

**Article**

# Embedded Control Architecture for Multi-Evaporator Industrial Dehumidification Systems

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**Abstract:** Industrial dehumidification plays a pivotal role in spice processing industries, where precise moisture control directly influences product quality, shelf life, and processing efficiency. However, in many industrial facilities, these systems are operated manually or using basic on-off control methods. Such practices often result in unstable operating conditions, frequent compressor switching, increased energy consumption, and reduced equipment lifespan. This study addresses the lack of affordable, hardware-level automation for multi-evaporator systems by presenting the design and implementation of a dedicated embedded control architecture. The proposed objective was to develop a dual-microcontroller system where a primary controller manages real-time decision-making based on temperature and relative humidity, while a secondary controller is strictly dedicated to safety and time-delay protection. The system was implemented and tested in an industrial spice processing facility. Key findings demonstrate that the autonomous mode reduced outlet air temperature variation to  $\pm 1 - 2$  °C and relative humidity fluctuation to  $\pm 4 - 5\%$ , compared to significantly higher variations in manual operation. Furthermore, the system reduced operator interventions from 1-2 per shift to 0-1 and minimized compressor cycling frequency. Beyond operational efficiency, the stabilization of the drying environment directly contributes to the preservation of critical quality parameters, such as volatile oil retention and color uniformity, which are frequently compromised under manual control regimes. These results imply that low-cost embedded automation can significantly enhance operational stability and safety in agro-industrial processing without requiring expensive infrastructure upgrades.

**Keywords:** Embedded control; Industrial dehumidification; Multi-evaporator systems; Automation; Micro-controller.

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## 1. Introduction

Industrial dehumidification is a fundamental unit operation in the agro-food processing sector, particularly for hygroscopic commodities such as spices, where precise moisture control is essential for preventing microbial growth and preserving volatile oil content [1]. These systems, often characterized by multi-evaporator vapor compression cycles, exhibit complex thermodynamic behaviors involving coupled heat and mass transfer processes [2]. Unlike simple residential air conditioning, industrial drying requires the maintenance of specific psychrometric conditions—defined by temperature and relative humidity (RH)—regardless of external ambient fluctuations [3].

The stability of these parameters is directly linked to product quality, energy efficiency, and equipment longevity [4]. Historically, drying technology has evolved from open-sun drying to advanced heat pump-assisted systems, with foundational work establishing the energy benefits of closed-loop dehumidification. Comprehensive treatments of these thermal systems can be found in recent literature, where the non-linear dynamics of condenser and evaporator loads are examined [5], [6]. However, ensuring stable and predictable operation in these systems remains challenging due to significant thermal inertia, dead-time effects, and load variations inherent in large-scale drying chambers [7]. Consequently, the control strat-

egy employed plays a decisive role in the operational success and reliability of industrial dehumidification facilities.

Despite theoretical advancements in process control, the practical management of dehumidification systems in Small and Medium-sized Enterprises (SMEs) presents significant techno-economic challenges. Feedback regulation in these facilities is frequently handled through manual operator intervention or rudimentary mechanical thermostats [8]-[10], which fail to account for the dynamic coupling between temperature and relative humidity [11]. Although advanced control strategies such as Model Predictive Control (MPC), fuzzy logic, and optimized PID schemes have been extensively investigated in academic studies [12], their industrial deployment often requires expensive Programmable Logic Controllers (PLCs) or complex computational infrastructure that is cost-prohibitive for many agro-industrial applications [13]. In response, recent research has increasingly explored Internet of Things (IoT) and microcontroller-based control solutions as lower-cost alternatives [14]. However, many of these approaches remain limited to simulation environments or lack robust hardware-level safety mechanisms suitable for continuous industrial operation [15].

A particularly critical limitation in existing low-cost embedded control implementations is the inadequate handling of compressor protection. Rapid switching of compressors, commonly referred to as short-cycling, can occur due to sensor noise, tight control thresholds, or improper hysteresis design [16], leading to increased mechanical wear, electrical stress, and premature equipment failure [17]. Recent advances in embedded computing have improved the potential for low-cost automation; however, their application to multi-evaporator industrial dehumidification systems remains fragmented, with limited emphasis on coordinated control and hardware-level safety. Applications in spice processing further highlight the need for a unified control framework that simultaneously satisfies stringent drying requirements while protecting high-power components such as induction motors and compressors [18]. Therefore, the objective of this study is to design, implement, and validate a low-cost embedded control architecture that ensures stable environmental regulation and compressor-safe operation in multi-evaporator industrial dehumidification systems used in spice processing facilities [19].

The main contribution of this paper lies in bridging the gap between theoretical control logic and robust industrial implementation using a cost-effective embedded architecture. Specifically, we propose:

- A novel dual-microcontroller architecture that decouples the primary environmental control logic from the critical safety protection mechanisms, overcoming the reliability limitations of single-processor systems.

- A specialized time-delay safety algorithm designed to eliminate compressor short-cycling, thereby extending equipment lifespan.
- A systematic field implementation that transforms a manual multi-evaporator system into an autonomous unit, validated through real-world testing in a spice processing facility.

This paper is organized as follows. [Section 2](#) details the methodology, including the system overview, embedded hardware architecture, and control logic design. [Section 3](#) presents the results and discussion, focusing on operational performance, stability, and energy efficiency under industrial conditions. Finally, [Section 4](#) concludes the paper with a summary of key findings and directions for future research.

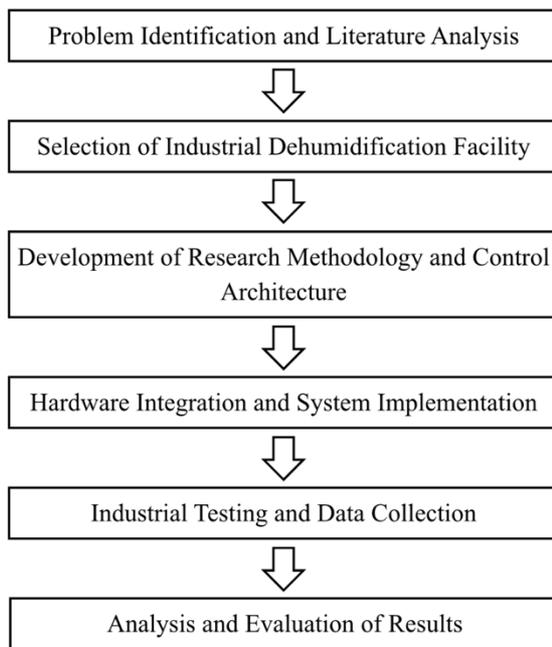
## 2. Methodology

This study adopts an applied engineering research methodology to develop, implement, and validate a low-cost embedded control architecture for a multi-evaporator industrial dehumidification system [20]. The research was conducted as a single-case industrial study in a spice processing facility under normal operating conditions, emphasizing practical implementation and operational reliability [21]. The research followed a structured workflow, as shown in [Figure 1](#), involving problem identification, system and control architecture development, hardware integration, and industrial testing. System performance was evaluated by comparing operational stability, compressor switching behavior, and operator intervention under manual and automatic operating modes.

### 2.1. System Overview

The physical configuration of the industrial dehumidification chamber and the spatial arrangement of its main components are illustrated in [Figure 2](#). The figure shows the cascade placement of multiple evaporators, condensers, airflow direction, centrifugal blower, and the locations of temperature and relative humidity sensors within the chamber. This configuration highlights the interaction between heat rejection, moisture removal, and air circulation, which directly influences the stability of outlet air conditions. Understanding this layout is essential for designing an effective control strategy, as improper coordination of evaporators and airflow can lead to uneven dehumidification and inefficient energy usage [22], [23].

The mechanical structure and airflow layout of the system were already established before this study. Therefore, the primary objective of this work was to design and implement an improved control and automation layer without modifying the existing mechanical components. This approach ensures that the proposed solution can be applied to similar industrial systems without major mechanical redesign.



**Figure 1.** Research workflow of the proposed embedded control architecture.

critical equipment protection tasks. The overall hardware configuration and interconnections among microcontrollers, sensors, user input interfaces, display units, and relay-based actuators are illustrated in Figure 3. This architecture was selected to enhance operational reliability and ensure safe control of high-power industrial components in a multi-evaporator dehumidification system.

An Arduino Mega microcontroller is employed as the primary controller due to its high number of inputs–output pins and sufficient processing capability to handle multiple sensors and actuators simultaneously. The primary controller is responsible for acquiring temperature and relative humidity data, comparing measured values against user-defined threshold settings, and generating control signals for evaporators, condensers, and the blower. This centralized decision-making approach enables coordinated operation of system components under varying operating conditions.

A secondary microcontroller, Arduino Nano, is dedicated exclusively to implementing time-delay protection for compressors and condensers. The secondary controller monitors the control signals issued by the primary controller and enforces predefined delay intervals before allowing compressor restart after shutdown. By isolating protection functions from the main control logic, this design prevents rapid compressor cycling caused by sensor noise, or frequent operator adjustments.

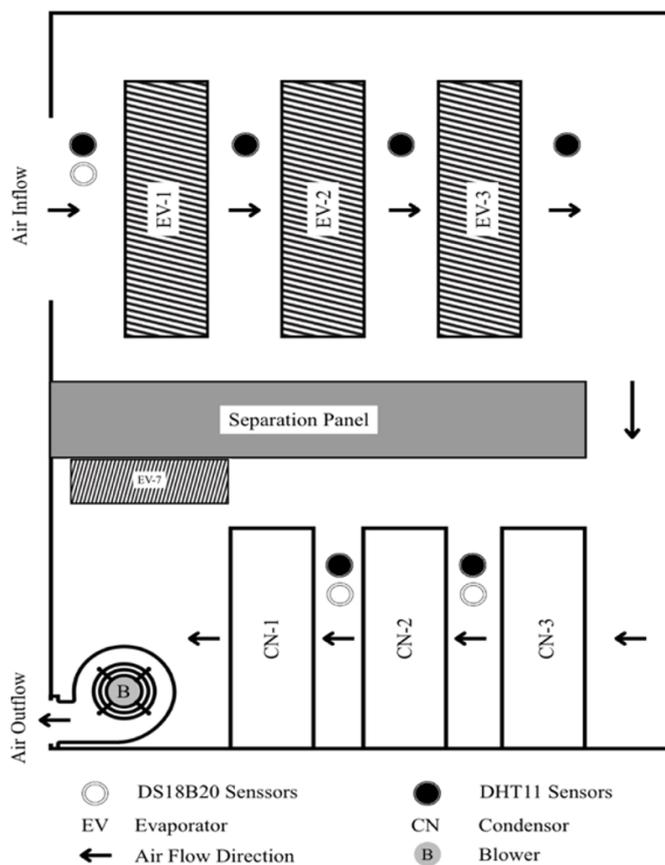
Temperature measurements are obtained using DS18B20 digital temperature sensors installed at multiple locations within the dehumidification chamber to capture spatial temperature variations. Relative humidity measurements are provided by DHT11 sensors positioned near the outlet air stream, enabling continuous monitoring of dehumidification performance. These sensor inputs provide the feedback required for stable regulation of environmental conditions inside the chamber [24]–[26].

To interface the low-voltage microcontroller outputs with high-voltage industrial equipment, solid-state relays are used in combination with electromechanical contactors. This configuration ensures electrical isolation between control and power circuits while providing reliable switching of compressors, evaporators, and the blower. The use of relay-based isolation improves operational safety and supports continuous industrial operation [27].

Overall, the proposed embedded hardware architecture provides a modular and scalable platform for industrial dehumidification control. By decoupling environmental regulation and safety protection at the hardware level, the system improves stability, equipment protection, and maintainability while remaining cost-effective for agro-industrial applications.

### 2.3. Control Logic Design

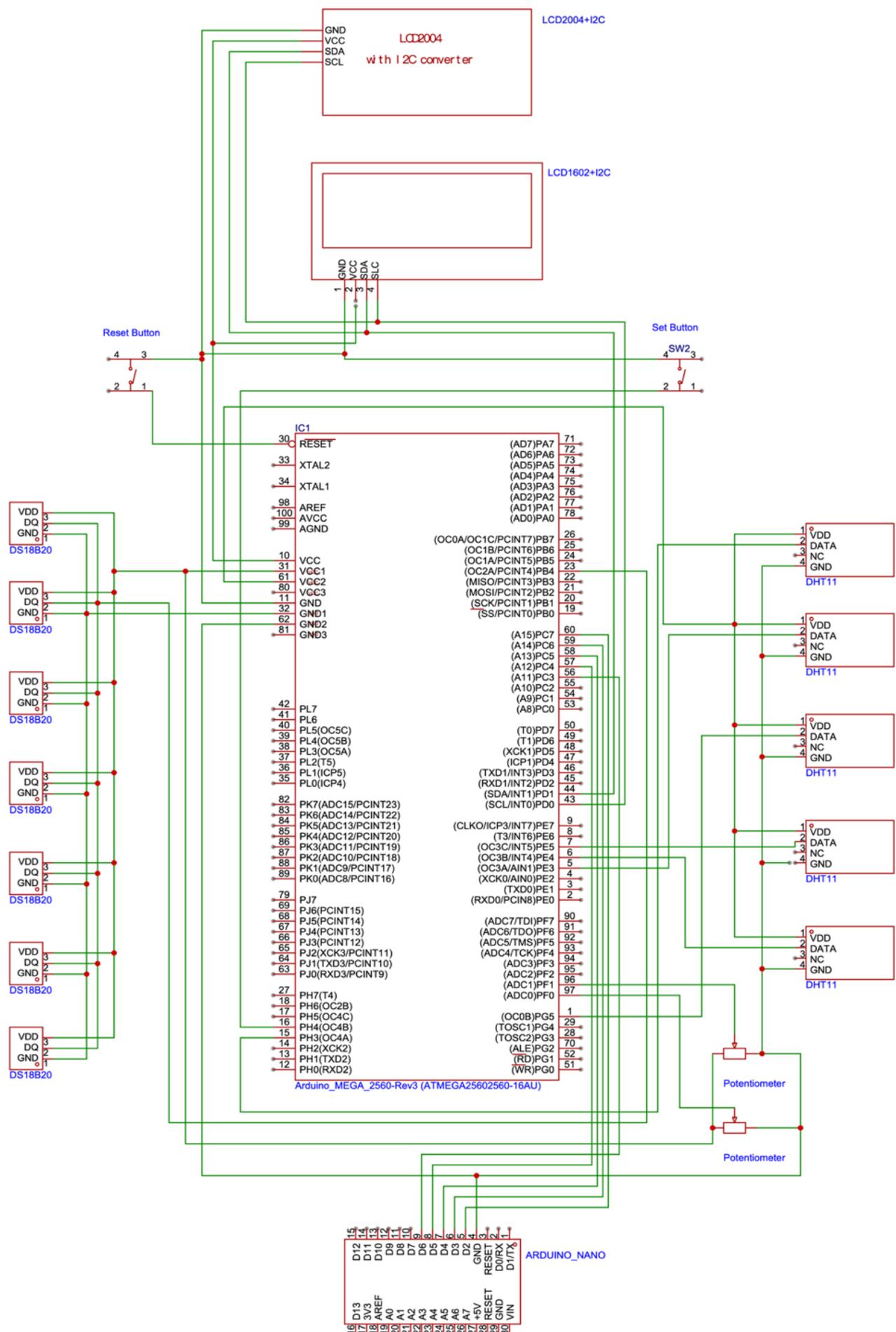
The control logic is designed to maintain stable outlet air temperature and relative humidity conditions within



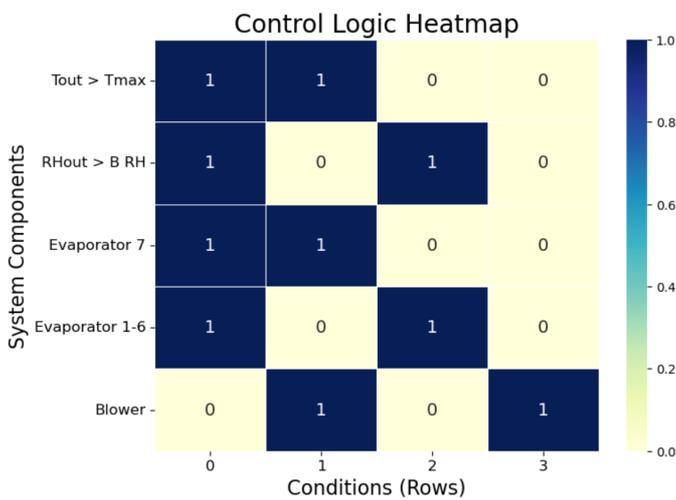
**Figure 2.** Schematic layout of the industrial dehumidification chamber showing the arrangement of evaporators, condensers, airflow direction, blower, and sensor placement.

### 2.2. Embedded Hardware Architecture

The embedded control system developed in this study is based on a dual-microcontroller architecture designed to separate real-time environmental control from



**Figure 3.** Embedded control system schematic showing microcontroller connections, temperature and humidity sensors, user input interfaces, display units, and inter-controller communication.



**Figure 4.** Control logic truth heatmap showing system responses for different outlet temperature and relative humidity conditions.



**Figure 5.** Implemented embedded control panel showing manual/automatic switches, safety controls, display units, and relay-based actuation modules for the industrial dehumidification system.

predefined limits as showed in Figure 4. The primary controller continuously monitors outlet air temperature and relative humidity using sensor inputs. User-defined threshold values for maximum allowable temperature and maximum allowable relative humidity are set using manual input controls.

When the measured outlet temperature exceeds the temperature threshold, a dedicated heat-rejection evaporator is activated to remove excess heat from the system (Evaporator 7). When the measured RH exceeds the humidity threshold, multiple evaporators are activated to increase moisture removal. During high-humidity conditions, blower operation is adjusted to prevent the movement of excessively humid air toward the raw material.

This rule-based control logic is simple, transparent, and easy to modify according to industrial requirements. It allows operators to adjust control parameters without complex programming and ensures predictable system behavior under different operating conditions.

#### 2.4. Time-Delay Protection Mechanism

Frequent on–off switching of compressors can cause mechanical wear, overheating, and reduced equipment lifespan [28], [29]. To address this issue, a time-delay protection mechanism is implemented using the secondary microcontroller. When a compressor is turned off, the secondary controller enforces a predefined delay period before allowing the compressor to restart.

This protection mechanism ensures that compressors are given sufficient time to stabilize before reactivation. The use of a dedicated microcontroller for this function improves system reliability and prevents unintended compressor cycling due to sensor signals.

#### 2.5. Manual and Automatic Operating Modes

The control system supports both manual and automatic operating modes. In automatic mode, all operations are governed by the embedded control logic based on real-time sensor data. In manual mode, operators can directly control individual system components for maintenance, testing, or emergency situations.

The inclusion of both operating modes enhances system flexibility and makes the proposed architecture suitable for industrial environments where operator intervention may occasionally be required.

#### 2.6. System Implementation and Testing

The embedded control system was implemented using industrial-grade wiring practices and installed inside a protective control panel. Liquid crystal displays are used to present real-time temperature and humidity readings, as well as system status information as shown in Figure 5. The system was tested under normal industrial operating conditions to verify functionality, stability, and safety.

### 3. Results and Discussion

This section presents and discusses the results obtained from the implementation of the proposed embedded control architecture in an industrial dehumidification environment. The evaluation focuses on system behavior under real industrial operating conditions rather than controlled laboratory experiments. Both manual and automatic operating modes were analyzed to understand the practical benefits of the embedded control system during routine spice processing.

The performance of the system was evaluated using qualitative and operational criteria commonly used in industrial practice. These criteria include overall system stability, frequency of compressor switching, consistency of

outlet air temperature and relative humidity, and the level of operator involvement required during operation. Observations were recorded over multiple normal processing cycles to reflect actual industrial usage conditions.

The results presented in the following subsections highlight the effectiveness of the embedded control architecture in improving operational reliability and reducing dependency on manual intervention. Where appropriate, comparisons between manual and automatic operation are discussed to demonstrate the advantages of the proposed approach.

### 3.1. System Operational Performance

The embedded control architecture was evaluated under normal industrial operating conditions in the spice dehumidification facility. The system was operated continuously during routine processing cycles, and its behavior was observed under both manual and autonomous operating modes. The evaluation focused on system stability, compressor switching behavior, energy usage patterns, and operator dependency.

During manual operation, workers typically allowed the dehumidification system to run continuously for long periods without precise control. In many cases, evaporators, condensers, and blowers were left operating even when the required temperature and relative humidity conditions had already been achieved. This practice resulted in unnecessary power consumption, as the system continued to operate beyond actual process requirements.

Under manual operation, compressors were observed to switch on and off approximately 1–2 times per hour, particularly during fluctuating ambient conditions. Extended continuous operation of components led to significant energy wastage and increased thermal stress on the system. This uncontrolled operation did not improve dehumidification efficiency and, in some cases, negatively affected raw material quality. In contrast, when the system operated in autonomous mode, component operation strictly followed the predefined embedded control logic. Evaporators and blowers were powered on only when required and switched off immediately once target temperature and relative humidity conditions were reached. Under autonomous operation, compressor switching frequency was approximately 3–4 cycles per hour, indicating more stable and energy-efficient operation.

The precise power-on and power-off behavior of the autonomous system significantly reduced unnecessary energy consumption. More importantly, controlled operation prevented over-drying and excessive heat exposure of spice materials [30]. As a result, moisture removal occurred more uniformly, helping to preserve product quality, aroma, and physical characteristics of the spices.

### 3.2. Impact on Energy Efficiency and Product Quality

The difference between manual and autonomous op-

eration had a direct impact on energy efficiency and raw material quality. In manual operation, continuous running of the system often caused over-processing of spices, leading to excessive moisture removal and prolonged exposure to conditioned air. This not only increased energy consumption but also risked deterioration of spice quality.

In autonomous mode, the embedded control system continuously monitored environmental conditions and adjusted system operation accordingly. By preventing unnecessary operation of evaporators and blowers, the system minimized power consumption while maintaining required dehumidification performance. This controlled approach ensured that spices were exposed to optimal conditions for the required duration only.

Improved control of operating time and environmental conditions resulted in better consistency of raw material quality. Uniform dehumidification reduced the risk of uneven moisture distribution, clumping, or loss of aroma in spice products. Therefore, the autonomous embedded control architecture contributed not only to energy savings but also to improved processing quality and industrial efficiency.

### 3.3. Effectiveness of Time-Delay Protection

One of the most important features of the proposed control architecture is the time-delay protection mechanism implemented using the secondary microcontroller. During testing, this mechanism successfully prevented rapid on-off switching of compressors. In manual operation, compressors were sometimes restarted immediately after shutdown, especially when operators attempted to quickly correct temperature or humidity deviations.

With the time-delay protection active, the system enforced a minimum compressor off-time of approximately 3 minutes before allowing restart. This delay significantly reduced mechanical stress on compressors and minimized electrical surges associated with frequent starting. The separation of protection logic from the main control logic ensured that safety functions remained active even when control parameters were modified by the operator.

The observed reduction in compressor switching frequency is a key indicator of improved system reliability. Fewer switching events directly contribute to longer equipment lifespan, reduced maintenance requirements, and improved operational safety, which are critical factors in industrial dehumidification environments.

### 3.4. Temperature and Humidity

Stability of outlet air temperature and relative humidity is essential for uniform dehumidification of spice materials. Under manual operation, outlet air temperature exhibited noticeable fluctuations due to delayed operator response and inconsistent decision-making. Temperature variations of approximately  $\pm 3\text{--}4$  °C around the desired operating range were commonly observed. Similarly, out-

**Table 1.** Performance comparison between manual and automatic operation.

Parameter	Manual Operation	Automatic Operation
Compressor switching frequency (cycles/hour)	1–2	3–4
Minimum compressor off-time	Not enforced	~3 minutes
Outlet air temperature variation (°C)	±3–4	±1–2
Outlet relative humidity variation (%)	±8	±4–5
Operator interventions per shift	1–2	0–1

let relative humidity showed fluctuations of up to  $\pm 8\%$ , leading to uneven moisture removal.

In automatic mode, the embedded control system responded immediately to sensor measurements and adjusted evaporator and blower operation accordingly. As a result, outlet air temperature variation was reduced to approximately  $\pm 1\text{--}2$  °C, while relative humidity fluctuations were reduced to approximately  $\pm 4\text{--}5\%$  around the target value. Although minor fluctuations were still present due to external environmental changes, their magnitude and frequency were significantly reduced.

The improved stability can be attributed to continuous monitoring and rule-based control logic, which eliminates delays associated with human intervention. These results demonstrate the advantage of embedded automation in maintaining consistent operating conditions in industrial dehumidification systems.

### 3.5. Comparison of Manual and Automatic Operation

A qualitative comparison between manual and automatic operation modes reveals several practical benefits of the proposed embedded control system. In manual mode, system performance was highly dependent on operator skill and attentiveness. Operators were required to intervene approximately 3–4 times per shift to adjust evaporator or blower operation, resulting in variability in system performance across different shifts.

In contrast, automatic operation provided consistent and repeatable system behavior. Once control parameters were set, the system followed the same decision rules regardless of time or operator. In most cases, automatic operation required zero or one operator intervention per shift, primarily for routine inspection. This significantly reduced operator workload and improved overall process reliability.

### 3.6. Summary of Performance Comparison

Table 1 summarizes the key performance differences between manual and automatic operating modes observed during industrial operation.

The results summarized in Table 1 clearly indicate that the proposed embedded control architecture improves operational stability, reduces mechanical stress on equipment, and minimizes dependency on manual intervention.

### 3.7. Reliability and Safety Considerations

Safety is a critical requirement in industrial dehumidification systems due to the presence of high-voltage electrical equipment and rotating machinery. The use of solid-state relays in combination with contactors provided reliable electrical isolation between low-voltage control circuits and high-voltage industrial loads. This significantly reduced the risk of electrical hazards and improved overall system safety. The dual-microcontroller architecture further enhanced reliability by separating control and protection functions. Even if the primary controller experienced abnormal behavior or software modification, the secondary controller continued to enforce time-delay protection. This layered safety approach is particularly suitable for industrial environments where system faults can have serious operational and economic consequences.

### 3.8. Industrial Applicability and Scalability

The proposed embedded control architecture is designed to be modular and scalable. Additional evaporators, sensors, or control outputs can be integrated with minimal changes to the existing system. This makes the architecture suitable for different sizes of dehumidification chambers and a wide range of agro-industrial applications beyond spice processing.

The use of widely available microcontrollers and sensors keeps system cost relatively low, making it accessible for small- and medium-scale industries. Furthermore, the architecture provides a strong foundation for future upgrades, such as integration with supervisory control systems or data-driven optimization techniques.

## 4. Conclusion

This study successfully demonstrated the effectiveness of a dual-microcontroller embedded architecture for automating multi-evaporator industrial dehumidification systems. By separating the primary control logic from the safety protection mechanism, the system achieved robust operation, reducing compressor switching frequency from intermittent rapid cycling to a stable 3–4 cycles per hour. The implementation of the specific time-delay protection significantly mitigated mechanical stress on the equipment, addressing a critical failure point in manual operations.

Field testing in a spice processing facility confirmed that the autonomous system outperformed manual control in stability and efficiency. Outlet air temperature fluctuations were reduced to  $\pm 1\text{--}2$  °C and relative humidity variations to  $\pm 4\text{--}5\%$ . These improvements not only mini-

mized energy wastage caused by over-processing but also ensured a higher consistency in the final spice product quality. The system proved that low-cost, modular embedded solutions are a viable alternative to expensive industrial PLCs for agro-industrial SMEs.

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## 5. Declarations

### 5.1. Author Contributions

**Pamodha Chathumal:** Conceptualization, system design, methodology development, embedded software development, validation, formal analysis, investigation, data collection, and writing – original draft preparation. **Sanath Amaratunga:** Supervision, methodology review, formal analysis, technical guidance, validation, review and editing of the manuscript.

### 5.2. Institutional Review Board Statement

Not applicable.

### 5.3. Informed Consent Statement

Not applicable.

### 5.4. Data Availability Statement

The data presented in this study are available from the corresponding author upon reasonable request.

### 5.5. Acknowledgment

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### 5.6. Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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