AGRO PRODUCTIVIDAD

Semi-automation of Ingredient Mixing Process in Artisanal Vanilla Extract Production for MSMEs in Orizaba, Veracruz

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ABSTRACT
The purpose of this study was to design and implement a semi-automatic system to optimize the integration of ingredients in the artisanal production of vanilla in a micro, small, and medium-sized enterprise (MSME) in Orizaba, Veracruz. The proposal sought to replace the manual process with one controlled by a Siemens Logo! 230RC PLC, supported by a jet pump, a 1,100 L tank, and a dosing machine, to increase productivity, operational efficiency, and the consistency of the final product.

Objective: Design and implement a semi-automatic system to optimize and standardize the mixing of ingredients in the artisanal production of vanilla at an SME in Orizaba, Veracruz, increasing productivity and consistency in the process.

Design/methodology/approach: An experimental-descriptive approach was used, employing a Siemens Logo! 230RC PLC, a jet pump, a 1,100 L tank, and a dosing machine. The methodology comprised manual process analysis, control logic design, simulation in Logo! Soft Comfort, and physical implementation.

Results: Semi-automation improved operating times and reduced manual intervention, increasing the efficiency and reliability of the system.

Limitations/implications: The system was implemented in a single company, so its transfer to other agro-industrial environments requires technical adjustments.

Findings: PLC automation is a viable alternative for modernizing artisanal processes and strengthening the competitiveness of agribusiness MSMEs.

Keywords: automation, PLC, artisanal vanilla, MSMEs, agribusiness.

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INTRODUCTION

Vanilla (*Vanilla planifolia* Jacks. ex Andrews) is one of the most valuable natural flavorings in the world, with wide applications in the food, perfume, and pharmaceutical industries (Gallage & Møller, 2015). Its high cost is due to the complexity of its production: less than 1% of commercial vanillin comes from natural pods, and about 500 kg are required to

obtain 1 kg of the compound (Gallage & Møller, 2015). Although microbial bioconversion and fermentation represent promising alternatives, they still present technical and economic constraints (Jiang *et al.*, 2023). Due to its distinctive sensory profile, natural extract continues to be the most highly prized, even compared to sustainable catalytic routes derived from lignin (D'Arrigo *et al.*, 2024).

Mexico, particularly the Totonacapan region in Veracruz, is recognized as the center of origin and domestication of *V. planifolia* (Nájera-Hernández & Coutiño-Cortés, 2023). In mountainous areas, cultivation and processing are carried out manually, preserving cultural identity but limiting efficiency and standardization (Pérez-Viveros *et al.*, 2025). Between 2017 and 2022, national production ranged from 505 to 518 tons, with 70% concentrated in Veracruz (INIFAP, 2017; SIAP-SADER, 2022). The chain is made up of micro, small, and medium-sized enterprises (MSMEs) and rural producers with low mechanization and high labor dependence (Rodríguez-Deméneghi *et al.*, 2023; Sánchez Morales *et al.*, 2024). This reality generates variability in product quality and losses associated with manual control of critical stages such as mixing or curing (Khoyratty *et al.*, 2018).

Mexican agro-industrial MSMEs face structural barriers: limited infrastructure, lack of standardization, and scarce technical personnel (Vargas-Canales, 2023). Although they represent 99.8% of economic units and generate about 39% of the national GDP (Ministry of Economy, 2024), their digitization remains in its infancy (Díaz-Arancibia *et al.*, 2024; Idemudia *et al.*, 2025). In contrast, industrialized countries have incorporated programmable logic controllers (PLCs) and smart sensors to optimize operations and reduce human error (Barz *et al.*, 2014; Amertet *et al.*, 2023). In Mexico, agricultural mechanization continues to lag behind, with less than 5% of producers using digital technologies for irrigation or monitoring (Hernández-Ávila *et al.*, 2022; Negrete, 2018). This technological gap hinders the productivity and competitiveness of the rural sector.

Industrial automation represents a viable strategy for modernizing artisanal production processes without compromising their traditional identity. PLCs minimize manual intervention, standardize operational parameters, and improve overall production efficiency (Koondhar *et al.*, 2023; Obermeier & Thiel, 2022). Meanwhile, the Internet of Things (IoT) enables real-time monitoring of critical variables, such as temperature and liquid levels, fostering resource efficiency and energy sustainability (Mirani *et al.*, 2019). These technological tools support the transition toward more precise, standardized, and sustainable production models aligned with the principles of Industry 4.0.

In the artisanal production of vanilla extract, the proportion and timing of ingredient mixing are decisive factors influencing the final quality of the product. Inadequate control of these variables results in inconsistencies in sensory properties and reduced productivity. PLC-based semi-automation provides an effective alternative for MSMEs, allowing synchronized control of pumps and valves, reducing process variability, and preserving the artisanal character of production.

This study describes the design and implementation of a semi-automated system for mixing ingredients in a 1,100-liter tank used in the artisanal production of vanilla extract. The system, developed in collaboration with a local company, incorporates a Siemens LOGO! 230RC programmable logic controller (PLC) programmed in contact diagram language (KOP) using LOGO! Soft Comfort V8.4 software. Prior to implementation, the control logic was validated through simulations in CADe SIMU, followed by laboratory-scale testing to evaluate performance and functionality. The system was designed to regulate ingredient integration time and dosing, ensuring repeatability and precision.

The experimental results confirmed that automation enhances both efficiency and reliability in the mixing process. The system represents a replicable technological model applicable to other MSMEs in the agro-industrial sector, particularly those engaged in artisanal food production. Its adoption can facilitate the integration of small producers into markets with high technical and quality standards, improving competitiveness and sustainability.

It is hypothesized that the implementation of a semi-automatic mixing system controlled by a Siemens Logo! 230RC PLC will increase process productivity by at least 20% and improve mixing consistency by more than 2% compared with the traditional manual method. This improvement will be achieved through a reduction in operating time by approximately 15 to 20%, optimization of energy consumption, and a decrease in batch-to-batch variability, thereby contributing to the standardization and modernization of the artisanal vanilla-extract production process in agro-industrial MSMEs.

MATERIALS AND METHODS

Type and Design of the Research

This study was designed as an applied experimental-descriptive research aimed at evaluating the effect of semi-automation on the artisanal ingredient mixing process during the production of vanilla extract. The research was carried out in a microenterprise located in the municipality of Orizaba, Veracruz, Mexico, during the first half of 2025. The primary objective was to determine the impact of implementing a programmable logic controller (PLC)-based system on process efficiency, precision, and energy use compared to traditional manual operation.

Experimental Design

The experiment was conducted under a completely randomized design with ten replicates per treatment, where each replicate represented a complete mixing cycle with an average duration of 40±2.1 minutes. Two treatments were evaluated: the traditional manual system, in which all operations were performed by personnel, and the semi-automatic system, controlled by a Siemens LOGO! 230RC programmable logic controller (PLC). The experimental system and components used are described in Table 1. The response variables analyzed included process time (min), dosing accuracy (%), energy consumption (kWh), and mixed volume (L), as detailed in Table 2. This design enabled an objective and systematic comparison between manual and semi-automated operations, allowing for the quantification of the impact of automation on the artisanal production of vanilla extract.

Table 1. Equipment and Materials Employed in the Semi-Automated Ingredient Mixing System.

Equipment/material	Main features
PLC Siemens Logo! 230RC	Compact, 8 digital inputs, 4 relay outputs
Logo! Soft Comfort v. 8.4	Programming and simulation platform
Jet pump (2)	Nominal power 1 HP
Tank IUSA 1,100 L (2)	High-density polyethylene
Dosing machine	Adaptation of artisanal system
Sensors, pilots, valves	Signaling and control devices

Developed According to Project Progress (2025).

Table 2. Evaluation Variables Defined for the Study

Variable	Unit of measurement	Technical description
Process time	Minutes (min)	Total duration of the mixing cycle
Dosing accuracy	Percentage (%)	Difference between the programmed volume and the dispensed volume
Energy consumption	Kilowatt-hour (kWh)	Total energy consumed during the cycle
Mixed volume	Liters (L)	Total volume processed per cycle

Developed According to Project Progress (2025).

Experimental procedure

The experimental procedure was structured into five sequential stages: diagnosis, control design, simulation, implementation, and validation of the semi-automatic system (Figure 1). This methodological structure ensured a logical progression from the analysis of the original process to the verification of the automated system under real operating conditions.

Initial Diagnosis

The initial diagnosis focused on characterizing the existing artisanal ingredient mixing process. The original system consisted of two storage tanks connected to jet pumps, control

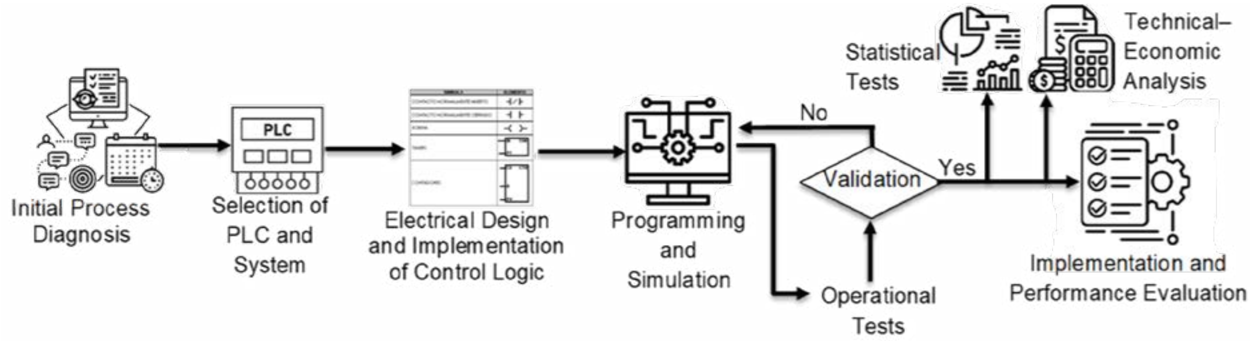

Figure 1. Flow diagram of the stages for system design, programming, implementation, and validation.

valves, and intermediate filters, through which the operator manually introduced the ingredients (Figure 2). To document the baseline operational parameters, the manual ingredient integration process was monitored through direct observation and timing, generating quantitative data used as a reference for subsequent comparisons (Table 3). This stage enabled the identification of critical points in the process, particularly those related to variability in dosing and operator dependency.

Control Design and Simulation

The control system was designed using LOGO! Soft Comfort v.8.4 software and subsequently verified through CADe SIMU to ensure functionality and reliability prior to physical implementation. The system was configured to include start, stop, manual operation, automatic operation, and fault management functions. Ladder diagrams were employed to represent the control logic (Figure 3). The programmed inputs were I1 (start), I2 (stop), I3 (manual), I4 (automatic), and I5 (fault), while the outputs were Q1 (motor), Q2 (green pilot light), Q3 (red pilot light), and Q4 (fault indicator). The simulation validated the logical sequence of operations, confirming that the system performed as expected in different operating modes. This stage was essential for minimizing programming errors and ensuring operational reliability before installation.

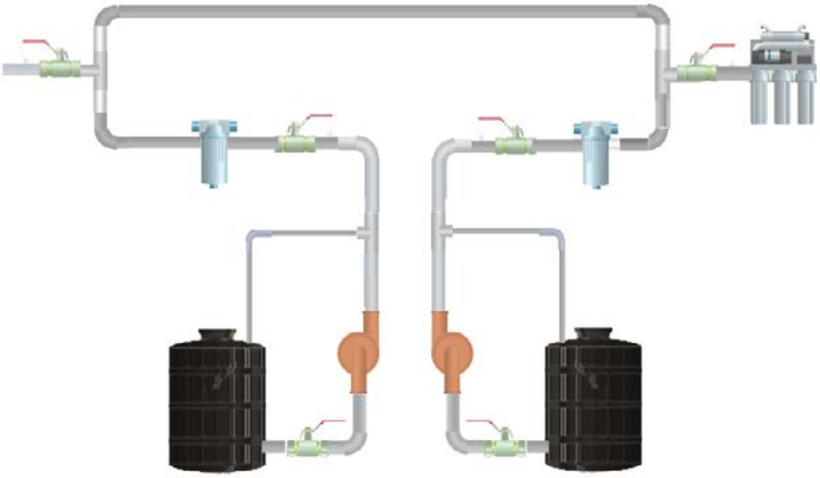

Figure 2. Diagram of the pumping and filtration system in the vanilla extract ingredient mixing process.

Table 3. Packaging capacity and operating times according to vanilla extract presentation.

POP*	QPC*	EOT* (min h^{-1})	Comments
Gallon (3.78 L)	288	40-50 min	Equivalent to ∼1088.6 L per cycle
Bottle (1 L)	1,000	90-120 min	Variability according to flow rate
Bottle (500 ml)	2,000	3 hr	∼1,000 L packaged
Bottle (250 ml)	4,000	5 hr	∼1,000 L packaged

*POP: Presentacion of packaging; QPC:Quantity packaged per cycle, EOT:Estimated operating time. Prepared based on the development of the project (2025).

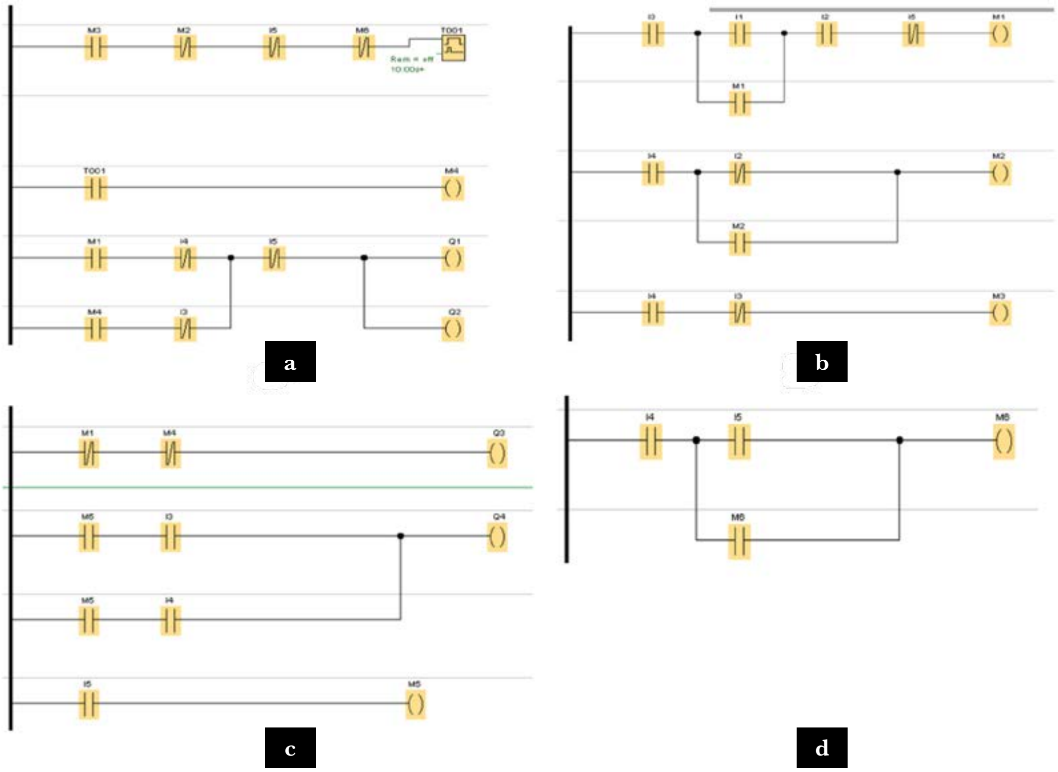

Figure 3. Program simulation in Logo! Soft Comfort with defined inputs and outputs.

Experimental Implementation and Physical Validation of the Semi-Automatic System

For the physical implementation, a Siemens LOGO! 230RC programmable logic controller (PLC) was installed in a control cabinet equipped with contactors, thermal relays, a jet pump, a metering pump, push buttons, selector switches, indicator lights, and 127 VAC to 24 VDC converters for signaling (Figure 4). Functional tests were conducted in both manual and automatic modes using start and stop cycles to assess the system's response to simulated faults. In laboratory conditions, 10-second cycles were used, while in the production plant the mixing time was set at 40 minutes. During operation, the green indicator light signaled normal system activity, whereas the yellow light indicated fault or caution conditions in accordance with the IEC-60204-1 Safety of Machinery standard (Figure 5). This validation stage confirmed the correct functioning of the control logic, the reliability of the system under different operational scenarios, and its suitability for integration into artisanal vanilla extract production.

Validation and Analysis

The validation stage focused on verifying the operational stability, safety, and reproducibility of the semi-automatic system under real working conditions. The control logic and operating parameters were fine-tuned to ensure consistent performance, with mixing times calibrated to 40±0 minutes. Safety routines were optimized, reducing process variability to a maximum of ±5%. In the electrical and instrumentation area, emergency

Figure 4. Physical wiring of the system in the PLC test module.

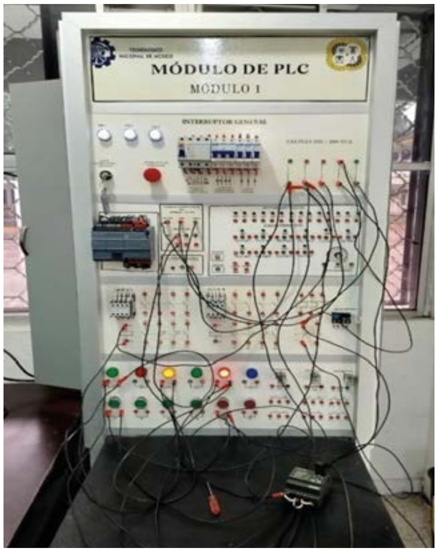

Figure 5. Practical demonstration of failure/precaution: activation of shutdown and failure/precaution indicators.

shutdown protocols were verified in accordance with the IEC 61511/ISA-84 standard through systematic testing and procedural review.

The performance of the system during plant operation was compared with the results obtained from prior simulations conducted in LOGO! Soft Comfort and CADe SIMU. This comparative analysis confirmed the correspondence between both environments, demonstrating that the operational behavior observed during implementation aligned with the simulated scenarios. These results verified the reproducibility and reliability of the control system, supporting its potential scalability and applicability in similar production environments.

Economic Evaluation

An economic evaluation was designed to compare the costs associated with the manual system and the semi-automatic system. The analysis will consider key cost components, including initial investment, annual maintenance, energy consumption, and operational expenses. The payback period (PBP) will be estimated based on labor savings and reductions in material waste resulting from process optimization. In addition, cost-benefit and profitability indicators will be calculated to assess the economic feasibility of the implemented automation. All financial values will be expressed in Mexican pesos (MXN) and adjusted according to the average prices corresponding to the year of implementation, ensuring the accuracy and relevance of the economic analysis.

RESULTS AND DISCUSSION

Process Performance

The performance of the semi-automatic mixing system was evaluated over a 20-day operating period and compared with the traditional manual process under controlled conditions of temperature (28±1 °C) and mixing volume (1,100 L per cycle). Each treatment was replicated ten times, corresponding to complete production cycles as defined in the experimental design. The Siemens LOGO! 230RC programmable logic controller (PLC) was programmed with a fixed mixing time of 40 minutes, enabling process standardization and eliminating the variability typically associated with operator intervention. The variables analyzed included process time (min), dosing accuracy (%), energy consumption (kWh), and processed volume (L), with the objective of assessing the efficiency, precision, and stability of the automated system in comparison with the manual method (Table 4).

The results demonstrated a significant improvement in operational performance with the implementation of the semi-automatic system. The fixed cycle time of 40.00±0.00

Table 4. Data from manual and semi-automatic treatments for the mixing process

RP*	Response Variables*						
	MT(min)	ST(min)	MA(%)	SA(%)	ME(kWh)	SE(kWh)	PV(L)
1	50.2	40	95.1	98.5	0.44	0.39	1085
2	49.8	40	96.3	98.7	0.43	0.37	1090
3	48.6	40	95.9	99.1	0.43	0.38	1092
4	47.9	40	97.2	98.9	0.42	0.36	1088
5	46.8	40	96.7	98.8	0.41	0.37	1086
6	47.2	40	95.4	99.2	0.42	0.38	1089
7	48	40	96.1	98.6	0.43	0.37	1087
8	47.1	40	97	99	0.41	0.36	1090
9	49	40	96.2	98.9	0.43	0.38	1091
10	48.5	40	95.8	99.3	0.42	0.37	1089
Media±DE**	48.31±1.14	40.00±0.00	96.17±0.67	98.90±0.26	0.424±0.0097	0.373±0.0095	1088.7±2.2

*RP: Repetition, MT: Manual Time, ST: Semi-automatic Tme, MA: Manual Accuracy, SA: Semi-automatic Accuracy, ME: Manual Energy, SE: Semi-automated Energy, PV: Processed Volume

**Standard deviations calculated from n=10 independent run.

minutes resulted in a 17.2% reduction in average process duration compared to the manual operation, which recorded a cycle time of 48.31±1.14 minutes. This reduction can be attributed to the synchronized control of pumps and valves, the elimination of non-productive pauses, and the automation of the mixing flow. In addition, dosing accuracy improved from 96.17±0.67% in the manual system to 98.90±0.26% in the semi-automated system, indicating enhanced uniformity between batches and a reduced incidence of human error. These findings confirm that automation not only improves efficiency but also contributes to greater process precision and consistency.

The implementation of the semi-automatic system resulted in a significant reduction in energy consumption, decreasing from 0.424±0.00971 kWh in the manual process to 0.373±0.0095 kWh in the automated process. This 12% improvement in energy efficiency is attributed to the precise control of motor operation achieved through the programmable logic controller (PLC), which optimized the synchronization of pumps and valves, minimized idle periods, and stabilized the mixing sequence. The processed volume remained constant at 1,088.7±2.2 L per cycle, confirming that the integration of automation did not compromise production capacity or affect batch throughput.

The correlation analysis between process time and energy consumption ($r=0.91$, $p<0.05$) revealed a strong and positive relationship, indicating that shorter cycle durations directly contribute to reduced energy usage. Furthermore, the observed improvement in dosing accuracy was closely associated with the reduction in mixing time, validating the effectiveness of the PLC in maintaining operational synchronization and process stability. These findings demonstrate that the adoption of semi-automation not only enhances precision and reproducibility but also improves energy efficiency, contributing to more sustainable and economically viable production practices.

Statistical Analysis of Performance

The statistical analysis was carried out to determine whether the observed improvements were significant. The normality of the data was verified using the Shapiro-Wilk test, confirming that all analyzed variables followed a normal distribution ($p>0.05$). Subsequently, a Student's t-test for independent samples was applied at a significance level of $p<0.05$ to evaluate differences between the manual and semi-automatic systems. The results, summarized in Table 5, indicated statistically significant differences in process time, dosing accuracy, and energy consumption, whereas the mixed volume variable showed no significant differences between treatments. These findings confirm that semi-automation leads to measurable improvements in process efficiency and precision without altering production capacity.

The results confirmed that the distributions for all variables were normal in both the manual and semi-automatic processes ($p>0.05$), validating the application of parametric statistical tests. Process time exhibited a highly significant difference ($p=2.52\times10^{-9}$), indicating that automation reduced the operating cycle time by an average of 17.20%. Dosing accuracy also showed a significant difference ($p=6.18\times10^{-8}$), reflecting improved uniformity of the mixture under PLC control.

Table 5. Results of normality tests and comparison between treatments.

Variable	Process**	SW (p-valor)*	DT*	t c*	p-v*	SD*
Process time (min)	MP	0.317	Normal	23.12	2.52*10	Yes
	SP	0.420				
Dosing accuracy (%)	MP	0.482	Normal	−12.07	6.18*10	Yes
	SP	0.356				
Energy consumption (kWh)	MP	0.614	Normal	11.91	$5.71*10^{-1}$	Yes
	SP	0.587				
Mixed volume (L)	MP	0.731	Normal	0.00	1.00	No
	SP	0.694				

*SW: Test Shapiro-Wilk, DT: Distribution, SD: Significant Difference ($p<0.05$), tc: t calculated, p-v: t-value tables (Student). ** MP=Manual Proceso, SP: Semi-automated Process.

Similarly, energy consumption was significantly lower in the semi-automatic system ($p=5.71\times10^{-10}$), confirming a 12.03% improvement in electrical efficiency compared to the manual method. In contrast, the mixed volume did not show significant differences ($p=1.00$), indicating that the introduction of automation preserved the production capacity of the artisanal process.

Overall, these results demonstrate that the semi-automatic system significantly improves temporal, energy, and operational efficiency while maintaining the productive capacity and artisanal quality characteristics of the traditional method.

System Validation and Operational Safety

System validation was conducted by comparing the results of simulations performed in LOGO! Soft Comfort v8.4 and CADe SIMU with the physical operation of the system in the plant. This comparison confirmed experimental reproducibility and operational stability. Start, stop, emergency, and mode change (manual-automatic) commands were evaluated to verify the execution of each instruction and the consistency of the programmed sequence.

The Siemens LOGO! 230RC PLC demonstrated reliable performance, with a switching time of less than 0.5 s, ensuring safe transitions between operating states. In automatic mode, the green indicator light signaled normal operation, and the mixing cycle was executed with a fixed duration of 40 minutes. The yellow indicator light indicated fault or caution conditions, triggering a safe stop in accordance with IEC 60204-1:2016 (Safety of Machinery-Electrical Equipment of Machines). Compliance with the functional safety cycle of IEC 61511/ISA-84 was verified through emergency shutdown and controlled restart tests.

Validation procedures also included the inspection of electrical connections, the response of contactors and thermal relays, and the integrity of PLC signals. No critical failures were detected, and the system's behavior was consistent with the simulation results. This confirms the reliability of the design, the stability of the control, and the robustness of the system, meeting the requirements for electrical safety and technical replicability in mixing processes for agro-industrial micro-enterprises.

Economic Evaluation

The economic evaluation compared the annual operating and maintenance costs of the manual and semi-automatic processes (Table 6). The implementation of the Siemens LOGO! 230RC PLC required an initial investment of MXN 45,000 and an annual maintenance cost of MXN 2,500. The analysis was based on data for energy consumption, operating time, and labor requirements obtained during the experimental period and projected over a one-year production cycle.

The results showed a 30% reduction in total operating costs, attributed primarily to lower labor requirements and increased energy efficiency. Although maintenance costs increased slightly, they were fully offset by the overall reduction in operational expenses. The payback period (PBP) was estimated at 14 months, confirming the economic viability of the system without the need for additional infrastructure or specialized personnel.

The findings of this study demonstrate that partial automation of the mixing process using a Siemens LOGO! 230RC PLC effectively reduces operating time, enhances dosing accuracy, and decreases energy consumption without compromising production capacity. These improvements are consistent with previous studies on small-scale process automation, where programmable controllers have been used to optimize production activities.

Löfving *et al.* (2018) evaluated flexible automation in small-batch production lines and reported reductions in cycle time and process variability. Similarly, this study observed a 17.2% decrease in mixing time, attributed to synchronized control of pumps and valves and the elimination of pauses caused by manual intervention. Both studies highlight the contribution of automation to improving process consistency and traceability.

Zgodavová *et al.* (2020) analyzed the integration of smart technologies into mixed-batch production systems, demonstrating reduced variability and enhanced operational accuracy. These findings align with the 2.84% increase in dosing accuracy observed here, confirming the ability of PLCs to execute control routines with greater precision than manual methods. In both cases, automation complements human work and contributes to maintaining uniform product quality.

Baek *et al.* (2024) evaluated a robotic system for loading ready-to-eat foods, reporting productivity increases of 12% to 31% through reduced handling times and improved uniformity. Similarly, the present study shows that automating repetitive, labor-intensive tasks can increase efficiency without altering the final product's characteristics. These results support the feasibility of applying low-cost, reliable automation technologies in agro-industrial micro-enterprises.

Table 6. Comparison of operating costs between processes.

Concept	MP** (MXN/year)	SP** (MXN/year)	Difference (%)
Labor	90 000	60 000	−33.33
Electricity	5 000	4 700	−6.00
Maintenance	1 200	2 500	108.33
Annual total	96 200	67 200	−30.15

** MP=Manual Process, SP=Semi-Automated Process.

The semi-automation strategy applied in this study helps to reduce the technological gap between artisanal and industrial production, offering a flexible and adaptable solution for rural environments. From an economic perspective, the 30% reduction in operating costs and the 14-month payback period further support the system's viability, in agreement with Löfving *et al.* (2018) and Zgodavová *et al.* (2020). Automation also contributes to sustainability by optimizing the use of energy and human resources, aligning with Sustainable Development Goal 9: Industry, Innovation, and Infrastructure.

A limitation of this study is that it focused on a single product type and a fixed production scale. Future work should consider integrating the PLC with temperature, pressure, and viscosity sensors to expand monitoring and control capabilities. In addition, the incorporation of adaptive control algorithms or artificial intelligence could enhance system accuracy and responsiveness to environmental fluctuations, as suggested by Baek *et al.* (2024).

CONCLUSIONS

The results obtained confirm the proposed hypothesis, demonstrating that the implementation of a semi-automatic mixing system controlled by a Siemens LOGO! 230RC PLC significantly improves operational efficiency and productivity in the artisanal production of vanilla extract.

The experimental analysis showed a resulted in a 17.2% reduction in mixing-cycle time. Assuming an 8-h operating day, this reduction could theoretically raise daily throughput by ≈20-22%, a value that requires experimental validation to the initial hypothesis and demonstrating the technical and economic feasibility of the proposed system.

The study confirms that such technological integration facilitates the modernization of artisanal practices without compromising their essential character, effectively improving the operational efficiency, reliability, and competitive potential of micro- and small-scale agro-industrial enterprises. The developed model is shown to be replicable in analogous production contexts, contingent upon appropriate adaptation to specific local requirements and infrastructural conditions.

For subsequent development phases, the integration of Internet of Things (IoT) sensors and scalable data acquisition systems is proposed. This advancement would enable continuous process monitoring and real-time operational optimization, establishing a foundational framework for smart manufacturing. Such a transition is critical for strengthening product traceability and implementing data-driven decision-making protocols.

Finally, it is recommended that public, academic, and technological institutions promote knowledge transfer and innovation initiatives within the agro-industrial sector to facilitate the scalability of this model. Establishing local training and financing centers for the adoption of digital technologies would extend the benefits of semi-automation to other rural MSMEs, thereby driving productive modernization, strengthening regional competitiveness, and contributing to the long-term sustainability of the Mexican agri-food sector.

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