ISSN: 1692-7257 - Volume 1 – Number 45 - 2025

RCTA
Revista Colombiana de Tecnologías de Avanzada
UNIPAMPLONA

Digital Object Identifier: [10.24054/rcta.v1i45.3283](https://doi.org/10.24054/rcta.v1i45.3283)

IoT and 4.0 technologies for traceability and food safety in cocoa

Sistema de trazabilidad de cacao soportado en Internet de las cosas

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Received: *july 01, 2024.* ***Accepted:*** *november 18, 2024.* ***Published:*** *january 01, 2025.*

How to cite: *J. Gómez Gómez, C. A. Parra Urueta, and J. J. Guzmán Pineda, "IoT and 4.0 technologies for traceability and food safety in cocoa", RCTA, vol. 1, no. 45, pp. 204–215, jan. 2025.*
Recovered from https://ojs.unipamplona.edu.co/index.php/rcta/article/view/3283

Abstract: This research ensures traceability and food safety throughout the cocoa agro-industrial process, from seed selection to commercialization. A traceability system was developed using Laravel, a web application, and a REST API for management and commercialization, along with an IoT device equipped with sensors (Raspberry Pi) to monitor fermentation, complying with the NTC 1252 standard. The project, conducted in Tierralta, Córdoba, involved three phases: characterization of producers' needs, system development, and testing with training. Additionally, an interactive timeline was implemented using Next.js to visualize processes. This solution improves product quality, optimizes resources, and generates key data for future decision-making, enabling the systematization and standardization of processes, as well as the identification of strengths and weaknesses across the cocoa production chain.

Keywords: traceability, food safety, IoT, cocoa industry, agricultural technology.

Resumen: Esta investigación asegura la trazabilidad y seguridad alimentaria en el proceso agroindustrial del cacao, desde la semilla hasta la comercialización. Se desarrolló un sistema de trazabilidad basado en Laravel, una aplicación web y una API REST para la gestión y comercialización, y un dispositivo IoT con sensores (Raspberry Pi) para monitorear la fermentación, cumpliendo la norma NTC 1252. El proyecto, en Tierralta, Córdoba, involucró tres fases: caracterización de necesidades de productores, desarrollo del sistema y pruebas con capacitación. Además, se implementó una línea de tiempo interactiva con Next.js para visualizar procesos. Esta solución mejora la calidad del producto, optimiza recursos, y genera datos clave para decisiones futuras, permitiendo la sistematización y estandarización de procesos, así como la identificación de fortalezas y debilidades en la cadena de producción del cacao.

Palabras clave: trazabilidad, seguridad alimentaria, IoT, industria del cacao, tecnología agrícola.

1. INTRODUCTION

Cocoa is an agricultural product of significant economic relevance worldwide. Countries like Ecuador are renowned for the quality of their cocoa, allowing them to export derivative products, such as cocoa butter and oil, to demand markets. However, participation in these markets may be hindered by the lack of quality certifications and the need to innovate to develop products with higher added value [1].

Cocoa cultivation and processing also have considerable social impacts. In regions such as Santander and Colombia, cocoa is a flagship product that has helped communities develop and tackle economic challenges, especially during global uncertainties such as the post-pandemic period [2]. The cocoa industry faces several challenges that affect its sustainability and growth, including

· The quality of cocoa can vary significantly owing to factors such as growing conditions and processing methods, which impact its utility [3].
· Maintaining food safety is crucial, especially in international markets where strict certifications are required to ensure the quality and safety of cocoa-derived products [1].

Traceability has become an essential requirement in the food supply chain because of the need to minimize risks to ensure product quality and reliability. This system enables tracking of the product throughout the entire supply chain and sharing information among the various stakeholders involved. Not only does it help comply with the required regulations but it also provides real-time information management capabilities, ensuring food safety through technological tools that enable complete monitoring. Implementing traceability systems is particularly relevant for products such as cocoa, where the quality can vary significantly depending on factors such as cultivation and processing. Traceability helps ensure that products meet the quality standards expected of consumers and auditors [4].

Food safety is crucial in cocoa production because of the risks associated with lack of control during the production process, such as contamination or inconsistencies in quality. Food safety involves not only the prevention of physical, chemical, or biological contamination but also ensures that products meet quality and safety standards [5].

The absence of an effective traceability system hinders the tracking of cocoa from its origin to the final consumer, potentially leading to quality issues and an inability to efficiently manage food safety. Moreover, the lack of transparency in the supply chain facilitates unethical practices, such as labor exploitation and unsustainable trade [6].

Using the Internet of Things (IoT) for cocoa fermentation allows real-time monitoring of environmental conditions, ensuring proper and consistent fermentation. This facilitates product traceability throughout the supply chain. This research seeks to implement a traceability system that contributes to food safety in the cocoa agro-industrial chain using Industry 4.0, and IoT technologies. The aim is not only to support the quality and safety of cocoa but also to provide valuable data for future decision-making.

This article is structured to begin with a review of the literature related to 4.0 technology applied to the cocoa sector. The implemented methodology is then described and organized into three main phases:

- Phase 1: Need for characterization and requirements design.
- Phase 2: Development of the Traceability System and IoT Device.
- Phase 3: Field Testing and Staff Training.

Subsequently, the results obtained in each phase are presented, followed by the discussions generated from this research. Finally, the conclusions of the study are outlined and the bibliographic references used are provided.

2. LITERATURE REVIEW

This state-of-the-art research is structured around two main thematic axes. The first focuses on IoT technologies applied to cocoa production processes and traceability, highlighting how these technological tools contribute to improving product quality and safety. The second thematic axis emphasizes precision agriculture, aligned with the objectives of this research. For the first thematic axis, we found that there is limited research applying the mentioned technologies to cocoa; however, the following relevant studies were identified:

IoTCocoa – an IoT platform to assist gourmet cocoa production: This research presents an IoT-based platform to monitor and control the fermentation and drying processes of gourmet cocoa. This study demonstrates how the use of middleware as an intermediary layer between hardware and software can optimize network traffic and reduce server load, improving the critical processes in fermentation and drying necessary for producing high-quality cocoa [7].

Combining REST and SNMP for HTTP traffic optimization: A case study on gourmet cocoa drying: This study explores the optimization of HTTP traffic during the gourmet cocoa drying process. It highlights the implementation of a decentralized application (DApp) that captures data from IoT devices and stores them in smart contracts, thereby enhancing the security and efficiency of the natural drying process of cocoa [8].

Assessment of the Role of Innovative Technology through Blockchain Technology in Ghana's cocoa bean food supply chains: This study evaluates the role of blockchain technology in Ghana's cocoa supply chain, highlighting how the integration of innovative technologies can improve traceability and transparency in cocoa production, with a particular focus on the quality and safety of the final product [9].

Enabling Privacy and Traceability in Supply Chains using Blockchain and Zero Knowledge Proofs: This study addresses the implementation of blockchain and zero-knowledge proofs to enhance privacy and traceability in supply chains. Although the study does not focus exclusively on cocoa, it offers a useful framework that can be applied to ensure integrity and transparency in the cocoa supply chain [10].

SVM-guided dynamic routing for postharvest quality preservation in smart warehouses with IoT: This article focuses on the use of advanced techniques such as SVM-guided dynamic routing to preserve postharvest quality in smart warehouses using IoT. While centered on warehouses, the methodologies discussed can be applicable for improving traceability and quality management in the cocoa production chain [11].

This study presents the design and implementation of a traceability system to support the cocoa production model in the Nariño mountain range, Colombia. Using a social mapping approach and spiral model, the system was designed to capture and query key information for decision-making. The system was adapted to the specific needs of producers, allowing for more efficient and personalized management of the cocoa production process [12].

The second thematic axis of this state of the art focuses on the application of precision agriculture in cocoa. Precision agriculture aims to optimize crop management using advanced technologies such as sensors, data analysis, and predictive modelling. In this context, the following studies explore how these technologies can improve efficiency, reduce waste, and ensure sustainability in cocoa production, thereby contributing to producers' competitiveness in demanding markets: Classification of Fresh Cocoa Beans with Pulp Based on Computer Vision: This study presents a computer vision technique for classifying fresh cocoa beans with pulp. This research uses morphological operations, k-means clustering, a visual bag-of-words model, and a support vector machine (SVM) to achieve high classification accuracy, thus enhancing the pulp removal process and estimating cocoa quality. This approach not only optimizes the quality of the final product but also reduces the time and labor required for small- and medium-sized cocoa farms [13].

Derivation of High Spatio-Temporal Resolution Leaf Area Index and Uncertainty Maps by Combining LAINet, CACAO, and GPR: This study proposes a framework for generating high spatio-temporal resolution Leaf Area Index (LAI) and uncertainty maps using a combination of wireless sensor networks (LAINet), climate adjustment methods (CACAO), and Gaussian process regression (GPR). This approach allows for precise vegetation monitoring, which is crucial for precision agriculture and the validation of LAI products in cocoa-growing regions [14].

Object Detection Approach for Batch Detection of Cacao Bean Defects: This study developed an object detection approach to identify defects in cocoa bean batches using advanced computer vision techniques. Early defect detection is essential for ensuring cocoa quality, and this research demonstrates how precision agriculture can be effectively applied in post-harvest quality control of cocoa [15].

Relevant Study: Urban Gardens with Precision Agriculture in Controlled Environments: This study explored the implementation of a precision agriculture system in urban gardens using controlled environments. This highlights how the integration of sensors, automated control systems, and real-time monitoring platforms can optimize crop production under adverse climatic conditions. Although this study focuses on crops other than cocoa, the methodologies and technologies discussed are highly applicable to cocoa management in controlled environments, where variables such as temperature, humidity, and light can be carefully regulated to maximize productivity and product quality [16].

3. METHODOLOGY

This research is structured in the following three phases, each described below.

3.1. Phase 1: Needs Characterization and Requirements Design.

In this phase, several analyses were conducted in collaboration with the Integrasinu Association to understand the specific needs of cocoa producers. Various UML diagrams were structured, including sequence, use case, activity, and sequence diagrams. These diagrams helped to clearly and thoroughly visualize the processes involved, allowing for the identification of key requirements for the information system needed to ensure traceability in the cocoa agri-food chain.

The following diagram illustrates the five-step flow developed to conduct the interactions for the needs characterization and requirements design.

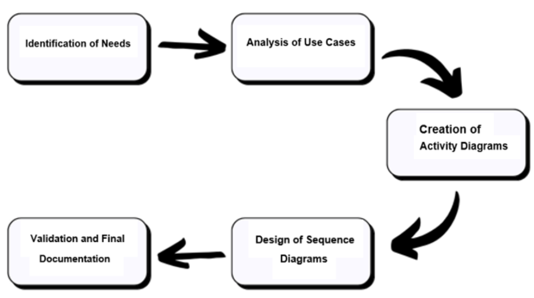

***Fig. 1**. Flow of Needs Characterization and Requirements Design.*
***Source:** own elaboration*

3.2. Phase 2: Development of the Traceability System and IoT Device.

With the software requirements defined, the system architecture was designed to ensure scalability and low implementation costs. During this phase, various technologies were evaluated to guarantee that the system could grow efficiently and meet the traceability objectives in the cocoa agro-industrial chain. Tools and frameworks were selected based on their balance between performance, scalability, and cost-effectiveness, allowing for agile development aligned with the needs identified in the previous phase.

The selected technologies are:

Laravel for the development of the logical traceability system due to its scalability and optimal performance in web environments. Laravel also offers robust tools for creating REST APIs, which were essential for integrating the public timeline and cocoa commercialization.

Next.js was chosen for frontend development, specifically for the interactive visualization of cocoa traceability in the timeline. Next.js enables rapid and efficient development with a focus on server-side rendering, enhancing the user experience.
Raspberry Pi and IoT Sensors: Raspberry Pi was selected due to its low cost and flexibility, along with temperature and humidity sensors such as DHT11 and DS18B20. These devices are ideal for monitoring critical conditions during cocoa fermentation.

The system architecture provides a modular and scalable approach, allowing future updates without significant restructuring. The main components of the system include a central database, a REST API, a web application, and IoT devices. Each module (backend, frontend, IoT) was efficiently designed and integrated to facilitate real-time data communication and synchronization. The web application development included functionalities to manage cocoa transformation processes, from post-harvest to commercialization. This included the ability to record, monitor, and visualize traceability data in real time. Additionally, an interactive public timeline was developed using Next.js, allowing end-users to view cocoa traceability from seed to final product, fostering transparency and building consumer trust.

For IoT device integration, sensors were configured on a Raspberry Pi to collect critical data, such as material temperature and relative humidity during fermentation, ensuring compliance with the NTC 1252 standard. This device was integrated with the traceability system to send real-time data to the central server, enabling continuous monitoring and alert generation if critical conditions deviate.

To ensure that all system components operated together seamlessly, integration testing was performed, including real-world usage scenario simulations to verify system functionality. Based on these test results, adjustments and optimizations were made to enhance system performance and usability.

Finally, detailed technical documentation covering all aspects of the system's development—from architecture and design to implementation and testing—was produced, which is essential for future maintenance and user training. Additionally, user manuals and guides were created for producers and other stakeholders, explaining how to use the system's functionalities and interpret the generated data.

3.3. Phase 3: Field Testing and Staff Training.

In this phase, in-person and virtual training sessions were conducted to ensure that end-users understood and could effectively use the developed tools. The in-person training sessions were held in Tierralta, Córdoba, where producers were trained on the use of the traceability software, the IoT device, and the timeline visualization. During these sessions, detailed instructions were provided on how to operate the traceability system, interpret the data collected by the IoT device, and use the visualization tool to track cocoa traceability from seed to final product.

4. RESULTS

The results obtained are presented for each phase executed in the methodology, as detailed below.

4.1. Phase 1: Needs Characterization and Requirements Design.

In the process diagram, three stages are identified. The first stage encompasses the agro processes, including the benefit center, the second is industrial transformation, and the last is commercialization. In figure 2, you can see the process diagram.

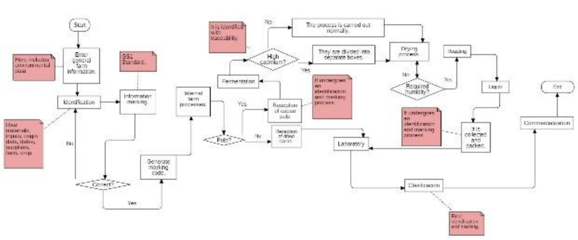

***Fig. 2**. Process Diagram*
***Source:** own elaboration*

When analysing the issues with the above diagram, an Inputs, Processes, and Outputs (IPO) diagram was detailed to determine the structure of the batch, such as its inputs and the output, which is a QR code with the URL to the timeline. The fermentation's environmental variables are provided by an embedded system (Raspberry Pi, sensors, and APIs); the process variables are recorded by farmers or field personnel, while scientific variables are recorded by researchers, see figure 3.

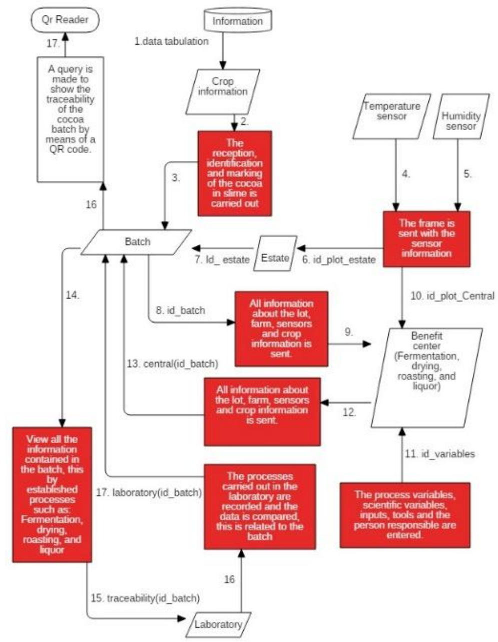

***Figure 3**. IPO Diagram*
***Source:** own elaboration*

This analysis led to a breakdown of the three-stage system. The first stage includes the following modules:

- Farm Management for fermenting cocoa in its raw pulp state.
- Nursery Management: Detailed nursery records, including information on cocoa genotype, irrigation, and agrochemical applications.
- Land Management: Land records with options to add significant events, including details on land preparation, permanent and temporary shade, linked to one or multiple nursery processes.
- Planting Management: Records and manages activities such as irrigation, agrochemical application, and soil treatments.
- Harvest Management: Records one or more harvests associated with a specific planting.
- Fermentation Management: Includes two modalities:
  - Collection Fermentation: Selects the farm, monitoring device, and genotype for foreign fermentation.
  - Farm Fermentation: Similar to the foreign fermentation, but the selected

item for fermentation is the specific harvest rather than the genotype.

- Drying Management: Selection of the fermentation process and record of the amount of dried cocoa at the end of the process.
- Collection Management: Generation of the collection order to create a shipping guide to the industry.

This is illustrated in the following general use case diagram.

For fermentation, various literature sources were consulted, as well as techniques used in the field, based on the experience of the Integrasinu association. From this analysis, it was determined that the temperature of the cocoa pulp, relative humidity, and ambient temperature are critical variables that must be carefully monitored during the fermentation process. These variables are essential for making informed decisions and ensuring adequate control at each stage of the process, thus guaranteeing the final quality of the cocoa.

Research highlights include the following:

The internal temperature of the cocoa mass during fermentation is a determining factor in grain quality, influencing flavor development and the elimination of undesirable compounds. Adequate temperature control optimizes microbial activity, essential for the formation of aroma and flavor precursors in cocoa.

The ideas of Schwan and Wheals regarding temperature's influence on grain quality, alongside the latest findings on the crucial role of temperature in optimizing microbial activity during fermentation, were particularly insightful [17], [18].

4.2. Phase 2: Development of the Traceability System and IoT Device.

In this phase, an architectural diagram was developed, providing a modular view of the solution, allowing for a clear understanding of how the different system components interact. The traceability solution was implemented as external software, designed to effectively integrate with the IoT device. This device is equipped with an SQLite database, serving as a backup system to safeguard collected data when internet coverage fails, ensuring no critical information is lost during fermentation. This modular and resilient structure allows the system to operate reliably even in environments with limited connectivity, see figure 4.

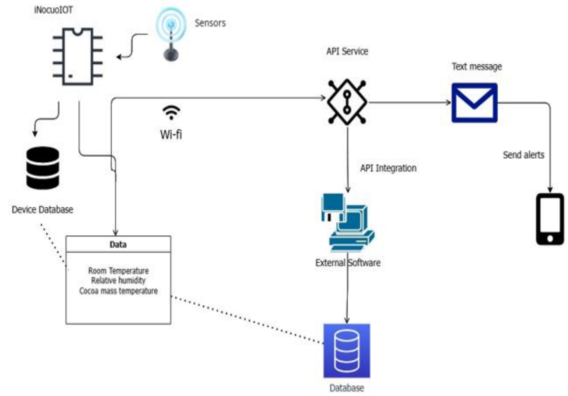

Fig. 4. *Architecture Diagram*
Source: *own elaboration.*

The class diagram for the first stage covers the agro and post-harvest phases. This diagram is essential for identifying and representing the abstraction of objects involved in the process, providing a clear visualization of the relationships between them and how they interact within the traceability system. Creating this diagram was key for structuring and organizing the data coherently, facilitating the development and implementation of the traceability system.

For the second stage, the following class diagram outlines the processes:

Cocoa Reception: Manages cocoa reception according to the NTC 1252 standard, ensuring the quality and classification of the received cocoa.

Roasting: Records variables such as temperature and roasting time, along with observations and resting processes.

Grinding: Details the grinding process, including initial and final weight, steps, and yield.
Shelling: Parameters such as speed, aspiration, and weight of obtained nibs.

Refining: Control of variables like temperature, time, yield, and particle size.

Conching: Tracks the mixture of ingredients, including cocoa liquor, butter, sugar, and additives, along with process conditions.
In figure 5, you can see the class diagram.

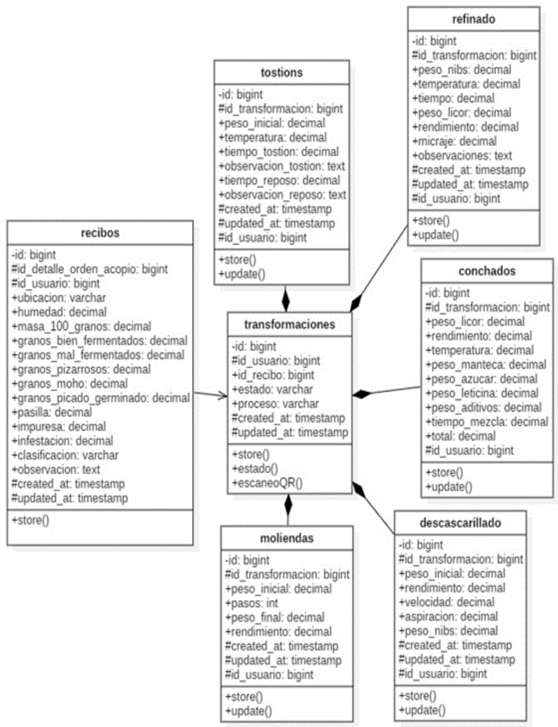

***Figure. 5**. Class Diagram for the Second Stage*
***Source:** own elaboration.*

The figure 6 shows relevant screenshots of the solution. Each module is designed to be intuitive and functional, facilitating access to information and managing critical processes within the system.

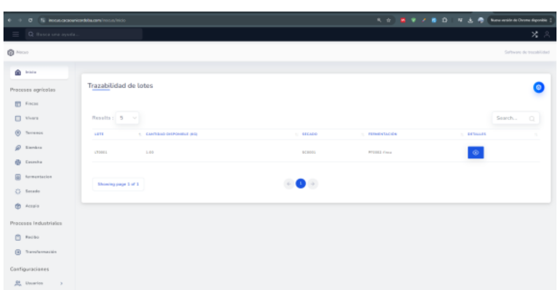

***Figure.6**. Traceability Software*
***Source:** own elaboration.*

The IoT device is equipped with four DS18B20 thermocouples, each of which can be assigned to a specific fermentation process. This allows for detailed and simultaneous monitoring of different fermentations, ensuring that critical variables, such as temperature, are precisely controlled in each batch. Assigning each thermocouple to an individual fermentation provides an additional level of control and precision in the process, which is fundamental for maintaining cocoa quality, see figure 7.

***Figure 7**. DS18B20 Thermocouples*
***Source:** own elaboration.*

The DHT11 sensor, responsible for measuring ambient temperature and relative humidity, plays a crucial role in monitoring environmental conditions during fermentation. This data is fundamental to ensure that the fermentation environment is optimal, allowing process parameters to be adjusted as needed to maintain cocoa quality, see figure 8.

***Figure 8**. DHT11 Sensor*
***Source:** own elaboration.*

The circuits are mounted on a PCB board, ensuring an orderly and secure layout of electronic components. Additionally, a fan was incorporated to maintain an adequate temperature for the components, preventing overheating and ensuring continuous and stable operation. A chassis was also designed to facilitate access for maintenance, enabling quick and efficient interventions, when necessary, see figure 9.

Figure 9*. Physical Circuit*
Source: *own elaboration.*

For commercialization, an interactive timeline was developed using Next.js, providing credibility and transparency to all stakeholders involved in the supply chain. This tool offers a clear and detailed visualization of the cocoa journey, from seed to final product, ensuring that each stage of the process is fully traceable. By scanning the QR code, users can access this timeline, obtaining a comprehensive view of the product's history, reinforcing trust in the quality and authenticity of the cocoa, see figure 10.

Figure 10*. Timeline for Commercialization*
Source: *own elaboration.*

4.3. Phase 3: Field Testing and Staff Training.

In this phase, the technological solution was implemented directly in the field, ensuring its integration into the actual processes of the cocoa agro-industrial chain. Field testing allowed for the validation of the system's functionality in an operational environment, identifying and adjusting for any specific challenges presented by the terrain. The following images capture key moments of this implementation, including the installation of the IoT device, real-time monitoring of fermentation conditions, and hands-on training of the producers and personnel involved. These images not only illustrate the technology deployment but also highlight Integrasinu's commitment to adopting new tools that enhance the traceability and quality of the produced cocoa, see figure 11.

Figure 11. *IoT Device Installation and Staff Training*
Source: *own elaboration.*

5. DISCUSSION

The primary objective of this research was to ensure traceability and food safety throughout the entire cocoa agro-industrial chain, from seed selection to the final product's commercialization. By implementing an information system based on Industry 4.0 and IoT technologies, the goal was to provide credibility and transparency at every stage of the process, ensuring that products meet the quality and safety standards demanded by international markets.

The results obtained demonstrate that this objective was successfully achieved. The implemented traceability system allowed for precise, real-time monitoring of critical conditions during cocoa fermentation, a key process that directly influences the final product's quality. Furthermore, the use of an interactive timeline for commercialization provided consumers and other stakeholders with access to detailed information about the origin and treatment of the cocoa, reinforcing confidence in the product.

Food safety was significantly improved by being able to monitor and record conditions such as temperature and humidity during fermentation. This ensured that critical variables remained within optimal ranges, minimizing the risk of contamination or deviations in cocoa quality.

The implementation of IoT and Industry 4.0 technologies played a crucial role in achieving this project’s objectives. The integration of IoT devices, such as the Raspberry Pi and DHT11 and DS18B20 sensors, enabled continuous, real-time monitoring of environmental conditions during cocoa fermentation.

Fermentation was conducted for genotype ICS-1, a clone valued not only for its sensory quality but also for its potential in the international market. The production of fine or aromatic cocoa, such as ICS-1, allows small and medium-sized farmers to access better prices and market opportunities globally. This is essential for the sustainable development of agriculture in cocoa-producing regions, such as Peru and Colombia [19].

It is important to note that the flavor and aroma quality of ICS-1 cocoa is influenced by the fermentation and drying processes. Studies have shown that adequate fermentation time and controlled drying can significantly enhance the sensory properties of cocoa, increasing the intensity of its aromatic notes, thereby categorizing it as a special cocoa for premium chocolate [20].

The following graph illustrates the material’s monitored temperature during this fermentation, conducted at an average relative humidity of 60% and an ambient temperature of 28.8°C, see figure 12.

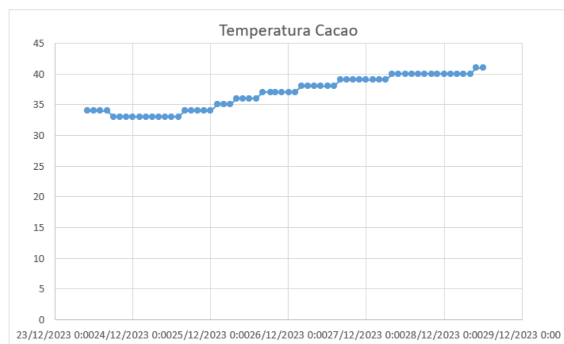

Figure 12. *ICS material temperature graph-controller.*
Source: *own elaboration.*

During the implementation of the traceability and real-time monitoring system, significant challenges were encountered related to connectivity. This region often has limited or unstable access to internet networks, which could have compromised the continuous collection of critical data for the cocoa fermentation process. To mitigate these challenges, an SQLite database was integrated into the IoT device, allowing temporarily collected data to be stored when the internet connection failed. This backup solution ensured that no information was lost, maintaining the integrity of monitoring and keeping control over the process.

The deployment of Industry 4.0 technology requires a learning curve that can be steep, as many farmers are not familiar with using electronic devices or interpreting the generated data. Additionally, the successful implementation of these technologies requires continuous training to ensure that users understand and can effectively use the tools at their disposal.

These technologies ensure that critical processes are carried out within optimal parameters. As a result, the produced cocoa is of superior quality, which enhances its perception both nationally and internationally. This quality improvement can increase the competitiveness of producers in markets where consumers increasingly value traceability and transparency in food production [21].

More precise control of the fermentation process not only reduces waste risk but also optimizes resource use, such as energy and water. This is crucial for minimizing the environmental impact of cocoa production, making the process more sustainable in the long term. Furthermore, the ability to monitor and adjust processes in real-time enables farmers to adopt more responsible practices, contributing to the economic and ecological sustainability [22].

6. CONCLUSIONS

This research has made a significant contribution to the field of traceability in the cocoa agro-industry, demonstrating the importance and positive impact of Industry 4.0 and IoT technologies in modernizing this sector. By providing a system that not only enhances the quality and safety of cocoa but also offers valuable data for future decision-making, this study establishes a reference framework for future technological implementations in the agro-industry.

The implementation of these technologies holds great potential to positively impact cocoa-producing communities. By improving product quality and facilitating access to international markets, these technologies can increase farmers' income, contributing to economic development and enhancing the quality of life in these communities. Moreover, the adoption of sustainable practices can have long-term benefits for both the environment and the economic stability of producers.

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