Monitoring, Automation, and Control System for Small-Scale Silos

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Abstract.

Brazil has an important role in the global grain production scenario. However, the country's grain storage infrastructure is usually inadequate and insufficient. The drying and storage of grains post-harvest are essential to ensure product quality, even over extended periods. In this context, research has been conducted on sensing, monitoring, and prediction of grain temperature and humidity, as well as the automation and control of the drying process. Therefore, this paper presents a system for monitoring, automation, and control of small-scale silos. This system is composed of a single-board computer, a microcontroller, temperature and humidity sensors, and a frequency inverter, which allows for the adjustment of the airflow of the drying process. It can be operated locally, using buttons and switches, or remotely, by means of a visual interface. Users can easily access the collected data, including the temperature and relative humidity of intergranular air. The system was designed using low-cost devices and free software, which makes it an accessible option for small-scale producers. It has been implemented and tested since 2024 in a 420-bag capacity small brickwork silo for stationary drying and storage of rice. This type of silo uses natural air insufflated by a fan, and it is available at the Araranguá Training Center of the Agricultural Research and Rural Extension Company of Santa Catarina (CETRAR/EPAGRI). The experimental results demonstrate that this system correctly monitors physical variables and can be used as a tool to manage the drying process. Currently, the automation and control strategies are being designed. It is expected that this work will contribute to improving the performance of the grain drying and storage process, particularly for brickwork silos, which are mainly used by small producers.

Keywords.

Automation, Monitoring, Silos.

1. Introduction

The preservation of grain quality is a determining factor in ensuring its safe and profitable use, whether for consumption, commercialization, or the next production cycle. Among the post-harvest operations, drying and storage are particularly important, as their primary objectives are to reduce deterioration and extend grain shelf life. These operations play a critical role in maintaining grain quality throughout the post-harvest period (Ziegler et al. 2021). Controlling key variables, such as grain moisture content and temperature, directly influences the success of these processes. These parameters influence both the physical preservation and the economic value of the product (Santos 2020).

Different grain storage systems are available depending on the quantity of grain, the required storage duration, and the level of environmental control desired. The conventional storage system, known as non-hermetic storage, generally uses bags or sacks to store grains. Hermetic storage employs sealed containers, such as drums or plastic silos, and is commonly used for small quantities of grain. Semi-hermetic storage systems, also referred to as bulk storage systems, include vertical silos and warehouses equipped with forced aeration systems. Refrigerated grain storage consists of cooling the air before it is forced into the silo by a fan. This air conditioning process modifies the air properties, enhancing its capacity to absorb moisture from the grain mass. In contrast, modified-atmosphere storage relies on the use of nitrogen (N_2) or carbon dioxide (CO_2) to reduce oxygen (O_2) levels and, consequently, decrease grain respiration rates (Ziegler et al. 2021).

Before grains can be safely stored, their moisture content must be reduced after harvest through a drying process. Grain drying can generally be classified into two main categories: batch (stationary) drying and continuous drying. In stationary drying, the grain mass stays still while a forced airflow moves through the grains. This usually happens in a perforated-bin silo with a false floor. Under these conditions, the drying front progresses from the bottom toward the top of the grain mass. In continuous drying, the grain mass is kept in constant motion inside the dryer, allowing the grains to be continuously exposed to the drying air until the desired moisture content is achieved (Garcia et al. 2004).

Excess moisture content is considered one of the primary risk factors affecting stored grain, as it promotes the development of microorganisms and pests while accelerating deterioration processes (Ziegler et al. 2021). Likewise, elevated temperatures within the silo intensify the respiratory activity of the grain mass, resulting in significant losses in both grain quality and quantity during storage. To mitigate these effects, monitoring, control, and automation systems are increasingly employed, as they enable the regulation of internal silo conditions and help maintain product stability throughout the storage period (Coradi et al. 2022).

The use of monitoring, control, and automation systems for grain storage and drying has been extensively investigated in the literature. For example, Bica et al. (2021) developed a wireless system for temperature monitoring in grain silos. Lopes et al. (2008) implemented an automatic aeration control strategy based on temperature and humidity sensors. Rodrigues (2019) proposed a real-time monitoring system for grain drying processes, while Schuler et al. (2024) employed remote communication technologies for storage management. Similarly, Stanga (2017) developed a low-cost monitoring system using sensors and microcontrollers to track storage conditions. Additional control-oriented approaches have been reported in studies such as those by Zhang et al. (2013), Guha and Mishra (2014), Delele et al. (2015), and Li and Chen (2020). Collectively, these studies demonstrate the significant potential of monitoring, automation, and control technologies to improve the efficiency, reliability, and safety of grain drying and storage operations. Although the principles governing temperature and moisture control in grain storage silos are well established, relatively few studies have focused on the development and validation of control systems, either through experimental investigations or simulation-based approaches, for stationary drying processes in small-scale silos (Krumreich et al. 2024).

Despite technological advances, the Brazilian agricultural sector still faces significant challenges in the storage stage. Recent estimates indicate that, although national grain production has reached record levels, the available storage infrastructure has not kept pace with this growth. According to the 8th monitoring bulletin of the 2025/26 grain harvest in Brazil, published by the National Supply Company (CONAB), the total grain production is estimated at approximately 358 million tons (CONAB 2026). However, according to CONAB (2025), the total storage capacity in Brazil is 225.83 million tons. Furthermore, only 28.8% of this infrastructure is equipped with grain drying capacity (Péra et al. 2023). This limitation emphasizes the necessity of financially accessible and efficient solutions that contribute to improving grain drying and storage processes while reducing post-harvest losses.

In this context, this paper presents a Monitoring, Automation, and Control System (MACS) designed for small-scale grain silos. Based on the preliminary results presented in the works of Tonneti et al. (2022) and Garcia and Scharlau (2021), the system consists of a Single-Board Computer (SBC), a microcontroller, temperature and humidity sensors, and a frequency inverter that allows airflow adjustment during the drying process. It can be operated locally through buttons and switches or remotely through a graphical user interface. The user can easily access the collected data, including the temperature and relative humidity of the intergranular air. The system was developed using low-cost hardware and open-source software, making it an affordable solution for small-scale producers.

This paper is organized as follows. Section 2 presents the topology of the proposed Monitoring, Automation, and Control System and describes its hardware and software architectures. Section 3 presents a case study involving the implementation of the system in a small brickwork silo for stationary drying and storage of rice (Martins et al. 2013) located in the city of Araranguá, Santa Catarina, Brazil. Section 4 presents and discusses the experimental results. Finally, Section 5 summarizes the main conclusions and outlines future directions for this research.

2. Monitoring, Automation, and Control System

The MACS was developed as a low-cost solution for monitoring environmental conditions and supporting aeration management in grain storage facilities. The system was designed to continuously acquire temperature and relative humidity data, provide real-time supervision of storage conditions, and enable local or remote control of ventilation equipment.

The proposed architecture, shown in Figure 1, integrates sensing devices, embedded electronics, communication infrastructure, supervisory software, and control elements into a unified monitoring and automation platform. Environmental data are acquired by distributed sensors and transmitted to a supervisory server through a wireless communication network. The supervisory platform is responsible for data storage, visualization, alarm management, and automation routines, while the control layer supports ventilation system operation. The modular architecture facilitates scalability and future expansions, allowing the incorporation of additional sensors, advanced control and automation strategies, and decision-support algorithms. As a result, the proposed system can be adapted to different grain storage facilities and agricultural monitoring applications.

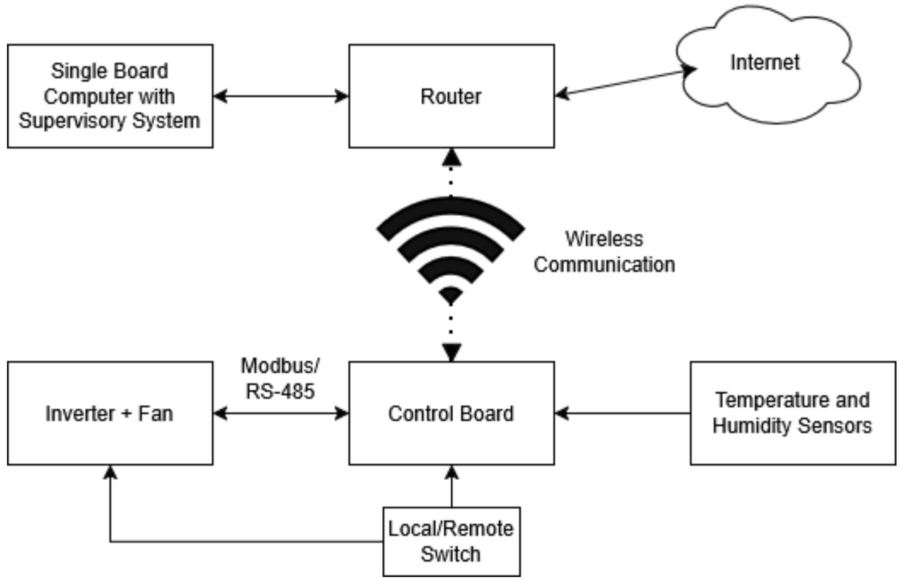

Fig 1. Diagram of the general architecture of MACS.

The supervisory platform provides real-time access to environmental measurements, operational information, and historical records through a web-based interface. Continuous data storage enables long-term analysis of storage conditions and supports decision-making processes related to grain preservation and aeration management.

Communication between field devices and supervisory services is based on Internet of Things (IoT) concepts and lightweight messaging protocols. This approach enables reliable data exchange while maintaining low computational and network requirements, facilitating the integration of sensors, controllers, and monitoring services.

In addition to monitoring capabilities, the system incorporates a ventilation control structure designed to support grain aeration operations. Through the integration of a frequency inverter and associated control devices, operators can activate ventilation equipment, adjust operating parameters, and monitor system status. The architecture supports both local operation through physical control interfaces and remote operation through the supervisory platform.

To improve operational reliability, fault detection and diagnostic mechanisms were incorporated into the system architecture. These functions allow the identification of communication interruptions, sensor malfunctions, power outages, and equipment failures. When abnormal conditions are detected, automated notification services can alert operators through messaging applications or e-mail, enabling rapid response to operational events and reducing system downtime.

The following subsections will provide more detailed information about the hardware and software.

2.1 Hardware

The developed system combines DHT22 temperature and humidity sensors, an ESP32 microcontroller, a frequency inverter, and an SBC to provide automation, control, supervision, and management of the aeration process.

The supervisory layer of the MACS is implemented using a Raspberry Pi SBC (Raspberry PI 2025). Raspberry Pi devices provide a compact, low-cost, and energy-efficient computing platform capable of supporting data acquisition, storage, visualization, and automation services while maintaining continuous operation. Their processing capabilities, network connectivity, and extensive software ecosystem make them suitable for agricultural monitoring applications requiring remote access and long-term reliability.

In the proposed architecture, the Raspberry Pi operates as the central supervisory unit, receiving information from field devices, storing operational data, and coordinating automation routines. The device hosts the supervisory software environment, manages communication services, and provides the user interface through which operators can monitor environmental conditions, visualize historical trends, and manage system operation. The use of a Raspberry Pi contributes to the development of a scalable and easily deployable monitoring infrastructure, allowing future integration of additional sensors, communication protocols, and control algorithms.

The control board is the main hardware component of the system. Figure 2 presents the principal components integrated into this board, namely the following:

- ESP32 microcontroller with antenna: selected due to its data-processing capabilities, Wi-Fi and Bluetooth connectivity, and the large number of available input/output pins.
- TTL-to-RS-485 conversion module: implemented using a MAX485 integrated circuit connected to the ESP32. This module is used to establish communication with the frequency inverter.
- Voltage converter: responsible for providing a 3.3 V supply voltage from the 5 V output of the main power supply. This conversion is necessary to ensure compatibility between the sensor and the ESP32 operating voltage levels.

The DHT22 (Aosong Electronics 2015) sensor is a device designed to measure temperature (−40 °C to 80 °C) and relative humidity (0% to 100%). The sensor uses a single-wire digital communication protocol and is supported by widely available libraries for Arduino and ESP-based platforms (Espressif Systems 2025).

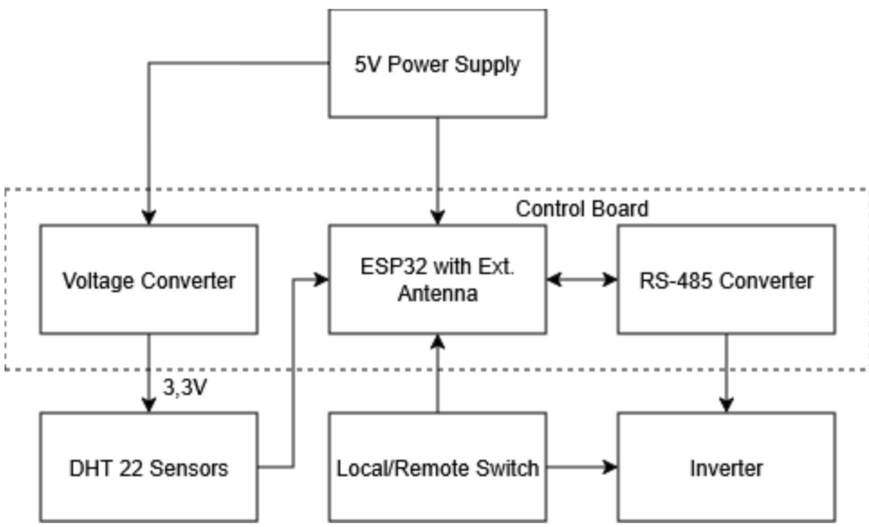

Fig 2. Control Board.

2.2 Software

The Home Assistant (HA) (HOME ASSISTANT, 2025) platform was selected as the supervisory software environment. HA is an open-source platform originally developed for home automation applications, providing integration between sensors, actuators, and smart devices through a unified interface. Although its primary purpose is residential automation, its flexibility, extensive device compatibility, and active development community have enabled its adoption in a wide range of monitoring and control applications beyond the domestic environment.

In the proposed system, HA functions as the central supervisory platform responsible for data visualization, alarm management, automation execution, and communication with external services. The software provides native support for communication protocols commonly used in

IoT systems, including Message Queuing Telemetry Transport (MQQT), enabling seamless integration with embedded devices and industrial equipment. In addition, the platform allows the development of customized dashboards for real-time monitoring of temperature, relative humidity, and equipment operating conditions.

Among the protocols commonly adopted in IoT systems, the MQTT protocol has become one of the most widely used due to its lightweight architecture and low bandwidth requirements (OASIS 2019). MQTT operates using a publish-subscribe model, where devices publish information to specific topics and other devices subscribe to those topics to receive updates. This communication structure reduces network traffic and facilitates the integration of multiple sensors, controllers, and supervisory applications.

One of the main advantages of HA is its accessibility. As a free and open-source solution, it significantly reduces implementation costs when compared with conventional Supervisory Control and Data Acquisition (SCADA) systems. Furthermore, the platform includes built-in tools for automation creation, historical data management, and third-party integrations, reducing the need for proprietary software solutions. Its modular architecture also allows users to customize interfaces and implement application-specific functionalities according to operational requirements.

These characteristics make HA a suitable alternative for agricultural monitoring systems where flexibility, scalability, and low deployment cost are important design requirements. The combination of Raspberry Pi hardware and HA software provides a robust supervisory infrastructure capable of supporting monitoring, automation, and decision-support applications in grain storage facilities.

Communication between the different components of a monitoring and control system is a fundamental requirement for ensuring reliable data exchange and coordinated operation. In agricultural IoT applications, communication protocols are responsible for transmitting sensor measurements, equipment status information, and control commands between field devices and supervisory platforms (Ojha et al. 2015).

In monitoring and automation systems, communication protocols provide the infrastructure required for data acquisition, remote supervision, automation routines, and alarm management. By enabling reliable information exchange between hardware devices and software platforms, these protocols support the integration of sensing, communication, and control functions within a unified supervisory environment.

Figure 3 presents an overview of the software communication structure adopted in the proposed monitoring system. The architecture is organized into three main layers: the sensing layer, responsible for data acquisition; the communication layer, responsible for processing and transmitting information; and the storage layer, responsible for data persistence and visualization services. Through this structure, sensor measurements collected by the control board are transmitted via MQTT to the supervisory platform, where they can be stored, processed, and used for monitoring purposes.

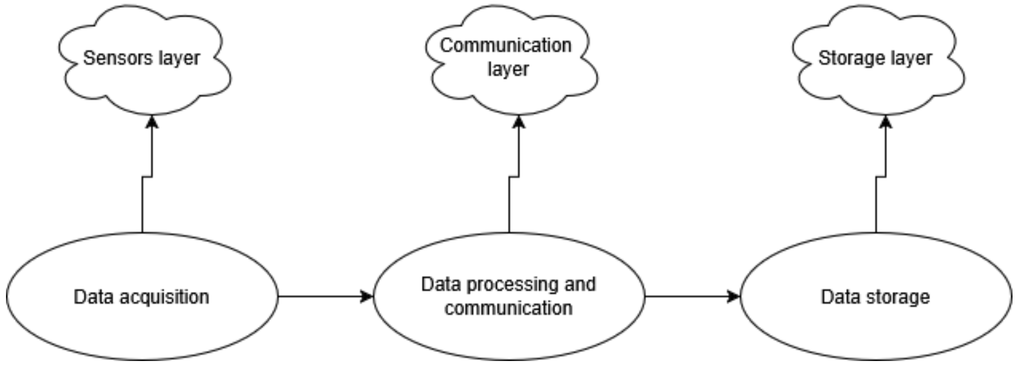

Fig 3. Diagram of the communication structure.

The publish-subscribe architecture enhances system scalability, enabling the addition of new devices and services without substantial changes to the current communication infrastructure. Additionally, MQTT supports real-time information exchange, making it suitable for monitoring applications that require continuous supervision of environmental conditions and equipment operation.

The platform receives temperature and relative humidity measurements collected by the control board through MQTT communication. In addition, operational data from the aeration system is obtained by the ESP32 from the frequency inverter using the Modbus RTU protocol. The acquired variables include, for instance, frequency, voltage, current, inverter operating status, power factor, active power, DC bus voltage, motor torque, and motor speed. These data are processed and organized into entities that can be used by dashboards, automation routines, and notification services. Through this structure, HA acts as the central integration layer between sensing devices, communication services, visualization tools, and control equipment.

In the proposed MACS, notification services are used to inform operators about system operation, equipment status, and abnormal conditions. The notification framework continuously monitors the information collected from sensors and field devices, enabling the generation of alerts whenever predefined conditions are detected.

The system is capable of notifying users about communication failures, sensor malfunctions and equipment operating faults, reducing the need for continuous supervision of the monitoring dashboards. Notifications can be delivered through e-mail and instant messaging services, allowing operators to receive timely information regardless of their location.

In addition to fault reporting, the notification system supports remote supervision by providing operational updates and status information related to the grain storage process. These capabilities improve situational awareness, facilitate decision making and contribute to the overall reliability of the monitoring and automation infrastructure.

3. Case Study

The MACS was implemented in a small brickwork silo (Figure 4) with a storage capacity of 420 bags (60 kg each) of rice. The silo is located at the Araranguá Training Center of the Agricultural Research and Rural Extension Company of Santa Catarina (CETRAR/EPAGRI), in Araranguá, Santa Catarina, Brazil. The silo is equipped with an ILS560 centrifugal fan manufactured by Projelmec Ventilação Industrial Ltda., driven by a WEG W22 three-phase electric motor with a rated power of 5 cv. More information regarding this type of silo can be found in the work of Martins et al. (2013).

Fig 4. Small brickwork silo where the MACS was installed.

To evaluate the behavior of temperature and relative humidity at different locations within the grain mass, nine sensors were distributed throughout the silo. The grain mass height was divided into three layers, with each layer containing three sensors positioned at different locations. An additional sensor was installed above the grain mass, while another was placed outside the silo, allowing the measurement of the temperature and relative humidity of the output air from the grain mass and of the ambient external air, respectively. Furthermore, a control panel was installed, housing the control board with the ESP32 microcontroller and the Variable Frequency Drive (VFD), which supplies variable-frequency electrical power to the motor-fan assembly. The ESP32 communicates with a Raspberry Pi 4 through a wireless network using the MQTT protocol. Figure 5 illustrates the implementation of the MACS.

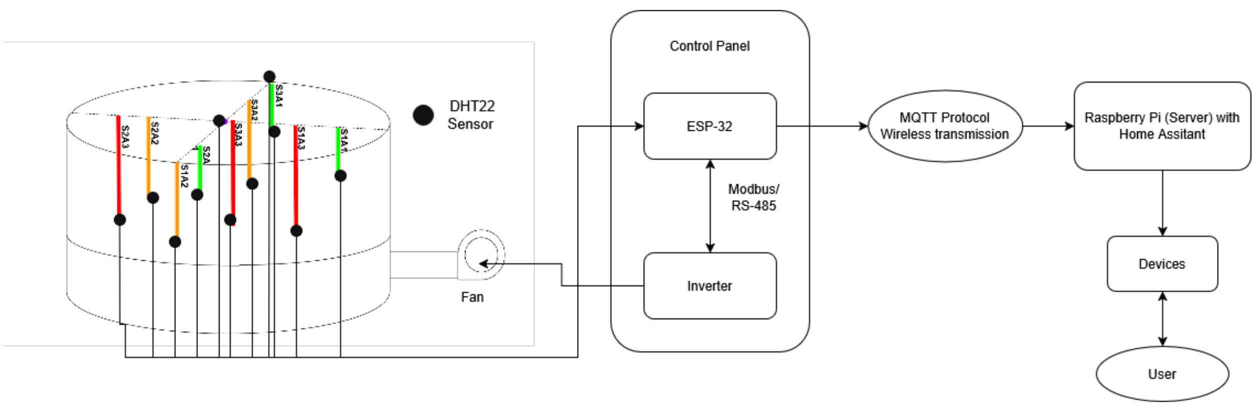

Fig 5. Diagram of the installation of MACS at EPAGRI.

Since the sensors may require maintenance during the rice drying and storage period, a structure was designed to allow maintenance procedures to be performed even when the silo is fully loaded with grain. In addition, aiming to provide a lower-cost alternative that would be more feasible for small-scale producers, sensor probes were developed using Chlorinated Polyvinyl Chloride (CPVC) pipes. These pipes provide greater mechanical strength than conventional Polyvinyl Chloride (PVC) pipes. As shown in Figure 6, the probes are attached to two metal crossbars installed at the top of the silo. Perforated cable trays were also mounted on these crossbars, allowing the sensor cables to be routed through the trays and into the probes.

Fig 6. Sensor installation inside the silo.

To ensure contact between the sensors and the intergranular air, multiple holes were made in the section of the pipe inserted into the grain mass. A fine mesh was added to prevent rice kernels from entering through these openings. Figure 7 shows the resulting probe design.

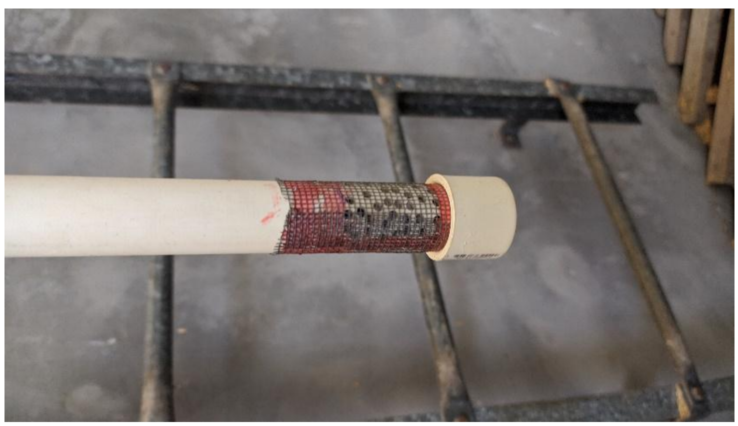

Fig 7. Measurement probe.

A control panel was installed inside an enclosure constructed from marine plywood. Since this structure is located outdoors, it is important to use materials capable of withstanding environmental exposure. The panel components were organized into three transparent-lid enclosures. One enclosure houses the control board and receives the wiring from all sensors. A second enclosure contains the WEG CFW500 VFD (model CFW500C14P0T4DB20), which controls the motor-fan assembly responsible for air circulation inside the silo. The third enclosure contains the surge protection devices and connectors used for three-phase power distribution. Figure 8 presents the complete assembly. The control panel also includes a selector switch that allows the operating mode to be chosen between local and remote operation. In local mode, fan motor activation and operating frequency adjustment are performed exclusively through physical devices, such as switches and a potentiometer. In remote mode, these adjustments can only be performed through HA. It is important to emphasize that the selection of the operating mode does not affect the monitoring functions of the system's physical variables.

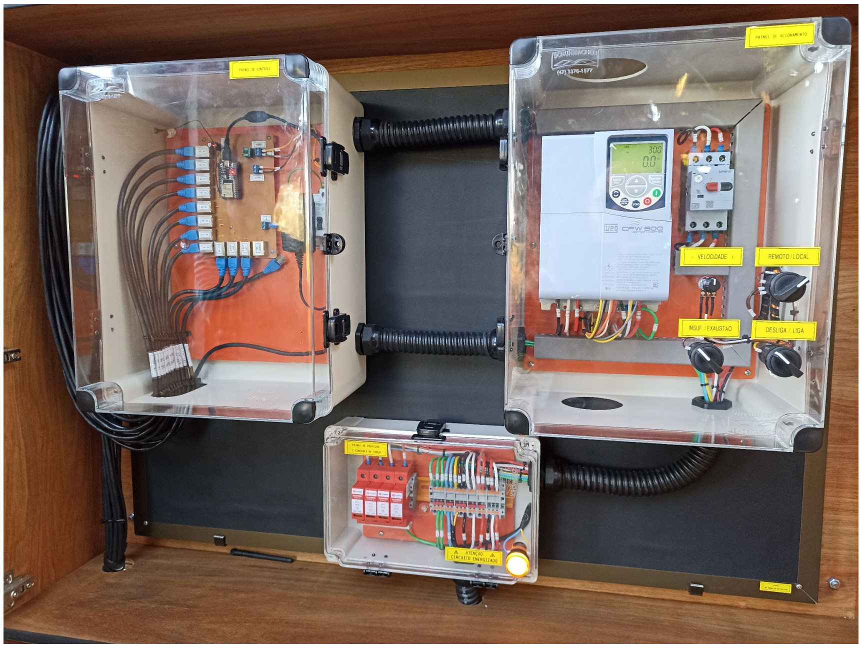

Fig 8.Control panel.

The supervisory and automation infrastructure of the proposed MACS was implemented using the HA platform installed on a Raspberry Pi 4 SBC. Several dashboards were developed for system supervision. The supervisory interfaces provide real-time visualization of sensor measurements, operating conditions, and alarm states. One example of these dashboards is shown in Figure 9. In addition to conventional monitoring panels, an interface for Proportional, Integral, and Derivative (PID) controller was developed, allowing operators to set up the gains and the variable to be controlled.

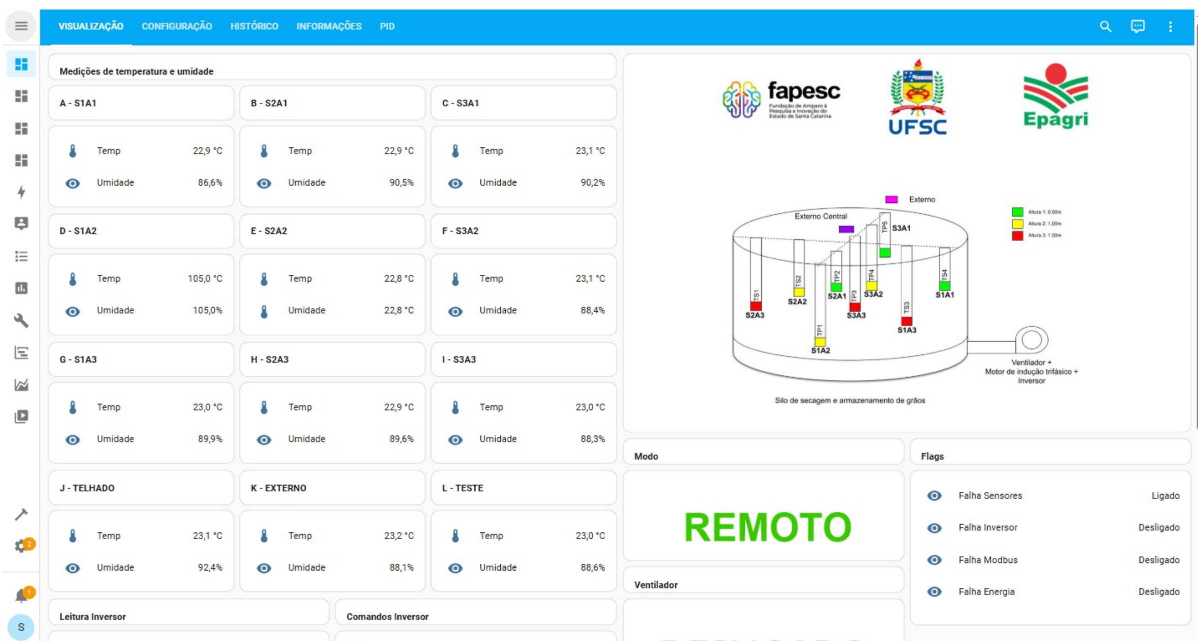

Fig 9. Main HA dashboard.

To support historical analysis of storage conditions, HA was integrated with the Grafana visualization platform. Sensor measurements are continuously stored and displayed through standardized dashboards, enabling users to evaluate temporal variations of temperature and relative humidity during drying and storage operations. The graphical environment allows the selection of specific periods and facilitates comparisons among sensors installed at different locations within the silo.

Routines were implemented to supervise the operational status of the monitoring system and the ventilation equipment. Dedicated variables were created to detect communication interruptions, MQTT failures, power outages, and ventilation system faults. Whenever abnormal conditions are identified, HA automatically updates the corresponding alarm indicators and executes predefined response actions.

A notification subsystem was also implemented to improve remote supervision capabilities. The platform was integrated with Telegram messaging services and e-mail delivery systems, allowing automatic alerts to be transmitted whenever fault conditions persist for a predefined period. In addition to fault notifications, periodic status reports are generated and distributed to authorized users, providing information regarding system connectivity and operational conditions.

To facilitate data management and future analysis, automatic routines were developed to export operational data in CSV format. Temperature, humidity, ventilation status, and inverter operating information are periodically recorded together with timestamp information and stored locally on the supervisory server. These files can be downloaded directly from the HA interface, simplifying data retrieval and post-processing activities.

The integration of monitoring, automation, visualization, notification, and data storage functions within a single platform simplified system management and reduced implementation costs, demonstrating the potential of HA as a supervisory solution for agricultural monitoring applications.

4. Experimental Results

The Monitoring, Automation, and Control System has been operating continuously in the grain storage facility since 2024. During this period, the system has been used to monitor environmental conditions within the grain mass, supervise ventilation system operation, and collect historical data for storage analysis.

The implementation demonstrated stable operation under field conditions, allowing continuous acquisition and storage of temperature and relative humidity measurements. The developed supervisory infrastructure also enabled remote monitoring, automated alarm generation, and long-term data archiving, reducing the need for on-site inspections.

To evaluate the system performance and illustrate its monitoring capabilities, data collected during a test with the fan operating at a 30 Hz frequency are presented in Figures 10 and 11. The temperature and relative humidity measured by sensors at 3 different layers are shown in the graphs: A1 is the top layer (0.5 m depth), A2 is the middle layer (1.0 m depth), and A3 is the bottom layer (1.5 m depth). The SUP and EXT correspond to measurements taken by the sensors above the grain mass and outside of the silo, respectively.

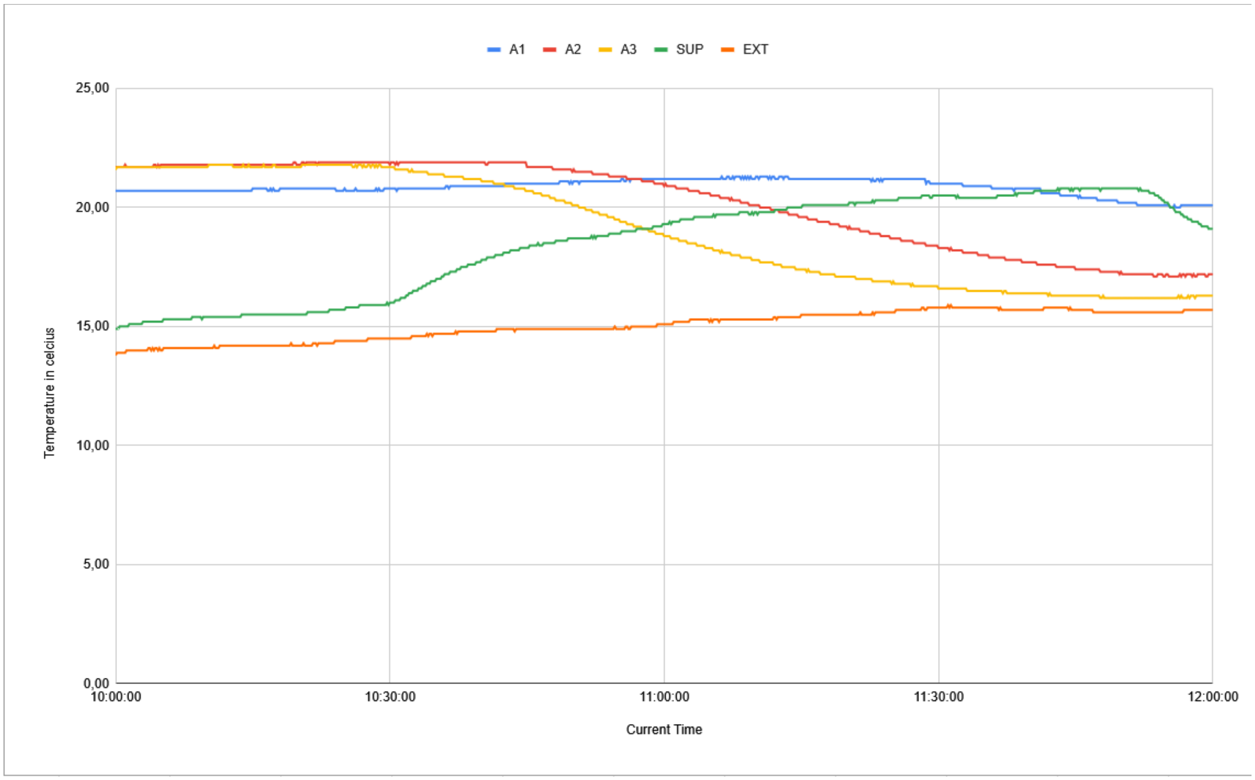

Fig 10. Temperature data collected for MACS during a test.

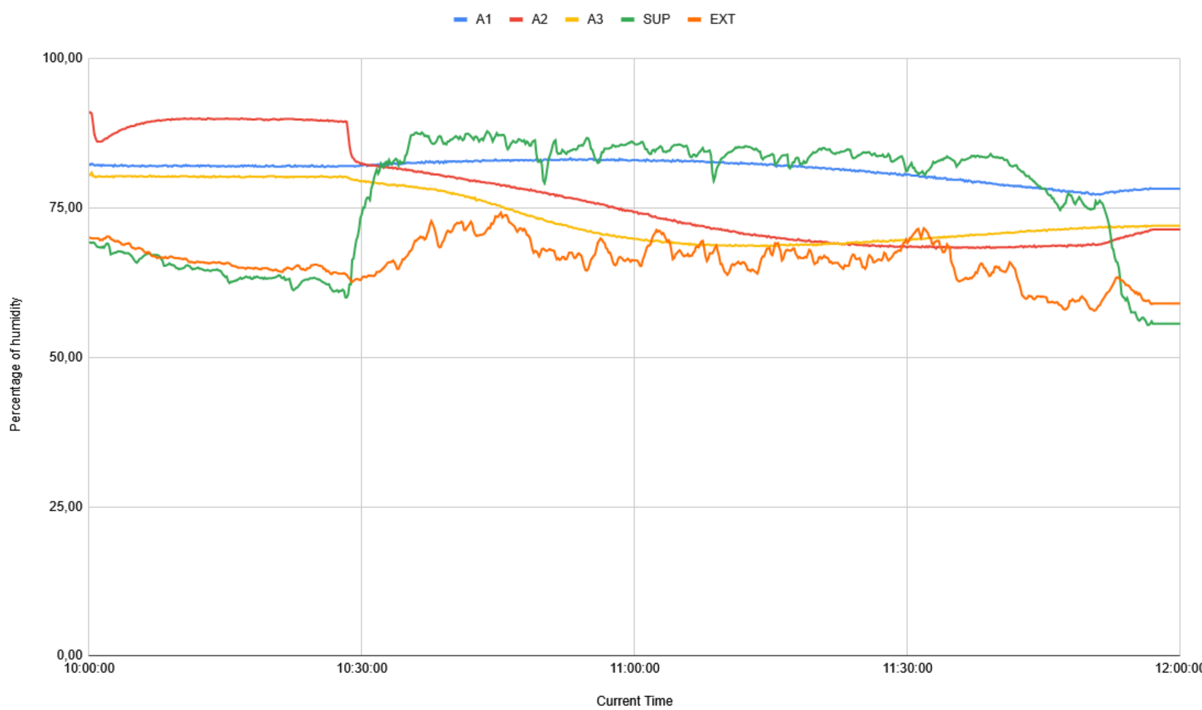

Fig 11. Humidity data collected for MACS during a test.

The silo was fully loaded with rice, and the fan was turned on approximately at 10:30. It is possible to observe on Figures 10 and 11 a propagation delay among the different grain layers. The bottom layer is the first to exhibit variations in intergranular air temperature and relative humidity. This response is followed by the middle layer and, finally, by the top layer. Both variables exhibit a tendency to follow the behavior of the external air temperature and relative humidity, indicating the influence of the aeration process on the grain mass. Additionally, analysis of the air temperature and relative humidity measured at the top of the silo, above the grain layer, reveals that these variables begin to increase as soon as the grain layers start to respond to the aeration process. This behavior suggests the upward movement of conditioned air through the grain mass, carrying heat and moisture toward the upper region of the silo. Since the natural air is insufflated on the bottom, this performance is consistent with the expected curves for this type of silo.

5. Conclusions and future works

A system for monitoring, automation, and control of small-scale silos was proposed in this paper. The MACS is composed of an SBC, a control board, temperature and humidity sensors, and a VFD, which allows for the adjustment of the airflow of the drying process. The system can be operated locally, using a potentiometer and switches, or remotely, by means of a supervisory system. The collected data, such as temperature and relative humidity of intergranular air and the electrical variables of the VFD, can be easily accessed by the user. The system was designed using low-cost devices and free software, which makes it an accessible option for small-scale producers. The MACS was implemented in a small brickwork silo for stationary drying and storage of rice, located in Araranguá, Santa Catarina, Brazil. The experimental results demonstrate that this system correctly monitors physical variables and can be used as a tool to manage the drying process.

The authors believe this work will contribute to improving the performance of the grain drying and storage process, particularly for brickwork silos, which are mainly used by small-scale producers. For future works, studies are being conducted to design and implement strategies that aim to improve the grain drying and storage process by means of the automatic control of the temperature and humidity of the intergranular air. Furthermore, these strategies would improve the grain quality, reduce the grain loss, and enhance the energy efficiency of the process, since it would be possible to adjust the airflow according to the drying and storage conditions.

6. Acknowledgements

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