ISBN: 978-628-96613-3-0. ISSN: 2414-6390. Digital Object Identifier: https://dx.doi.org/10.18687/LACCEI2026.1.1.1132

# CAFEMEC: Automated Dryer via Arduino–PLC Communication

Ricardo Daniel Gómez Grant
*Facultad de Ingeniería*
*Universidad Tecnológica Centroamericana (UNITEC)*
Tegucigalpa, Honduras
ricardogogra08@unitec.edu

Marco Antonio Rivera Oviedo
*Facultad de Ingeniería*
*Universidad Tecnológica Centroamericana (UNITEC)*
Tegucigalpa, Honduras
junior2001rivera@unitec.edu

Jaime Alejandro Amador Delgado
*Facultad de Ingeniería*
*Universidad Tecnológica Centroamericana (UNITEC)*
Tegucigalpa, Honduras
j.amador2003@unitec.edu

Fávell Eduardo Núñez Rodríguez
*Facultad de Ingeniería*
*Universidad Tecnológica Centroamericana (UNITEC)*
Tegucigalpa, Honduras
favell.nunez@unitec.edu

***Abstract*—This paper introduces CAFEMEC, an automated drying prototype for raised (African) beds that integrates advanced sensing, control, and actuation through a hybrid Arduino–PLC architecture. An Arduino Nano 33 BLE Sense Rev2 is utilized for real-time monitoring of ambient temperature, relative humidity, and bean moisture content, computing a reference moisture value. This data is transmitted via the Modbus RTU (RS-485) protocol to a Schneider M221 PLC, which executes the control logic. The PLC compares ideal versus actual moisture levels to manage forced ventilation, auxiliary heating, and an automated raking mechanism, incorporating hysteresis and minimum-time constraints for operational stability. The mechanical solution features a stepper-driven raking system (belt-and-pulley transmission with a PVC paddle), a plenum-based airflow duct system, and a foldable frame designed for compatibility with standard African beds.**

**Bench tests validated stable and traceable data acquisition, robust Arduino–PLC communication, and consistent actuator response under safety interlocks. Due to seasonal constraints, corn kernels were employed as a process surrogate during the commissioning phase. The results establish a foundation for real-time solar drying regulation, aiming to enhance moisture uniformity and hygiene compared to traditional manual handling. Future research will focus on scaling the system to 6-meter beds with zoned control, solar-hybrid power integration for resilience, and coffee-specific calibration profiles for natural, parchment, and honey processes.**

***Index Terms*—Coffee drying, African beds, automation, Arduino, PLC, Modbus RS-485, forced convection, automated raking, moisture control.**

## I. Introduction

Coffee constitutes one of the most critical economic, social, and cultural pillars of Honduras, accounting for over 5% of the agricultural Gross Domestic Product (GDP) and serving as the primary source of income for more than 120,000 farming families nationwide [2]. Within the coffee value chain, the drying stage is a critical phase that definitively determines the final organoleptic quality of the bean. Consequently, ensuring a controlled and standardized drying process is vital for the industry's competitiveness.

In Honduras, solar drying remains the predominant method due to its low operational cost. However, this approach offers limited environmental control, leading to moisture heterogeneity, increased contamination risks, and the development of physical defects in the beans caused by process variability. To address these challenges, this paper introduces CAFEMEC, an automated drying system specifically designed for raised (African) beds.

The proposed solution integrates an accessible automation architecture that combines sensing and industrial control. By utilizing a hybrid Arduino–PLC system, CAFEMEC enables real-time monitoring of critical variables and automatically orchestrates the activation of forced ventilation, auxiliary heating elements, and a mechanical raking system. This integration aims to significantly enhance drying uniformity and operational efficiency, providing a scalable technological alternative to traditional manual handling.

## II. Objectives

### A. General Objective

The primary objective of this research is to design and construct an automated system for parchment coffee drying, capable of orchestrating mechanical raking and forced air circulation based on real-time environmental and grain-specific variables.

### B. Specific Objectives

To achieve the general objective, the following specific goals were established:

- Implement a robust monitoring system to regulate the drying process through real-time acquisition of ambient temperature, relative humidity, and bean moisture content.
- Develop an integrated automation stack for mechanical turning (raking) and forced ventilation, specifically optimized for operation on African (raised) beds.

- Design a modular and adaptable mechanical structure compatible with existing standard African bed infrastructures to facilitate technological adoption.
- Evaluate the impact of the automated control system on moisture uniformity and drying efficiency compared to traditional manual methods.

## III. State of the Art

### A. *Principles of Coffee Drying*

The coffee drying process is one of the most critical stages of post-harvest processing; it directly influences the physical, microbiological, and sensory quality of the bean. Once the cherries have been harvested, pulped, and washed, they must be dehydrated from an initial moisture content of approximately 50-55% to a target level of 10-12%. This range is essential to ensure microbiological stability, allowing for long-term storage and commercialization without qualitative deterioration [3].

This process is delicate and highly prone to failure; any thermal or mechanical error at this stage is irreversible and compromises the final cup profile. Efficiency depends on a complex interplay of variables, including ambient temperature, relative humidity, grain bed thickness, initial bean quality, and the precision of the control strategies applied during operation [4].

### B. *Coffee Drying Methods*

Coffee drying is generally classified into natural and mechanical methods. Natural drying—typically performed on patios, parabolic solar dryers, or African (raised) beds—is cost-effective but highly dependent on weather conditions. It requires intensive manual labor for turning and is susceptible to uneven drying, unwanted fermentation, or environmental contamination [5]. Conversely, mechanical drying utilizes forced hot air to control temperature, airflow, and final moisture content. While it achieves superior uniformity, it entails significantly higher energy and capital costs [6].

The work presented in [1] investigates the effect of combining drying processes on the quality of coffee comparing 100% solar, 100% mechanical (M), and hybrid configurations (S40M and M40S) using moisture–time curves. Their findings indicate that hybrid systems reach the 12% target approximately 11% faster than purely solar methods with lower energy consumption than purely mechanical ones. Specifically, the S40M approach excels by accelerating the final phase through the application of forced hot air. These results support the hybrid, automated architecture of CAFEMEC on African beds to maximize small-scale efficiency.

### C. *Mechanical Turning and Bed Uniformity*

Periodic turning (raking) during the drying process is fundamental to preventing bed compaction, equalizing moisture distribution, and improving interstitial aeration. Maintaining a bed thickness of approximately 3 cm is recommended to promote uniform evaporation [7]. Traditionally, this is performed 4–5 times per day using wooden rakes (see "Fig. 1").


Figure 1: Traditional wooden rake utilized in manual coffee turning.

However, manual raking often lacks the consistency required for high-specialty coffees, highlighting the need for automated mechanical solutions that ensure uniform force and coverage across the entire bed surface.

### D. *Actuation and Control Hardware*

The selection of actuators is critical for automated drying. Stepper motors are ideal for this application as they transform electrical pulses into discrete angular increments, providing precise, open-loop positioning control without the need for complex feedback sensors in low-speed applications [9]. Furthermore, in systems requiring environmental regulation, the operating frequency of ventilation fans must be dynamically adjusted based on the mass of the coffee and the current moisture gradient to optimize energy use [8].

### E. *Variable Monitoring and Sensor Fusion*

Real-time measurement of the bean's internal moisture remains a significant technical challenge. While gravimetric methods (oven-drying) are the gold standard for accuracy, they are incompatible with real-time automation. Consequently, calibrated resistive sensors have emerged as a viable alternative, showing a strong correlation with true moisture levels during the critical mid and final drying stages [11]. Maintaining moisture between 10-12% preserves the structural integrity and sensory attributes of the bean; levels above this range promote fungal growth (e.g., ochratoxins), while levels below 10% lead to the degradation of volatile aromatic compounds [10].

### F. *Automation and Forced Ventilation in Drying*

Automation in equatorial regions is hindered by high initial moisture and volatile climates [12]. Recent developments, such as the 25-kg convective dryer by Cisneros using PID control on a Siemens PLC, demonstrate the efficacy of industrial-grade automation in improving repeatability [13]. Forced ventilation is the cornerstone of these systems, as it enhances heat transfer and moisture removal, eliminating condensation zones and ensuring uniform dehydration across the grain bed.

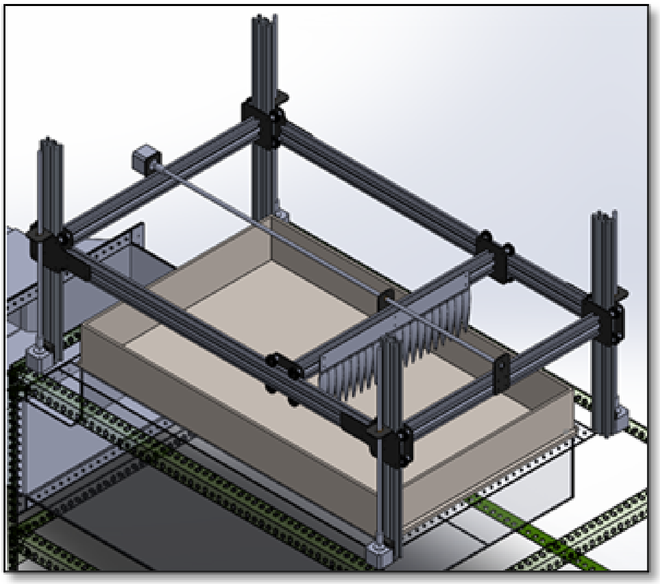

Figure 2: Mechanical design of the CAFEMEC raking system developed in SolidWorks.

## IV. Methodology

This research employs a quantitative and experimental approach aimed at numerically evaluating the impact of controlled process variables on the coffee dehydration cycle. This methodology is selected to ensure the acquisition of objective, measurable data, facilitating a rigorous statistical analysis of the system's performance. The study focuses on the systematic manipulation of independent variables—including forced ventilation cycles, auxiliary heating regulation, mechanical raking frequency, and bed thickness—to observe their direct influence on critical dependent variables such as moisture content, drying kinetics, and batch uniformity.

The experimental nature of the study is defined by trials conducted under controlled conditions, where specific interventions are isolated to ensure that observed outcomes are attributable to the system's control logic rather than stochastic environmental fluctuations. This framework allows for the validation of the Arduino–PLC architecture as a reliable solution for precision agriculture.

### A. Variables

1) **Independent Variables:** Controllable design and operational parameters.
   - **Fan duty cycle:** Minutes per hour of forced convection to enhance interstitial air circulation.
   - **Auxiliary heating runtime:** Activation period of the 250 W thermistor to accelerate moisture desorption.
   - **Raking frequency:** Number of mechanical cycles per hour performed by the stepper-driven paddle to redistribute the grain.
   - **Grain bed thickness:** Height (cm) of the parchment coffee layer on the African bed, affecting heat transfer resistance.
   - **Structural configuration:** Mechanical design and material selection, evaluated for adaptability to existing infrastructure.
2) **Dependent Variables:** Measurable outcomes of the drying process.
   - **Drying Uniformity:** Statistical variance of moisture content across multiple sampling points within the batch.
   - **Final Moisture Content:** Percentage of residual water in the bean at the end of the process (target: 10–12%).
   - **Total Drying Time:** Total hours required to reach the target moisture threshold.

### B. Materials and Hardware Specifications

The selection of materials was governed by industrial standards to ensure robustness in greenhouse environments.

- **Structural Components:** 2"×2" gauge #14 metal angle, 3/4"×3/4" gauge #14 square tubing, and PLA-printed custom fittings.
- **Linear Motion System:** SBR16 linear slide rails (800 mm) with SBR16UU blocks, 8 mm toothed pulleys, and 6 mm timing belts.
- **Actuation:** High-torque NEMA 23 stepper motor with a DM556 CNC driver (20–50 Vdc).
- **Sensing Stack:** Arduino Nano 33 BLE Sense Rev2 and anti-corrosion capacitive soil/grain moisture sensors.
- **Industrial Control:** Schneider Modicon M221 PLC, 3-pole 110 Vac contactors, and 12 Vdc electromagnetic relays.
- **Thermal and Airflow System:** 110 Vac axial fans and a 250 W thermistor heater with an integrated 12 Vdc cooling/airflow fan.
- **Power and Interface:** Dual power supplies (24 Vdc at 5 A; 12 Vdc at 3 A), industrial push buttons, and 12/24 Vdc pilot lights for status indication.

## V. Results and Discussion

The experimental validation of the CAFEMEC prototype focused on evaluating data traceability, the mechanical reliability of the turning system, and the efficiency of the thermal regulation logic. The prototype design can be observed in "Fig. 2".

### A. Data Acquisition and Control Architecture (DAQ)

The hybrid Arduino–PLC architecture was successfully implemented to ensure robust real-time monitoring. The Arduino Nano 33 BLE Sense Rev2 processed ambient temperature ($T$) and relative humidity ($RH$) via the HS3003 sensor, alongside dual capacitive grain probes filtered through a moving-average algorithm to mitigate signal noise.

Data transmission was executed via the Modbus RTU protocol over an RS-485 physical layer (MAX485). As illustrated in "Fig. 3", the Schneider M221 PLC utilized specialized `READ_VAR` and `WRITE_VAR` blocks to manage data buffers. This separation of read/write registers ensured high data integrity and a deterministic response for the drying control loop.

The Arduino-calculated "Ideal Moisture" reference served as a dynamic setpoint for the PLC's decision-making logic.

### B. Automated Turning and Air-Flow Systems

1) **Mechanical Structure:** A modular 2.10 m × 1.20 m metal frame was fabricated to provide a stable chassis for the automation components ("Fig. 4"). Its bolt-on design facilitates rapid deployment on existing African beds without requiring structural modifications.
2) **Raking Mechanism:** The turning paddle was engineered based on Cenicafé geometric standards ("Fig. 9") to ensure optimal grain displacement. The final 3D-printed and PVC assembly travels along the bed, replicating the kinematics of manual raking with superior consistency.
3) **Transmission System:** Paddle motion is driven by a high-torque NEMA 23 stepper motor via a belt-and-pulley transmission. This configuration, synchronized through the PLC, allows for precise control of raking speed and frequency, preventing grain damage while ensuring total surface coverage.
4) **Forced Ventilation:** The ventilation subsystem utilizes a plenum-based box with a 45° elbow PVC duct network and distribution hoods. This geometry ensures a uniform air velocity profile across the bed, eliminating stagnant moisture zones.

### C. Airflow Simulation and Prototype Integration

To ensure the efficient distribution of heated air across the drying bed, Computational Fluid Dynamics (CFD) simulations were conducted. These simulations allowed for the optimization of the plenum and duct geometry, ensuring a uniform velocity profile and minimizing pressure drops within the transmission system. As illustrated in "Fig. 5", the results guided the final design to achieve consistent thermal coverage.

The complete structural and electronic integration is shown in "Fig. 6", depicting the fully assembled prototype compatible with standard African beds. This integration validates the synergy between the mechanical airflow design and the automated control stack.

### D. Experimental Setup and Test Material

Due to the specific seasonal availability of coffee during the prototyping phase, corn kernels were utilized as a process surrogate to evaluate the effectiveness of the automated drying system. Corn was selected due to its similar hygroscopic behavior and mechanical properties when arranged in a bed, providing a reliable baseline for validating the performance of the raking mechanism and the forced ventilation logic.

The use of this surrogate allowed for the precise calibration of the capacitive moisture sensors and the verification of the PLC's control algorithms under real thermal load conditions. The results obtained during these trials establish a robust foundation for subsequent validation with parchment coffee.

Table I: Hourly Environmental and Moisture Data During Validation

| Time (h) | T (°C) | RH (%) | Real M. (%) | Ideal M. (%) |
|---|---|---|---|---|
| 06:00 | 34.4 | 87.5 | 30.18 | 29.18 |
| 12:00 | 28.1 | 96.7 | 17.05 | 16.05 |
| 18:00 | 29.0 | 82.6 | 13.75 | 12.75 |
| 02:00 | 27.0 | 84.1 | 12.74 | 11.74 |

### E. Drying Kinetics and Uniformity Analysis

The system's performance was validated through intra-batch sampling at representative points (see "Fig. 9"). As detailed in "Table I", the actual moisture content dropped from 30.18% to 12.74% over the experimental period.

"Fig. 7" illustrates the African bed with the designated verification points, while "Fig. 8" shows the capacitive sensor utilized to measure the internal grain moisture. Measurements were recorded throughout the test trial, documenting the final moisture percentage for each point and utilizing the target curve ($M_{ideal}$) as a reference for the comparative analysis.

The convergence of these experimental values toward the theoretical model confirms that the integration of automated raking and forced ventilation significantly reduces moisture variance across the batch, ensuring a high-quality standardized output.

The convergence of the "Real Moisture" toward the "Ideal Moisture" curve demonstrates the efficacy of the PLC's regulation. Furthermore, the minimal dispersion between sampling probes $S1$ and $S2$ confirms that the automated raking and forced ventilation achieved high moisture uniformity. The target band of 10–12% was reached in the final stage with high stability, satisfying the success criteria for high-quality post-harvest processing.

## VI. Conclusions

The development and validation of the CAFEMEC prototype led to the following conclusions:

- A robust sensing-control-actuation architecture was successfully integrated, enabling real-time monitoring of ambient temperature, relative humidity, and grain moisture. The system effectively computed the ideal moisture trajectory, allowing the Schneider PLC to execute regulation cycles based on hysteresis and minimum-time constraints, ensuring high decision traceability.
- The automated turning mechanism, utilizing a high-torque stepper motor and a specialized PVC paddle, achieved uniform grain redistribution. Bench tests confirmed total surface coverage, consistent repeatability under industrial control, and safe operational limits via integrated limit switches.
- The plenum-based forced ventilation system, supported by a specialized duct network, optimized interstitial airflow distribution across the African bed. Experimental analysis defined operational bands that sustained the process's thermal stability, effectively mitigating condensation risks and accelerating moisture desorption.

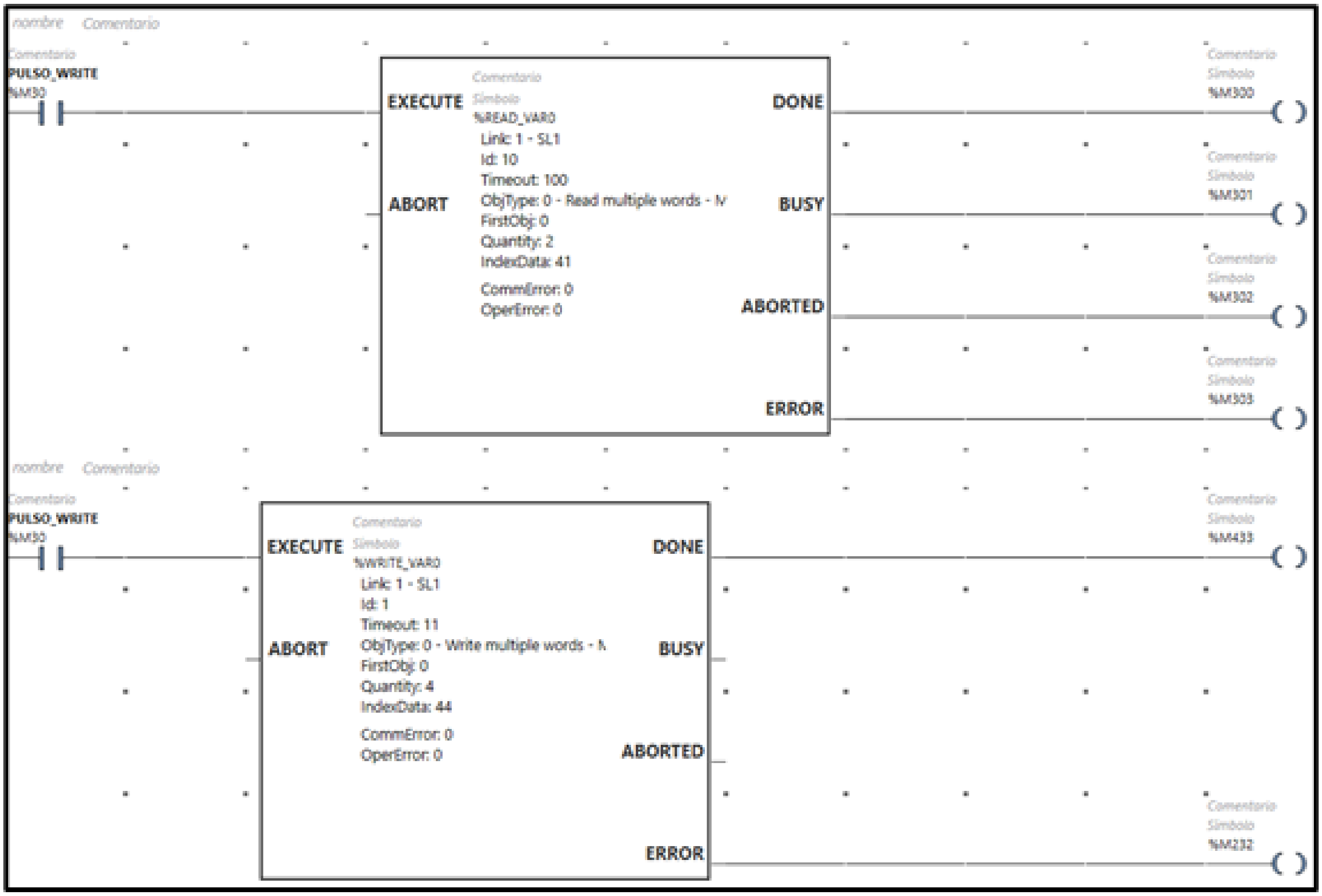


Figure 3: Mapping of Modbus RTU read and write data blocks in the EcoStruxure Machine Expert software.

Figure 4: Integrated automated raking and linear motion system.

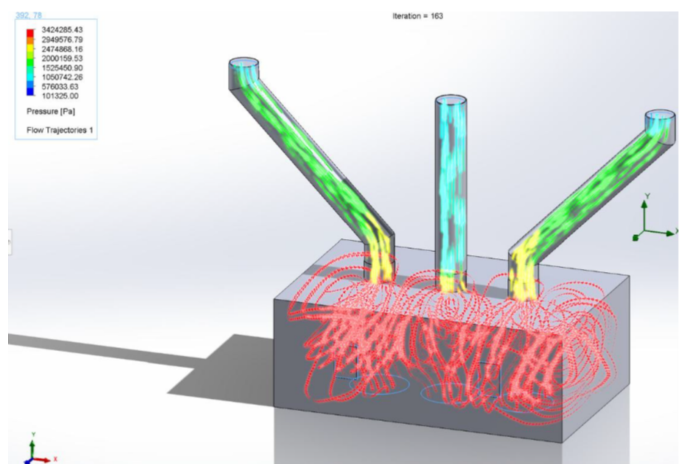

Figure 5: Ventilation System Fluid Simulation

- The mechanical design resulted in a foldable and modular structure compatible with existing African bed infrastructures. The framework maintains high structural rigidity and precise rail alignment, facilitating installation, maintenance, and periodic inspection without requiring permanent modifications to traditional farm setups.

## VII. Future Work

Future research directions for CAFEMEC focus on scaling the system and enhancing its intelligence for industrial-grade deployment:

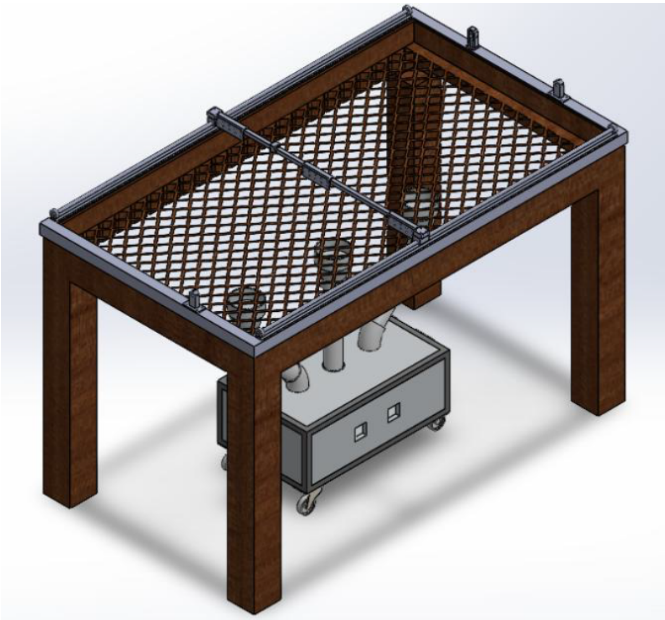

Figure 6: Cafemec prototype assembly

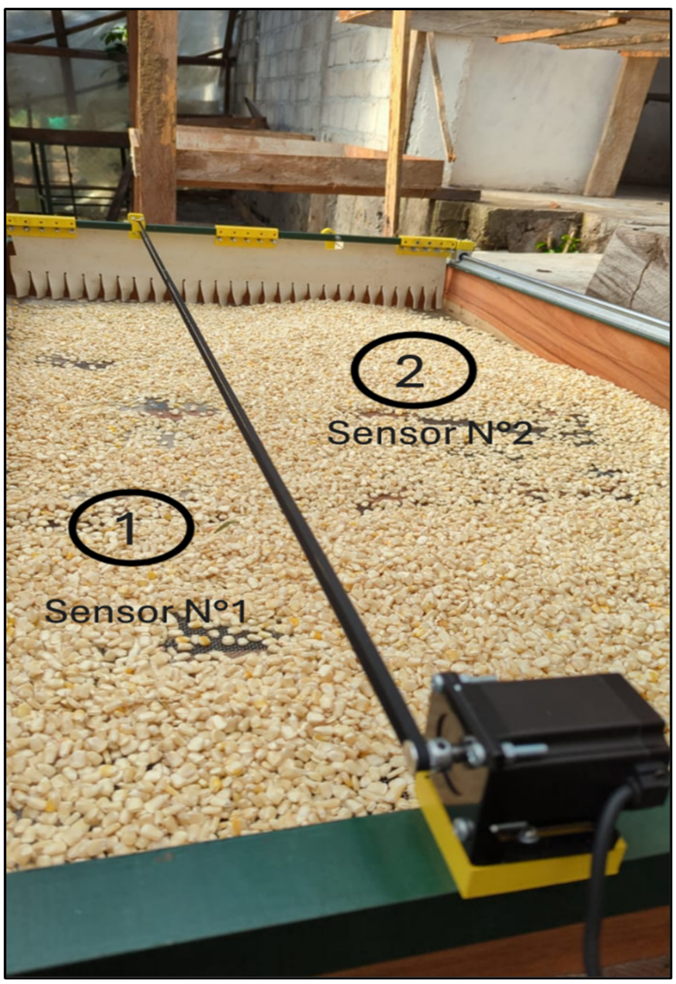


Figure 7: Sampling points.

Figure 8: Capacitive sensor used to measure the moisture content of corn kernels

- **System Scaling:** Transitioning to 6-meter industrial beds by implementing modular raking units, reinforced linear guides, and zoned ventilation control. This expansion aims to manage localized moisture gradients more precisely, further reducing total batch processing times.
- **Energy Resilience:** Integration of a hybrid power system utilizing solar energy with MPPT (Maximum Power Point Tracking) chargers and battery storage. This will enable energy-saving modes that prioritize critical sensing and PLC functions during low-radiation periods.
- **Advanced Process Modeling:** Maturing the control software to include selectable profiles for specific coffee types (e.g., Natural, Parchment, Honey). Future iterations will incorporate adjustable hysteresis thresholds and full data logging to enable predictive drying models and further enhance organoleptic uniformity.

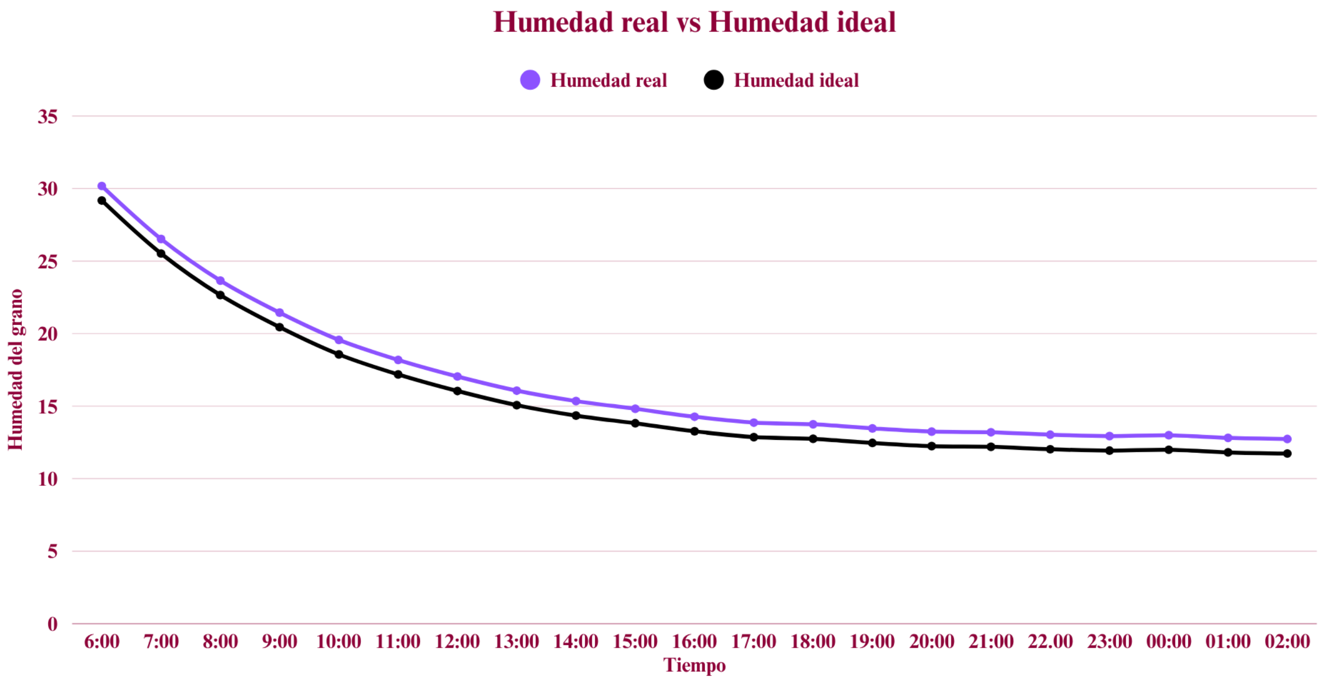


Figure 9: Drying kinetics: Convergence of real moisture to the calculated ideal setpoint.

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