform moisture removal and preventing over-drying or under-drying. The integration of a fan system and controlled heating element enhances air circulation and thermal distribution, improving drying efficiency. Additionally, the system includes a user-friendly interface that allows farmers to customize drying settings according to crop requirements. Emphasis is also placed on energy-efficient operation to reduce power consumption while maintaining performance. The proposed system offers a cost-effective, scalable, and sustainable alternative to conventional methods, improving grain quality, minimizing losses, and increasing overall agricultural efficiency. This intelligent approach supports the advancement of modern farming practices through automation and precise environmental control.

Keywords: Grain Drying, Raspberry Pi Pico (RP2040), Temperature Control System, Humidity Monitoring, Automated Agriculture, Post-Harvest Technology, Embedded Systems.

1. INTRODUCTION

Conventional grain drying approaches, particularly those dependent on natural sunlight and open-air exposure, suffer from major drawbacks in reliability and uniformity. Since these methods rely entirely on external environmental conditions, they are highly sensitive to sudden weather changes such as rain, humidity fluctuations, and inconsistent airflow. This often results in uneven drying, where some portions of the grain remain moist while others become overly dry, ultimately affecting storage life and quality. In addition, the process demands continuous human supervision for spreading, turning, and protecting the grains, making it labor-intensive and inefficient for large-scale agricultural operations. These challenges frequently lead to post-harvest losses, reduced market value, and increased effort for farmers.

To overcome these limitations, an advanced automated drying system has been designed using the Raspberry Pi Pico as the central processing unit. This system establishes a controlled internal environment where key parameters such as temperature and humidity are continuously monitored using dedicated sensors. Based on the collected data, the microcontroller intelligently regulates heating elements and ventilation systems to maintain optimal drying conditions. The heater ensures that sufficient warmth is provided to remove moisture effectively, while the fan enables proper air circulation to distribute heat evenly across all grains. This closed-loop mechanism allows real-time adjustments, ensuring that the drying process remains stable and consistent even when external conditions change unpredictably.

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The system also incorporates programmable control logic, allowing users to define desired temperature thresholds and operational settings according to the type of grain being processed. This adaptability ensures that different crops can be handled efficiently without compromising quality. Furthermore, safety mechanisms can be integrated to prevent overheating or excessive moisture removal, thereby protecting the grains from damage. The overall design focuses not only on performance but also on usability, making it accessible for practical deployment in agricultural environments.

From an operational perspective, this automated solution significantly reduces the need for manual intervention, saving both time and labor costs. It also enhances energy efficiency by supplying heat and airflow only when required, avoiding unnecessary power consumption. Consistent drying conditions help inhibit the growth of mold, bacteria, and other contaminants, thereby extending shelf life and improving storage stability. As a result, farmers can achieve higher-quality output with reduced wastage and better economic returns.

In summary, this intelligent drying system represents a modern, efficient, and sustainable alternative to traditional practices. By combining sensing technology, automated control, and optimized resource usage, it ensures precise and reliable grain drying. This innovation not only improves productivity and crop quality but also aligns with the growing need for smart agricultural solutions that can handle real-world challenges effectively.

2. LITERATURE REVIEW

Sreedhar Reddy, et al. [1] conducted an in-depth evaluation of a mobile paddy drying system under real operational conditions using a large quantity of freshly harvested grain. Their analysis focused on airflow distribution, moisture reduction, temperature variation, and humidity behavior across different layers of the drying chamber. The study revealed that air velocity was not uniform throughout the system, with noticeable differences between loaded and unloaded conditions, which directly influenced drying performance. Moisture content decreased progressively from the initial stage to the final stage, while the coefficient of uniformity improved, indicating more consistent drying over time. Additionally, variations in temperature and relative humidity between the top and bottom layers highlighted the importance of proper airflow management. The findings confirmed that the dryer was capable of achieving acceptable moisture levels within a relatively short duration, demonstrating its effectiveness for practical agricultural use. Kumara Reddy Rao, et al. [2] provided a comprehensive review of grain drying challenges faced by small and medium-scale farmers, particularly in rural regions. Their work emphasized the limitations of conventional sun-based drying, including dependence on weather conditions, vulnerability to rain, and disturbances caused by animals or environmental contamination. The study also highlighted the lack of accessibility to large-capacity industrial dryers for small farmers, forcing them to rely on inefficient traditional methods. To address these issues, the authors explored the development of a cost-effective drying system with minimal heat loss and improved practicality. Their findings suggested that low-cost, efficient drying solutions can significantly enhance grain preservation while reducing labor requirements and operational difficulties in rural settings. Aditya Jain, et al. [3] designed and developed an automated solar-powered grain drying system that integrates renewable energy with intelligent control mechanisms. The system utilized a conveyor-based design where grains were evenly distributed and exposed to heated air generated within a controlled chamber. Sensors continuously monitored moisture content, temperature, and system performance, while a microcontroller dynamically adjusted the conveyor speed and airflow to maintain optimal drying conditions. The use of solar photovoltaic energy made the system energy-efficient and sustainable. Experimental results demonstrated a substantial reduction in moisture content without affecting the nutritional quality of the grains, highlighting the effectiveness of combining automation with renewable energy technologies. I. A. Khan, et al. [4] focused on the conceptual design of a domestic-scale grain

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drying unit intended for small-scale applications. Their system employed a structured drying chamber with multiple trays to ensure uniform distribution of grains and efficient heat transfer. Heated air was circulated through the chamber using exhaust mechanisms, enabling controlled moisture removal. Sensors were integrated to continuously monitor internal temperature, and a control system was implemented to maintain stable drying conditions. The study emphasized the importance of maintaining a constant temperature to avoid quality degradation and ensure consistent drying outcomes. Their design demonstrated a practical and accessible solution for household-level grain processing.

Yadollahinia, et al. [5] investigated the drying behavior of agricultural products through experimental analysis of thin-layer drying systems. Their research focused on understanding the relationship between drying parameters such as temperature, airflow, and moisture reduction rate. The study found that temperature had a significant influence on drying speed, with higher temperatures leading to faster moisture removal, while variations in air velocity had comparatively limited impact. The drying process was observed to occur mainly in the falling-rate period, indicating that moisture diffusion plays a key role. Additionally, the authors evaluated multiple mathematical models to predict drying behavior and identified the most accurate model for representing moisture changes over time. Their work provides valuable theoretical and experimental insights for designing efficient drying systems. Olaniyan, et al. [6] emphasized the critical role of drying in the overall post-harvest processing chain of rice. Their study highlighted that improper moisture removal can lead to severe quality deterioration during storage, milling, and transportation. They discussed the nutritional importance of rice and the need to preserve its value through efficient processing techniques. The authors proposed a column-type drying system and evaluated its performance in terms of moisture reduction and operational efficiency. Their findings indicated that controlled drying methods are essential to minimize losses and maintain grain quality, especially in large-scale agricultural practices. Angula, et al. [7] presented a comprehensive review of solar-based drying technologies for agricultural products. Their work categorized different drying techniques, including direct, indirect, and mixed-mode solar drying systems. The study analyzed key performance factors such as air temperature, airflow rate, drying duration, and moisture removal efficiency. It was observed that solar drying provides an environmentally friendly and cost-effective alternative to conventional methods. The authors also highlighted the importance of system design and environmental conditions in determining overall performance, concluding that solar drying systems are highly suitable for sustainable agricultural applications. Kallai, et al. [8] developed and evaluated a continuous-flow grain drying system designed for moderate capacity operations. The system consisted of a drying chamber with structured ducts, a blower unit for airflow generation, a heating element, and a mechanical discharge mechanism. Experimental trials demonstrated that the system achieved effective moisture reduction within a reasonable time frame while maintaining better grain quality compared to traditional drying methods. The study also noted that integrating alternative energy sources, such as biomass, could further reduce operational costs and improve efficiency, making the system more viable for practical use.

Agrawal, et al. [9] examined the broader issue of post-harvest losses in agricultural supply chains, with a particular focus on the role of drying. Their work highlighted that inadequate drying is one of the primary causes of both quantitative and qualitative losses in grains. The study discussed various stages of post-harvest handling and emphasized the importance of proper moisture control to prevent spoilage during storage and transportation. The authors concluded that improving drying techniques is essential for enhancing food security, reducing economic losses, and maintaining product quality. Ahmad, et al. [10] designed and evaluated a solar-assisted grain drying system aimed at improving drying efficiency and reducing processing time. The system incorporated a central air distribution mechanism, a drying chamber, and a solar air collector to enhance heat utilization. Experimental results showed that the

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proposed system achieved faster moisture removal compared to conventional sun drying methods, significantly reducing drying duration. The study also demonstrated that the system is cost-effective and suitable for rural applications, with the potential to improve agricultural productivity and reduce dependence on traditional drying practices. Beheshti, et al. [11] investigated the influence of drying parameters on grain quality, particularly focusing on the formation of cracks during the milling process. Their study analyzed different drying temperatures and final moisture content levels across multiple rice varieties. The results showed that grain sensitivity varies depending on the variety, with some being more affected by temperature while others are more sensitive to moisture levels. It was observed that higher drying temperatures and improper moisture control increase the likelihood of structural damage in grains. The authors identified optimal drying conditions that minimize cracking and preserve grain integrity, emphasizing the importance of precise environmental control during the drying process. Mbuge, et al. [12] developed a hybrid grain drying system that combines solar energy with a supplementary heating mechanism to improve reliability and performance. The system included a solar collector, drying chamber, airflow system, and a backup heater to ensure continuous operation even under low solar conditions. Their experimental analysis demonstrated that the integration of an auxiliary heating source significantly improved drying efficiency and reduced overall drying time. The study also reported higher thermal efficiency compared to standalone solar systems, highlighting the advantages of hybrid designs for maintaining consistent performance under varying environmental conditions. Mumba, et al. [13] addressed the challenges of grain drying in regions with high humidity and unpredictable weather conditions. Their work focused on the development of a photovoltaic-powered drying system that utilizes forced air circulation to enhance drying performance. The system was designed to operate without reliance on conventional power sources, making it suitable for rural and remote areas. Results indicated that the use of controlled airflow significantly reduced drying time and improved grain quality by preventing contamination, rewetting, and pest interference. The study concluded that such systems offer a reliable and sustainable alternative to traditional open-air drying methods, particularly in challenging climatic conditions.

3. PROPOSED SYSTEM

The system is designed as a comprehensive embedded control framework that integrates sensing, processing, actuation, user interaction, and wireless communication to achieve precise and automated grain drying. At the core, the Arduino Mega microcontroller functions as the central controller, interfacing with all peripheral components and executing the control logic based on real-time environmental data. The DHT11 sensor continuously measures temperature and relative humidity within the drying chamber, and these parameters are periodically sampled and converted into digital signals for processing. The controller compares these values against predefined threshold limits to determine the operational requirements of the system. When humidity exceeds the desired level, the controller activates the heating element to increase temperature and accelerate moisture evaporation, while the fan is triggered to ensure proper air circulation and uniform heat distribution across all grain layers, preventing uneven drying. The system incorporates dual-mode operation, allowing both automatic and manual control. In automatic mode, the entire process is self-regulated through programmed logic, ensuring optimal drying without human intervention. In manual mode, push-button inputs connected through pull-up configurations enable the user to directly control individual components such as the heater and fan, providing flexibility for testing or specific operational needs. The interface is enhanced with a 16x2 LCD display, which presents real-time information including temperature readings, humidity levels, and the current mode of operation, allowing users to monitor system performance continuously. A buzzer module is also integrated to provide audible alerts in cases where environmental parameters exceed safe limits or when specific conditions are met, ensuring timely

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user awareness. As illustrated in Fig. 1, the architecture extends beyond standalone operation by incorporating a Wi-Fi module for IoT-based communication. This module enables the system to transmit sensor data to a remote server using serial communication protocols, allowing real-time monitoring, historical data storage, and remote analysis.

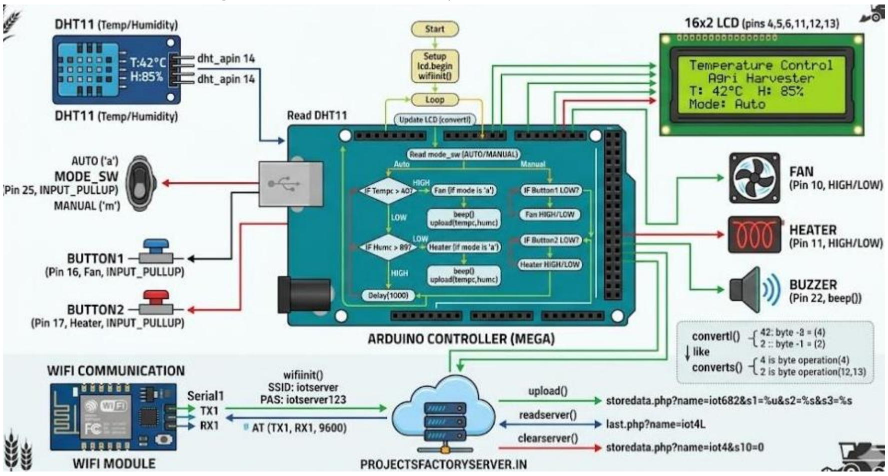

Fig. 1: Proposed system architecture

The server-side integration supports functionalities such as data logging, status updates, and potential remote control, making the system scalable and suitable for smart agriculture applications. Additionally, proper voltage regulation and signal interfacing mechanisms are implemented to ensure stable communication between components and to protect the system from electrical inconsistencies. The overall design emphasizes reliability, efficiency, and adaptability by combining hardware and software elements into a unified system. Continuous feedback from sensors enables dynamic adjustments, ensuring that drying conditions remain within optimal ranges. This reduces the risk of over-drying or under-drying, preserves grain quality, and minimizes energy consumption by operating components only when necessary. By automating critical processes and enabling remote monitoring capabilities, the architecture significantly reduces manual effort, enhances operational precision, and provides a robust solution for modern grain drying applications.

3.1 Raspberry pi pico Mirco Controller

The RPS module converts the 230 volts into 5V of dc. The 5v of power supply goes to all components in the system. The Input of the research is Temperature and Humidity sensor, mode switch, manual switches. The Temperature and Humidity sensor (DH11) is used to sense the wet percentage of Grains/Beans in the drum. The mode switch is used for switching the modes either manually or automatically, and two manual switches are provided in the circuit i.e, fan and heater switches by manual mode of operation.

The output module has LCD, Buzzer, IOT, Relay-1 is attached with DC fan and Relay2 is attached with heater. The IOT server can send the data and display the data in web server app. In Raspberry pi pico microcontroller contains the software programming code in embedded C. The main purpose of the microcontroller is to process the data and then controlling the data. Once we should on the kit, we need to reset the kit because to connect wifi to IOT server. The kit is reset and then the LED displays "Temperature Control Harvester". After we configure to IOT server by using an web application. Once the mobile data of your mobile is ON and connect your hotspot to the circuit, so that it can access internet for uploading the data of temperature and humidity levels of the grains in web application. The DH11 sensor sense the temperature and humidity levels in the grains and displays it on LCD as shown in Fig. 2.

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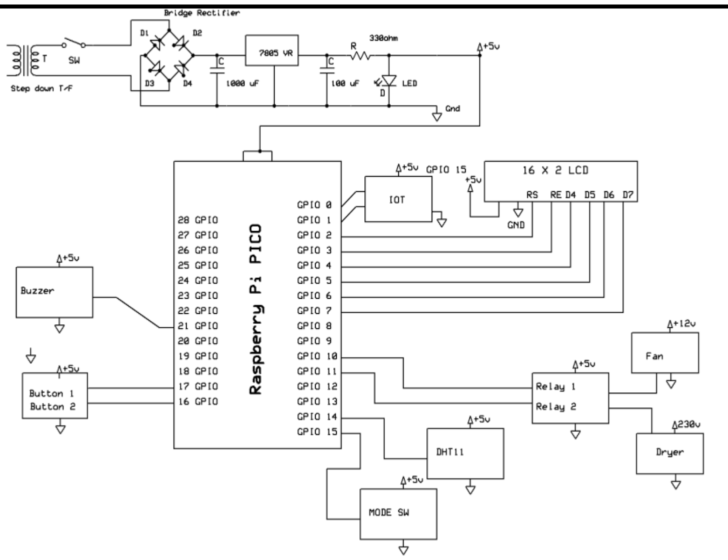

Fig. 2: Block Diagram of Raspberry pi pico Mirco Controller

In Automatic mode the microcontroller receives the data from the sensor and performs the operation of grain drying. We can also operate this circuit by using the manual mode function. And finally the grains are ready for packing and selling.

4. RESULTS AND DISCUSSION

Fig. 3 illustrates the overall hardware implementation of the developed IoT-based temperature and humidity control system, integrating key components such as the Arduino microcontroller unit, DHT temperature and humidity sensor, relay module, fan, heater (dryer), LCD display, WiFi communication module, and buzzer. It depicts how the sensing, control, and actuation units are interconnected to form a complete embedded system for environmental monitoring and regulation. The figure represents the real-time interaction between sensor inputs and output devices for automated decision-making. It highlights the role of the relay module in controlling high-power devices like the fan and heater based on threshold conditions.

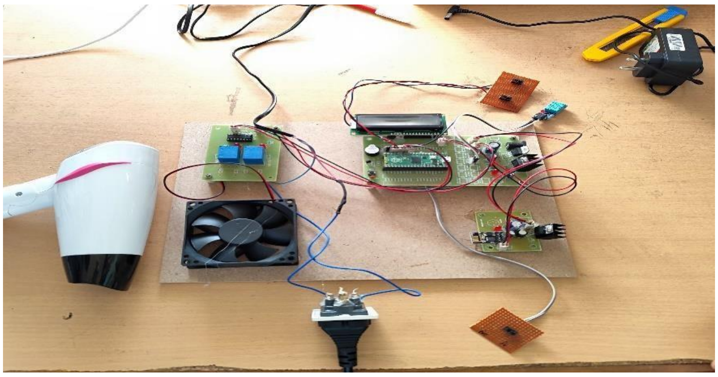

Fig. 3. IoT-Based Temperature and Humidity Controlled Smart Dryer System Prototype

Fig. 4 depicts the initial system interface displayed on the LCD module, indicating the startup status of the temperature control system for agricultural harvesting applications. It illustrates how the LCD (16x2 display) is utilized to provide system identification and operational readiness to the user. The figure represents the initialization phase where the microcontroller configures connected hardware components such as the DHT sensor, relay module, and communication interfaces. It highlights the importance of user interface modules in embedded systems for conveying system status.

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Fig. 4. LCD Display Showing Temperature Control Harvester System Interface

Fig. 5 illustrates the real-time monitoring interface of the developed system, where the Arduino microcontroller processes inputs from the DHT temperature and humidity sensor and displays the corresponding values on the LCD module. It depicts the operational mode selection, enabling the system to function in automated or manual control based on user input. The figure represents how the relay module controls the fan and heater according to sensed environmental conditions. It highlights the continuous interaction between sensing, processing, and actuation units within the embedded system.

Fig. 5. LCD Display Showing Real-Time Temperature, Humidity, and Auto Mode Status

Fig. 6 depicts the cloud-based data logging system enabled through the WiFi module, where temperature and humidity data collected from the DHT sensor are transmitted to a remote server. It illustrates how the IoT infrastructure supports real-time data storage, monitoring, and analysis through a centralized platform. The figure represents the structured recording of environmental parameters along with timestamps for tracking variations over time. It highlights the role of wireless communication in extending system capabilities beyond local control.

Hello, iot682 Welcome to IOT Server

Refresh

Switch to Graph View

Page 1 of 3 Next

S.No	Temperature	Humidity	Date
1	41	41	2024-02-16 12:27:46
2	43	36	2024-02-16 12:27:26
3	45	34	2024-02-16 12:27:06
4	47	36	2024-02-16 12:26:46
5	42	45	2024-02-16 12:26:26
6	34	90	2024-02-16 12:25:29
7	34	90	2024-02-16 12:25:09
8	32	91	2024-02-16 12:21:35
9	31	90	2024-02-16 12:21:15
10	41	40	2024-02-16 10:55:12
11	43	36	2024-02-16 10:54:51
12	44	34	2024-02-16 10:54:31
13	48	29	2024-02-16 10:53:51
14	48	30	2024-02-16 10:53:31
15	34	90	2024-02-16 10:52:51
16	34	90	2024-02-16 10:52:31
17	35	90	2024-02-16 10:48:16
18	33	92	2024-02-16 10:44:02
19	33	92	2024-02-16 10:43:42
20	33	92	2024-02-16 10:43:22

Fig. 6. IoT Server Dashboard Displaying Logged Temperature and Humidity Data

5. CONCLUSION

The developed Raspberry Pi Pico-based temperature-controlled harvester provides an effective solution to the limitations of conventional grain drying methods by introducing automation and precision. It minimizes manual effort while ensuring consistent drying through continuous monitoring of temperature and humidity using sensors. The system intelligently adjusts heating and airflow conditions in real time, preventing issues such as over-drying or insufficient drying. Integration of key components like the microcontroller, fan, and sensing units enables accurate environmental control and stable operation. Its user-oriented design allows customization of drying parameters, making it adaptable to different conditions. Additionally, the focus on energy-efficient operation reduces resource consumption and operational costs. Overall, the system enhances grain quality, reduces post-harvest losses, and supports modern, sustainable agricultural practices.

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