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Development of a low-cost virtual instrumentation prototype for coffee roasting based on the Internet of Things (IoT)

Desarrollo de un prototipo Low-Cost de instrumentación virtual para el tostado del café basado en el Internet de las Cosas (IoT)

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Abstract

Implementing an instrumentation system in the coffee roasting process can help to improve the quality of the coffee produced by small-scale farmers in the Ecuadorian Amazon region. The proposed system aimed to design and implement a low-cost device capable of monitoring the coffee roasting process locally or remotely by applying Internet of Things (IoT) technology. The implemented IoT architecture was based on a model that integrates a data acquisition unit (DAQ), a main control unit (MCU), an IoT communication protocol, and a software-defined network (SDN) that connects the IoT broker, nodes, data server, Internet access gateway, and end-user devices. As a result, a low-cost virtual instrumentation system based on IoT technology was implemented, which enabled the publication of process variables acquired by the DAQ to the Mosquitto IoT broker through the Message Queuing Telemetry Transport *(MQTT) protocol. These variables were stored in the InfluxDB time-series database and visualized through a dashboard designed in Node-RED and Grafana.*
Keywords: Broker; Coffee roasting; IoT; MQTT.

Resumen

La implementación de un sistema de instrumentación en el proceso de tostado del café puede incidir en la mejora de la calidad del producto elaborado por los pequeños productores de la región amazónica ecuatoriana. El sistema propuesto tuvo como objetivo diseñar e implementar un equipo de bajo costo que permita monitorear de manera local o remota el proceso de tostado del café aplicando la tecnología del internet de las cosas (IoT). La arquitectura de IoT implementada se basó en un modelo que integra una unidad de adquisición de datos (DAQ), una unidad de control principal (MCU), un protocolo de comunicación IoT y una red definida por software (SDN) que conecta el broker IoT, los nodos, el servidor de datos, el Gateway de acceso al internet y dispositivos finales de usuario. Como resultado de la presente investigación se implementó un sistema de instrumentación virtual de bajo costo basado en la tecnología IoT, el cual permitió publicar en el broker IoT Mosquitto mediante el protocolo MQTT los valores de las variables instrumentados por unidad de adquisición de datos (DAQ), las cuales fueron almacenados en la base de datos de series temporales InfluxDB y visualizados mediante un Dashboard diseñado en Node-RED y Grafana.
Palabras clave: tostado de café; MQTT; IoT; Broker.

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1 Introduction

Coffee production (*Coffea* sp.) involves a coordinated sequence of agronomic management, classification, drying, and heat treatment, with each stage affecting the behavior of the bean during roasting and the final profile of the beverage. In the commercial sphere, this crop sustains a global trade worth approximately 70 billion USD in annual exports (Figueroa *et al*., 2015). Within this scenario, differentiation based on origin, traceability, and specific sensory characteristics has become increasingly important, responding to a demand that prioritizes batches with productive identity and stability in quality attributes (Samoggia & Busi, 2023).

The most widely produced and commercialized coffee species worldwide are *Coffea arabica* (Arabica coffee), which accounts for nearly two-thirds of global production, and *Coffea canephora* (Robusta coffee), which represents about one-third of world production (Vega et al., 2017). In Ecuador, both species are cultivated: Robusta in the Amazon and coastal regions, and Arabica at higher altitudes (between 1,000 and 1,800 m above sea level).

Coffee is considered one of Ecuador's main crops and has excellent quality potential; however, it faces several challenges, including climate change, sustainability, and shifts in consumer behavior. In this context, the demand for specialty or gourmet coffees has increased in line with international trends. Nevertheless, due to the low price competitiveness of Ecuadorian coffee (high production costs) and the weakness of associative processes, these markets have not yet been fully exploited. It has been identified that Ecuador lacks certain factors necessary to be competitive in coffee exports, suffering from inadequate crop management, low productivity, unfavorable grain prices, and limited technological adoption (Yosa & García, 2021).

Currently, the best Ecuadorian coffee is no longer exported directly abroad (Cisneros, 2017). In cities such as Quito, Guayaquil, and Cuenca, there is a growing presence of coffee roasters using equipment from internationally recognized brands such as Diedrich, Probat, Toper, and The San Franciscan Roaster Company. Some coffee shops, e.g., Traviesa Coffee Roasters, perform on-site roasting to provide consumers with a closer experience, while most specialty projects choose to carry out their processes in dedicated production facilities, ensuring greater consistency and production volume.

Attaining high coffee quality is influenced by several factors, including post-harvest management and technological operations such as roasting and grinding (Bolka & Emire, 2020). Roasting degree and beverage flavor are determined by roasting time and temperature (Bauer *et al*., 2018; Gallardo *et al*., 2022). Achieving the ideal roast is a complex task since coffee beans behave differently and yield varying results in their physical properties, chemical composition, and biological activities under different roasting conditions (Hernández et al., 2018; Santos *et al*., 2016).

Over the last decade, the Internet of Things (IoT) has gained considerable visibility in monitoring and automation processes due to its inherent characteristics (Babun *et al*., 2021). The IoT has been implemented in diverse contexts, notably in agroindustry, precision agriculture, and livestock production (Mateos *et al*., 2022). Within this framework, a device was developed with the purpose of automating and supervising processes in the agro-industrial sector, enabling interventions both on-site and through IoT services. The instrumented data can be stored locally or via a cloud-based service (Chaparro *et al*., 2021).

Lawrence and Tariq (2019) proposed a SCADA (Supervisory Control and Data Acquisition) system based on the ESP32 microcontroller, which receives and processes data from various sensors. Historical data and human–machine interactions are stored on the IoT server *ThingsBoard*. Data transfer between the Message Queuing Telemetry Transport (MQTT) client and the *ThingsBoard* IoT server is carried out via a local Wi-Fi connection using the MQTT protocol. IoT plays a crucial role in coffee production under hygienic conditions, enabling the delivery of a product free from cross-contamination, ensuring both hygienic and efficient operation, and ultimately translating into profitable growth for investors (Rajendran *et al*., 2021).

MQTT has become established as the ideal communication protocol for IoT environments, as it is considered the most efficient protocol, specifically designed for unreliable networks with limited bandwidth and high latency (Hmissi & Ouni, 2022). MQTT operates through a publish/subscribe model, in which multiple clients connect to a single broker (Longo *et al*., 2020). The work developed by Guijarro-Rubio *et al*. (2025) proposed an open-source hardware and software monitoring system for environmental variables in greenhouse crops using a wireless sensor network based on IoT technology. The system integrates ESP32 and ESP8266 modules, Node-RED, and employs the MQTT protocol through a local Wi-Fi network to enable data exchange between client nodes and the server node. This system allows users to monitor temperature, atmospheric humidity, soil moisture, and ambient light levels. Complementarily, in the context of coffee processing, it has been shown that indirect monitoring based on computational processing contributes to process standardization, especially when it is necessary to maintain reproducibility between batches and reduce the variability associated with subjective operational criteria (Hernandez-Aguirre *et al*., 2019).

Processed coffee in the Amazon region faces significant limitations, as the methods employed remain largely traditional and highly dependent on climatic factors, particularly high environmental humidity. These conditions affect critical stages such as drying and post-harvest handling, directly impacting the quality of the beans destined for roasting and grinding (van Rikxoort *et al*., 2013). A technological gap has been identified between artisanal and industrialized processes, which influences both quality standardization and the competitiveness of Amazonian producers. Therefore, this research aimed to reduce this technological gap through the incorporation of innovative solutions based on electronics and virtual instrumentation, enabling small and medium-sized producers to improve process consistency and traceability during coffee roasting.Accordingly, the objective was to design and implement a low-cost, easy-to-install electronic device that allows coffee roasting to be monitored locally or remotely by applying IoT technology.

2 Materials and methods

The virtual instrumentation system based on IoT technology (Figure 1), implemented for monitoring the physical variables of the coffee roasting process, was developed from an architecture that integrates a data acquisition unit (DAQ) for signal capture, a main control unit (MCU) responsible for local processing, and an IoT communication protocol that ensures efficient information transmission. For data management, an MQTT client was employed to send information to an MQTT broker, which enables distribution to the different nodes within the network. The implemented IoT architecture facilitates both local supervision and remote access to process information, using low-cost open-source hardware (OSHW) (Bonvoisin *et al*., 2021) and open-source software (Nuñez *et al*., 2024).

2.1 Data Acquisition Unit (DAQ)

During the roasting process, coffee beans are exposed to temperatures between 100 and 200 °C, which triggers various internal chemical reactions (Juárez, 2017). In this process, the beans increase in size by 50 to 80% and lose 11 to 20% of their weight. The speed of the drum paddles influences the interaction between the beans and the hot air and the walls; if it is low, the beans overheat due to prolonged contact, increasing the risk of over-roasting.

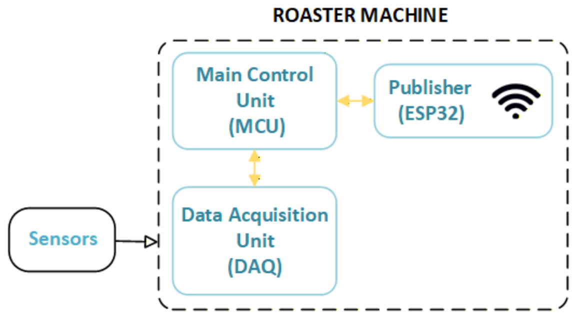

Figure 1. Electronic instrumentation system.

To ensure that the roasting process was properly carried out, the coffee roasting machine incorporated a DAQ that enabled the collection of information (Chaparro *et al*., 2021). Through this system, it was possible to monitor the drum temperature, the propelling motor temperature, and the paddle rotation speed.

The instrumentation of the roasting process involved the installation of five PT100 temperature sensors with a coefficient of 0.385 ?/°C to measure thermal conditions at different points on the drum surface and a K-type thermocouple for the motor, chosen for its resistance to high temperatures. An NPN inductive sensor recorded the speed of the drum without mechanical contact.

The data was acquired and processed in real time using an open-hardware micro-controlled platform, optimized for industrial monitoring, which transmitted the information to the MCU for centralized analysis and supervision.

Figure 2 shows the connection of the different sensors used in the electronic instrumentation system. The data acquisition system followed a master–slave communication approach, in which data transfer was carried out in a point-to-multipoint configuration using the Serial Peripheral Interface (SPI) protocol. The sensors transmitted data only when requested by the data acquisition system (Guijarro Rubio *et al*., 2021).

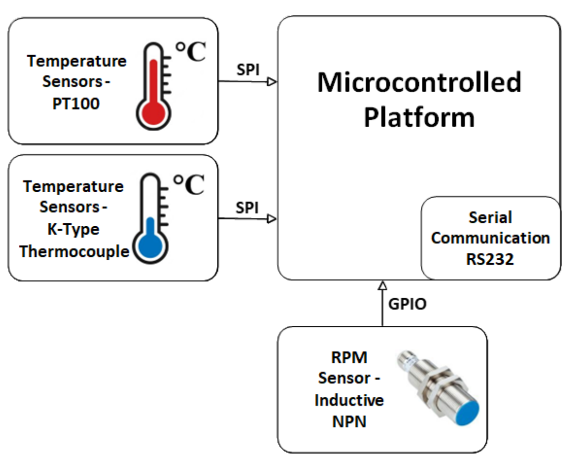

Figure 2. Data Acquisition System.

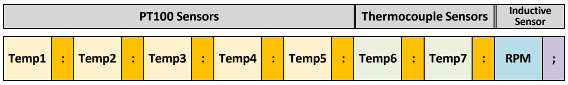

Figure 3. Data frame – Data Acquisition Unit (DAQ). Note. Temp: instrumented temperatures in the plant; RPM: revolutions per minute of the motor; ":" constant used as a data delimiter; ";" constant marking the end of the data frame.

The DAQ exchanges data with the MCU using the RS232 serial communication standard (Recommended Standard 232) at a transmission speed of 57,600 baud, with a transmission period of one second. Figure 3 shows the data frame generated by the DAQ. The data frame consists of 32 bytes. Each data value is transmitted using a fixed length of 3 bytes; 7 bytes are used as data delimiters, while 1 byte identifies the end of the data frame.

2.2 *Main Control Unit (MCU)*

The drum roaster machine for the coffee bean roasting process was designed, built, and semi-automated by the *Instituto Superior Tecnológico Francisco de Orellana* for the *Asociación de Producción Alimenticia Pueblo Nuevo*. The machine integrates various electromechanical systems, which are managed by the MCU. The MCU is based on an open-source hardware and software platform under the GNU General Public License and GNU Lesser General Public License (GNU, 2023). The unit was built on an ATmega2560 microcontroller from the 8-bit Atmel AVR family, featuring single-pipeline Harvard architecture (Mejía *et al*., 2022).

Based on the embedded firmware in the microcontroller, the MCU processes information from the various input peripherals, executes control actions on the roasting machine through actuators, manages the graphical liquid crystal display (GLCD), and interacts with the DAQ. Through the GLCD, the operator can visualize the different instrumented variables of the roasting process. Figure 4 presents a heuristic diagram of the process managed by the MCU within the coffee bean roasting machine.

2.3 *IoT Communication Protocol*

This research used the publish/subscribe communication model for the IoT network, which allows devices to publish and consume information through an intermediary or "topic," thus separating the data generator from the consumer (Oviedo *et al*., 2019).

Several communication protocols are compatible with IoT, including HyperText Transfer Protocol (HTTP), MQTT, Advanced Message Queuing Protocol (AMQP), Data Distribution Service (DDS), and Constrained Application Protocol (CoAP).

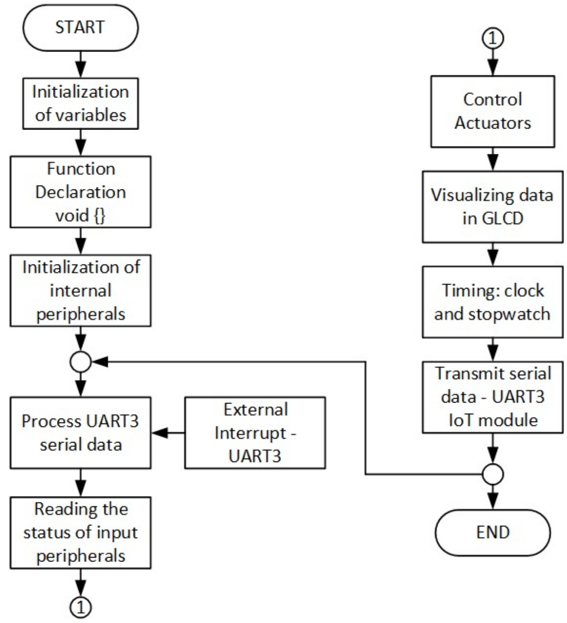

Figure 4. Flow diagram – Roasting machine control unit.

After analyzing its characteristics and compatibility with the ESP32 platform, MQTT was selected for this project. This protocol, based on the publish/subscribe model, is lightweight and efficient in bandwidth use, ideal for devices with limitations or unreliable networks. It offers three levels of Quality of Service (QoS); in this study, Level 2 was used to ensure the integrity of message delivery (Escobar & Villazón, 2018).

2.3.1 *MQTT client*

The IoT enables various physical devices to connect, communicate, and share data automatically through both private networks and the Internet. IoT devices have been applied across multiple sectors, ranging from domestic to industrial (Sánchez *et al*., 2022), and have been implemented in contexts such as agroindustry, agriculture, industry, and medicine (Chanchí *et al*., 2022). Several development platforms are compatible with IoT; among the most widely used are development modules based on System-on-Chip (SoC), e.g., ESP32, ESP8266, MGM240P, and DA16200.

Due to its hardware characteristics and versatility, the ESP32 platform was selected as the main module of the MQTT client. This device offers dual core with 600 DMIPS and IEEE 802.11 b/g/n Wi-Fi connectivity, operating at 2.4 GHz and compatible with various IoT protocols. It was configured in station mode to connect to the network and publish data to the broker via MQTT (Vera *et al*., 2022).

Through UART communication, the MQTT client receives the values of the variables instrumented by the DAQ, which are then published to the MQTT

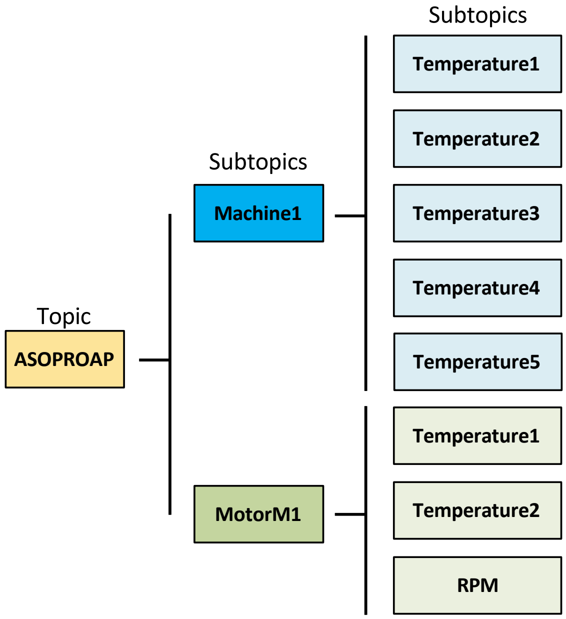

Figure 5. Topics and subtopics for data publishing.

broker using topics and subtopics. Figure 5 illustrates the topics and subtopics through which the values of the different sensors installed in the coffee roaster are published.

The temperature sensor values and the motor RPM of the roasting machine are published through two main subtopics, “Machine1” and “MotorM1”, which belong to the topic “ASOPROAP” (Asociación de Producción Alimenticia Pueblo Nuevo [Pueblo Nuevo Food Production Association], Ecuador).

2.3.2 *MQTT broker*

The IoT broker is responsible for distributing data among clients (publishers and subscribers) and enables connection and communication between IoT devices and applications or services. For data routing, a primary broker and a backup broker were used.

Eclipse Mosquitto is a cross-platform open-source software distributed under the EPL/EDL license that supports the MQTT protocol and is compatible with low-resource hardware. It was implemented as the primary broker on an IBM System x3250 M2 server running Ubuntu 18.04. As the backup broker, HiveMQ was used, which operates in the cloud with high availability.

2.4 *IoT network architecture*

The implemented IoT architecture was based on a four-layer model (capture, storage, analysis, and visualization) (Chanchí *et al*., 2022):

1. **Capture:** This layer consists of the DAQ built on the Arduino Nano development board, which orchestrates the coffee roasting process through various sensors.

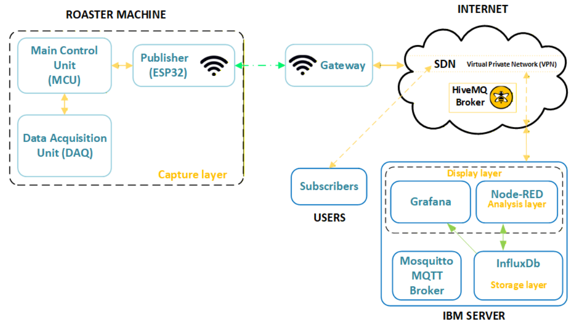

Figure 6. Implemented IoT network architecture.

2. **Storage:** The MQTT client establishes a TCP/IP connection with the broker, which registers the clients and keeps the connection active until it is closed. After the CONNECT and CONNACK messages are exchanged, the variables acquired by the DAQ are published via the main or backup broker using MQTT.

Node-RED, installed together with InfluxDB on an IBM server, acts as a subscriber client and stores the received data in the InfluxDB time series database.

3. **Analysis:** The published data are processed and analyzed using the Node-RED program before being stored in the database.

4. **Visualization:** The variables of interest are visualized in real time through dashboards developed in Node-RED and Grafana, which can be accessed by users locally or remotely through a Software-Defined Network (SDN). At this stage, the instrumented variables involved in the coffee roasting process can be continuously monitored.

The IoT infrastructure consists of an SDN that interconnects the IoT broker, MQTT clients, data server, Internet access gateway, and end-user devices. Figure 6 illustrates the IoT network architecture implemented for the virtual instrumentation of the coffee roasting machine.

In terms of hardware, the implemented IoT infrastructure is composed of the following components:

1. **End-user device:** This enables direct interaction with the user through computers, mobile phones, and IoT end nodes, among others.

2. **Server:** Two types of servers are employed: a physical access server that runs the IoT broker, various services, and databases; and a cloud-based server specialized for MQTT (Message Queuing Telemetry Transport) messaging.

3. **Gateway:** The gateway connects the IoT nodes to the Internet and the SDN, enabling data exchange between the local broker and the cloud server.

4. **Smart devices:** These are the publisher nodes that integrate the IoT network and exhibit the following characteristics (Medina et al., 2022):

a) **Processing capacity:** The MQTT client is based on the ESP32 module, which can be programmed to meet the needs of the roasting machine and is compatible with various IoT communication protocols.

b) **Identification:** Each node has an IP address for its connection to the Internet and the SDN and a unique MQTT identifier for recognition.

c) **Interaction with the environment:** The IoT node of the roasting machine perceives its environment through the DAQ.

d) **Connectivity:** The MQTT client was developed using the ESP32 module as the main component, which features Wi-Fi connectivity in the 2.4 GHz band and is compatible with the IEEE 802.11 b/g/n/e/i standard.

Regarding software, management was carried out through four levels closely linked to the hardware.

1. **Frontend:** Two user interfaces are provided, depending on the assigned access level.
   a. **End-user access level:** The end user can view real-time and historical data using Grafana software but does not have access to programming.

   b. **Programmer access level:** In addition to the end-user access level, the programmer can configure the IoT broker, databases, server, and Grafana and Node-RED dashboards (Torres *et al.*, 2023).

2. **Backend:** This layer manages information, including storage, processing, and conversion. For this project, the open-source time-series database InfluxDB was used (Navarro *et al.*, 2021).

3. **Communication:** The MQTT protocol was used for communication between the MQTT client and the IoT broker.

4. **Software – smart devices:** The Arduino Integrated Development Environment (IDE) was used to program the ESP32 module; however, this device is compatible with various programming languages, such as MicroPython, C, and C++.

To validate the applicability of the end-user interface, semi-structured interviews and surveys were conducted with twelve coffee producers belonging to ASOPROAP. The instruments were designed to collect qualitative and quantitative information related to usability, perceived benefits, and the adaptability of the system to roasting practices. The survey included closed-ended questions based on a Likert scale (1–5) to assess ease of use, reliability, and perceived impact on product quality, while open-ended questions allowed suggestions for improvement to be collected. The information obtained was used to complement the experimental validation results and analyze the system's potential for adoption in real production contexts.

3 Results and discussion

The virtual instrumentation system, implemented using open-source hardware and software (Chanchí *et al.*, 2022) and based on IoT technology (Puranik *et al.*, 2019), enabled the continuous and structured recording and storage of critical variables in the coffee roasting process in the InfluxDB time series database. The implemented architecture combined local signal acquisition, reliable data transmission, and temporary/historical storage for traceability/ This facilitated not only real-time monitoring but also subsequent analysis to optimize roasting profiles and detect anomalous events.

The data acquisition unit (DAQ) was developed with Arduino (Wali & Areeb, 2018) and integrated five PT100 sensors and a K-type thermocouple, strategically distributed over the surface of the drum and in the motor housing to capture thermal gradients and critical thermal stress points. These sensors provided measurements with an approximate stability of ±2 °C in the operating range of 100–200 °C, which is sufficient to control and reproduce roasting profiles. The combination of resistance sensors (PT100) and K-type thermocouples takes advantage of the accuracy and linearity of PT100s in medium ranges and the robustness of thermocouples in areas of high thermal variability.

According to the literature, the optimal thermal window for achieving light, medium, or dark roasting profiles is between 180 and 200 °C. Within this range, key phenomena such as caramelization, Maillard browning, and the degradation of organic acids, responsible for sensory and aroma changes in the bean, are intensified (Bauer *et al.*, 2018; Freitas *et al.*, 2024). The availability of time records enables the accurate correlation of chemical breakages and sensory events, such as the onset of the first crack, thereby standardizing profiles that reduce variability between batches.

Storing the variables in the InfluxDB database and the open IoT architecture facilitated integration with visualization and analysis tools, providing traceability, feedback capability for automatic control, and support for advanced modeling and control techniques. These benefits are aligned with best practices in industrial environments where databases optimize queries, compression, and the retention of data relevant to predictive maintenance and operational efficiency (Wang et al., 2025).

The NPN inductive sensor accurately recorded the drum's rotational speed, an essential parameter to ensure homogeneous heat transfer. Low rotational speeds expose the beans to overheating due to prolonged contact with the drum wall, whereas excessively high speeds limit their interaction with hot air (Juárez, 2017).

The MQTT client developed on the ESP32 module demonstrated highly efficient and stable performance, confirming its suitability for real-time industrial monitoring applications. Using a QoS 2 quality of service level, a 99% delivery rate of 32-byte frames was achieved, even under latency conditions of up to 2 seconds, validating the robustness of the MQTT protocol in environments with unstable or unreliable connectivity. This behavior is due to the intrinsic characteristics of the protocol, which guarantee the delivery of messages exactly once, avoiding duplication or loss of information. In Industrial Internet of Things (IIoT) systems, where the continuity of data flow is critical in order to monitor production processes, MQTT's ability to maintain communication integrity under network variations is essential (Hmissi & Ouni, 2022).

Recent studies have shown that implementing QoS not only improves message integrity and reliability; it also optimizes energy performance and transmission efficiency in low-power IoT devices. In agro-industrial environments, this feature is particularly relevant, as it allows for accurate information to be collected from sensors distributed in rural areas with limited connectivity, ensuring the traceability of critical parameters such as temperature and humidity (Sadeq *et al*., 2019). The integration of the MQTT protocol with distributed architectures with time series databases enhances scalability and reduces overall system latency, making its application viable in automation and control processes in smart agro-industrial plants (Hoque *et al*., 2024).

The publish/subscribe architecture implemented in the system allowed for efficient decoupling between the data producer, represented by the coffee roasting machine, and the information consumers, such as display panels or dashboards. This approach enabled greater scalability and flexibility, as multiple devices or applications can simultaneously subscribe to the data without affecting system performance. The dashboards developed in Node-RED and Grafana provided an intuitive interface for real-time monitoring, allowing the operator to view critical process variables and access stored historical records for trend analysis and batch traceability. Unlike low-cost systems that use limited platforms such as Blynk or simple mobile applications, this integration offers more robust, secure, and professional data management geared toward industrial automation and data-driven decision-making (Purnata *et al*., 2025).

During the practical validation of the system, control panels were implemented in Node-RED and Grafana, which permitted the real-time visualization of process variables and complete traceability of the roasting stages (Castillo Landínez *et al*., 2019). Thanks to these tools, the operator could continuously monitor critical parameters such as drum temperature, motor temperature, and the motor's revolutions per minute (RPM), ensuring thermal and mechanical stability during the process. In addition, the panels provided visual and dynamic graphical alerts, facilitating the early detection of anomalies or deviations from optimal values. This monitoring and historical recording capability improved the repeatability of the roasting process and also optimized the quality of the final product by ensuring the precise control of operating conditions and promoting data-driven decision-making.

Figure 7 shows the data obtained by five temperature sensors strategically located at different points on the roaster drum in order to evaluate the thermal distribution of the system. The sensors recorded values between 184.5 and 196.7 °C, a range that falls within the optimal thermal window for achieving light, medium, or dark roasting profiles typical of specialty coffee (Bauer *et al*., 2018; Habara & Horiguchi, 2024). This behavior confirms adequate heat uniformity in the roasting chamber, an essential condition for ensuring the balanced development of the chemical reactions responsible for the aroma and flavor of the bean. An engine temperature of 40.9 °C and a rotation speed of 44 RPM were recorded; these values ensure the mechanical stability of the system and homogeneous heat transfer, minimizing the risk of overheating or uneven roasting.

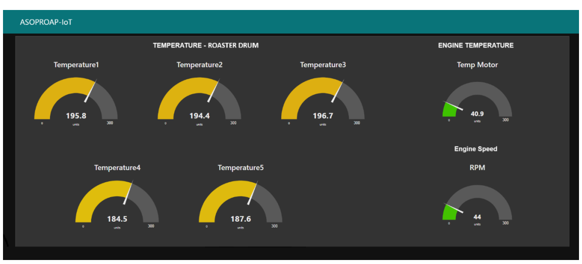

Figure 7. Dashboard developed in Node-RED for monitoring temperatures and motor speed in the coffee roaster.

Figure 8. Dashboard developed in Grafana with historical records of temperature and rotational speed.

The thermal behavior recorded during roasting is directly related to the physicochemical changes that the beans undergo. Gradual reduction favors the expansion of the internal matrix and a decrease in apparent density, which coincides with the phase where an increase in volume and the appearance of the first crack are observed (Al-Shemmeri *et al.*, 2024). At temperatures above 150 °C, the conditions recorded by the system will favor the Maillard reaction between reducing sugars (glucose and fructose) and amino acids present in the bean matrix (Alamri *et al.*, 2022). During this phase, intermediates such as 5-hydroxymethylfurfural, furfural, maltol, and reductones are formed, which progressively give way to alkyl pyrazines (2-methylpyrazine, 2,3-dimethylpyrazine), furfuryl mercaptan, and 2-acetylpyrrole (Alamri *et al.*, 2022; Alcantara *et al.*, 2025; Toledo *et al.*, 2016). These compounds have been identified as direct precursors of the aromatic profile of roasted coffee due to their contribution to nutty, caramel, and toasted bread notes (Obando & Figueroa, 2024).

As the temperature approaches the range between 180 and 200 °C, conditions for sucrose caramelization become evident, contributing to sweet notes and more complex aromatic profiles (Zakidou *et al.*, 2021). In more advanced stages of the thermal profile, the pyrolysis of chlorogenic acids and lipids begins to modify acidity and bitterness (Cao *et al.*, 2023).

The need for thermal control is related to the results obtained in industrial-scale rotary drying processes, where adjusting the air temperature and mass flow has been shown to directly influence the thermal efficiency and energy consumption of the process (Prada *et al.*, 2019). In Guardiola-type systems, the optimization of operating parameters made it possible to reduce energy consumption by up to 15.8% while maintaining the bean temperature below 45 °C, a necessary condition for preserving the sensory quality of coffee (Hernández-Díaz *et al.*, 2013). This supports the viability of scaling monitoring systems based on continuous data acquisition.

Figure 8 shows the Grafana interface, where, in addition to instantaneous values, the temporal trends of drum and motor temperature are plotted. This historical recording capability strengthens process traceability, as it allows the identification of thermal fluctuations, real-time parameter adjustments, and the evaluation of machine performance across different roasting batches. Such features are consistent with the observations of Xu *et al.* (2018), who emphasize the importance of dynamic monitoring to ensure consistency in the final product.

The incorporation of an SDN into the system infrastructure allowed for the efficient structuring and control of data flow, ensuring that only previously authorized devices could access the network. This type of architecture facilitates the logical segmentation of traffic, optimizing communication between different IoT nodes and reducing exposure to external vulnerabilities. SDN enables centralized and dynamic network management, allowing intrusion attempts to be detected, isolated, and mitigated in real time, thus strengthening the security of the information transmitted (Theodorou & Mamatas, 2017). This approach is consistent with current trends in industrial cybersecurity, which promote the integration of adaptive control mechanisms and advanced authentication policies in IIoT environments to protect the integrity and reliability of operational data (Babun *et al.*, 2021).

The proposed system is a low-cost, scalable, and easy-to-install alternative for small- and medium-sized producers in the Amazon region, who still rely on traditional methods based on sensory experience to control the roasting process. Thanks to the real-time instrumentation and monitoring of critical variables such as drum temperature and rotation speed, it is possible to reduce losses due to over-roasting and ensure consistent flavor profiles between production batches. This technological capability allows for greater precision in thermal management, improving the quality of the final product and reducing the variability associated with manual operation. The system supports complete process traceability, an attribute increasingly valued by international specialty coffee markets, which demand homogeneity, technical control, and evidence of sustainable production. In this way, the adoption of IoT technologies in the coffee agroindustry strengthens the competitiveness and commercial projection of Amazonian producers, aligning with the growing global demand for specialty coffees (Samoggia & Busi, 2023).

According to our survey results, the coffee producers showed high acceptance of the IoT-based virtual instrumentation system, highlighting its ease of use (92%) and effective integration into artisanal roasting processes (85%). The participants agreed that monitoring the drum temperature and the speed in real time improves roasting consistency and product quality, reducing reliance on sensory judgment and enabling more objective decisions. The need for initial training in the use of the Grafana interface was identified, as well as an interest in extending the technology to other stages, like drying or storage. These results confirm the technical and social viability of the system, its scalability to larger capacity facilities, and its potential application in other associations or pilot plants. In line with recent studies, the adoption of open technologies and IoT systems in agribusiness improves the competitiveness, sustainability, and traceability of small producers (De Felice *et al*., 2025).

The analysis of the local socioeconomic context revealed that small- and medium-sized producers in the Amazon region face financial and technological constraints that limit their adoption of automated systems. Most producers operate under family or associative schemes with low profit margins, highlighting the need for low-cost, open, and easy-to-implement technologies, such as the one proposed in this study. Opportunities for financing mechanisms were identified, namely public programs to promote agro-industrial innovation driven by the Ministry of Agriculture and Livestock (MAG) and international cooperation funds. Although limited in rural areas, the local technological infrastructure offers favorable conditions in terms of electricity availability and basic connectivity, thus enabling the stable operation of the IoT system with remote support. The integration of virtual instrumentation contributes to strengthening coffee quality and traceability certification systems by ensuring the historical recording of critical process variables.

The standardization of roasting processes through electronic instrumentation increases the added value of coffee, as specialized markets offer higher prices when there is technical evidence of quality control (Yosa & García, 2021). The ability to record and analyze historical data allows one to optimize the production process and reduce energy consumption and emissions associated with roasting, which is consistent with studies that highlight the environmental benefits of IoT in sustainable agro-industrial operations (Liu *et al*., 2025; Tsai et al., 2025). This alignment between technological innovation, socioeconomic context, and regulatory frameworks reinforces the practical, economic, and environmental viability of the system, as well as its regional scalability to other associations and pilot plants.

The incorporation of IoT technologies not only optimizes operational efficiency but also strengthens the competitiveness, traceability, and sustainability of the Amazonian coffee sector. This digitization process represents a key axis for the modernization of agribusiness, facilitating data-driven decisions, process automation, and continuous improvement in product quality. Various studies highlight that the adoption of smart solutions in the agricultural value chain contributes to increased productivity and reduced environmental impact, thus enhancing the resilience of small producers in the face of global market demands (Ciruela *et al*., 2020).

The main contribution of this system lies in its ability to transform raw data into meaningful and actionable information, representing a substantial advance over traditional sensory control methods. Before the implementation of this system, operators relied exclusively on empirical criteria and subjective perceptions to determine the roasting point, which led to variability in the quality of the final product. With the implementation of the IoT system, critical process variables such as temperature, rotation speed, and heat exposure time can be monitored in real time and automatically adjusted according to defined parameters. In addition, the ability to store and analyze historical records for each batch enables comparative evaluations and iterative optimization of roasting profiles, ensuring greater consistency and operational efficiency. This data-driven approach promotes a culture of continuous improvement and consolidates the use of technology as a decision-making support tool in the coffee agroindustry sector.

The data stored in InfluxDB provides essential information for the development of a dynamic mathematical model of the roasting system, as well as for the identification of its transfer function, opening up the possibility of designing advanced automatic control systems based on fuzzy logic, optimized PID control, or predictive strategies (MPC). These methodologies will make it possible to accurately follow customized roasting profiles, adapting to the variable conditions of each batch and ensuring uniformity in the final quality of the product. In line with Rajendran *et al*. (2021), the integration of IoT in the coffee industry contributes to improving efficiency and operational safety and also drives the automation of critical stages. This strengthens the competitiveness of Amazonian producers and favors their insertion in global markets dedicated to specialty coffee.

From a technological scalability perspective, the proposed system can be expanded to larger industrial platforms by integrating multiple synchronized IoT nodes that record thermal, mechanical, and environmental variables from several roasters or even entire processing plants. The architecture based on InfluxDB, Node-RED, and Grafana allows for the management of large volumes of data with high sampling frequency without compromising performance, while the use of the MQTT protocol ensures efficient communication between thousands of geographically distributed devices. In this way, people can build comprehensive roasting and traceability management systems that are scalable and replicable in associations or production networks, consolidating an Industry 4.0 model applicable to the Amazonian and Latin American coffee sector.

In order to strengthen the practical applicability of the system and its potential impact in the real world, a stakeholder mapping exercise will be carried out in the future to identify the key players in the coffee ecosystem, including producers, associations, government institutions, higher education institutions, certification bodies, and financial institutions. This process will enable the identification of barriers to technology adoption, as well as opportunities for public-private collaboration. The analysis of these interactions will facilitate the design of participatory strategies to promote technology transfer and the sustainability of the proposed model. These actions complement the technical basis developed in this work, contributing a social and economic dimension that enhances the scalability, acceptance, and sustainability of the IoT system in real agro-industrial production contexts.

Conclusions

This study demonstrates the technical and economic feasibility of a low-cost virtual instrumentation system based on IoT for local and remote monitoring of the coffee roasting process. The architecture developed with open-source hardware and software overcame the reliance on empirical methods by providing real-time quantitative data that enabled process standardization and ensured product homogeneity. The integration of the ESP32 module as an MQTT client, along with Node-RED for backend management and InfluxDB for historical data storage, ensured accurate variable acquisition, reliable data transmission, and process traceability—key elements for improving the final quality of coffee in semi-industrial environments.

An additional contribution of this research was the in-house design and fabrication of the data acquisition board, which reduced costs and enabled scalability by facilitating the future integration of new sensors or actuators. In this way, the system not only enhances roasting consistency and provides traceability but also offers an adaptable model for other agro-industrial processes. Consequently, it stands as an accessible tool for small- and medium-sized producers, contributing to the democratization of IoT technology and laying the foundation for future developments in automation and advanced coffee roasting control.

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