Implementation of an Automated Quality Control System for pH, Acidity, and Bacteriological Testing in the Dairy Industry

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Abstract *— Manual quality control processes in the dairy industry are prone to human error, inefficiency, and inconsistencies, leading to production delays and risks to product quality. This research addresses these challenges by implementing an automated quality control system for pH, acidity, and bacteriological testing. Using the DMADV methodology, interviews, observations, and comparative experiments were conducted. Results showed a 40% reduction in testing time, over 70% decrease in error rates, and greater reliability in results. Staff reported positive perceptions of automation, highlighting improved traceability and reduced rework. This article concludes that automation is a reliable and superior alternative to manual testing, enhancing efficiency, accuracy, and compliance in the dairy industry.*

Key Terms *— Automation, Dairy Industry, DMADV, Quality Control, Six Sigma.*

PROBLEM STATEMENT

Manual quality control processes in the food manufacturing industry often suffer from inefficiency, inconsistency, and human error, which can delay production and compromise product quality. With growing consumer demands for stricter food safety standards and regulatory compliance, adopting advanced technologies has become essential to ensure accuracy, reduce testing times, and improve overall productivity. This research addresses these challenges by implementing an automated quality control system in the dairy industry, specifically focusing on pH, acidity, and bacteriological testing. The study seeks to analyze current manual practices, design and implement an automated system to enhance precision and speed, train staff to ensure proper adoption, and evaluate the system's impact on reducing errors and improving efficiency. The expected contributions include significant improvements in testing accuracy and reliability, a reduction in human errors, and greater consistency in product quality. Furthermore, the project promotes technological integration within traditional food manufacturing processes, equips employees with new skills for operating automated systems, and establishes a benchmark case study for automation in quality control, offering valuable insights and a model for other companies in the food industry to follow.

RESEARCH DESCRIPTION

This study applied the DMADV methodology to design and implement an automated system for quality control in dairy production. The main objectives were: (1) identify inefficiencies in current manual testing, (2) design and integrate an automated system for pH, acidity, and bacteriological analysis, (3) train staff to operate the system, and (4) evaluate improvements in accuracy, efficiency, and staff acceptance.

RESEARCH TIMELINE

The research project was carried out during the semester period from August 4, 2025, to October 25, 2025, following a structured schedule aligned with the DMADV methodology. The process began with a literature review (Aug 4 – Aug 16), which served as the foundation for identifying the limitations of manual testing methods and the potential of automation in quality control. This was followed by a current process analysis (Aug 11 –

Aug 25), where direct observations and staff interviews were conducted to understand inefficiencies, sources of error, and time delays in manual pH, acidity, and bacteriological testing. Once the problems were clearly identified, the system design phase (Aug 18 – Sep 3) took place, in which digital probes, automated titrators, and rapid microbial detection technologies were proposed and structured into an integrated solution. The pilot and implementation phase (Sep 3 – Sep 19) introduced the system in a controlled environment, allowing the team to validate feasibility and collect initial feedback from users. Afterward, comparative testing (Sep 19 – Oct 3) was conducted to generate empirical data comparing manual and automated methods. This testing produced measurable results in terms of speed, accuracy, and consistency, which were later examined during the data analysis phase (Oct 3 – Oct 12) using statistical tools such as t-tests and ANOVA to validate the improvements. The project concluded with the final writing and review phase (Oct 12 – Oct 20), ensuring that the findings were well documented, followed by presentation preparation (Oct 18 – Oct 25), where results were organized into visual and oral formats to communicate the benefits of the automated system. This structured timeline ensured that every stage of the DMADV cycle was completed within the academic term and that the project advanced from theoretical research to practical verification in an organized manner.

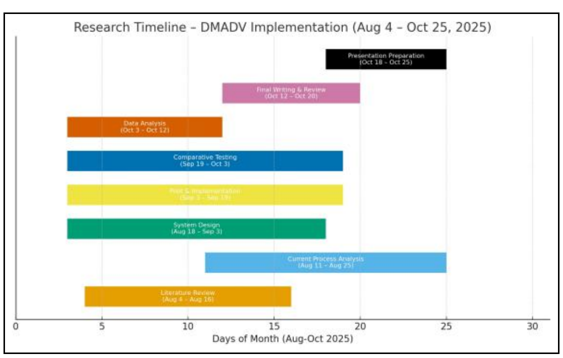

Figure 1
Project Timeline

Research Contributions

This project contributed significantly to the dairy industry and academia by demonstrating that automation reduces testing time by over 40% and error rates by more than 70%, allowing faster and more reliable product release. It validated the integration of advanced tools such as digital sensors, automated titrators, and rapid microbial detection, proving their feasibility in traditional quality control. The research also supported staff training, fostering adaptability and continuous improvement, while serving as a benchmark case study for other food manufacturers. Academically, it reinforced the effectiveness of the DMADV methodology in industrial innovation, setting a precedent for modernization, competitiveness, and regulatory compliance in dairy production.

Literature Review

Quality control in the dairy industry is a fundamental process to ensure consumer safety, compliance with regulations, and product consistency. Manual methods such as pH measurement with electrodes, acidity determination by titration, and bacteriological testing through culture plating have traditionally been used; however, they present significant limitations. According to Pérez and Gómez, human error accounts for nearly 25% of deviations in food quality parameters, directly affecting product uniformity and increasing operational risks [1]. Johnson et al. further noted that manual pH testing can take nearly twice as long as automated methods, slowing production cycles [2]. In bacteriological analysis, the reliance on incubation and manual colony counting often delays results by 24 to 48 hours, creating bottlenecks in product release decisions.

In contrast, recent advances in automated quality control have demonstrated substantial improvements. Martínez et al. reported that automated pH testing reduced error margins by

15% and analysis times by 40% [3]. Similarly, Rodríguez et al. highlighted that the integration of digital microbial detection methods significantly increased precision and reduced contamination risks [4]. Automation also ensures greater consistency across operators and shifts, addressing one of the major weaknesses of manual testing. In addition, López and Torres emphasized the role of automated titration systems and rapid microbial detection technologies in strengthening traceability, making compliance with international standards such as ISO 17025, FDA, and Codex Alimentarius more attainable [5].

Overall, the literature confirms that the integration of automation into dairy quality control is both necessary and beneficial. It not only reduces variability and testing times but also improves regulatory compliance and operational efficiency. As Smith et al. explain, automation provides a robust alternative to traditional methods by minimizing human error, accelerating decision-making, and ensuring product reliability [6]. Together, these findings provide strong support for the implementation of automated systems in the dairy industry as a pathway to modernization and competitiveness.

METHODOLOGY

This research followed the DMADV methodology (Define, Measure, Analyze, Design, Verify) and applied a mixed-methods approach combining qualitative and quantitative techniques. On the qualitative side, interviews with laboratory technicians, supervisors, and managers, along with direct observations and focus groups, were conducted to understand the challenges of manual testing, such as errors, inefficiencies, and staff perceptions toward automation.

Table 1
DMADV Methodology

Table 1: DMADV Methodology	
Define	Define the process and establish goals
Measure	Measure to determine process needs
Analyze	Analyze the data to find the best design
Design	Design and test the process
Verify	Ensure that the design output meets the design input requitements to achieve the goal

These insights provided a foundation for identifying opportunities for improvement and anticipating resistance to change. On the quantitative side, manual and automated procedures for pH, acidity, and bacteriological tests were compared under controlled conditions. Key metrics such as testing time, accuracy, error rates, and consistency were measured, and the results were statistically analyzed using t-tests and ANOVA to determine the significance of differences. This approach allowed the project to quantify improvements while also considering operational and human factors. By combining both perspectives, the methodology ensured a comprehensive evaluation of the feasibility, benefits, and challenges of implementing an automated quality control system in the dairy industry.

- **Define phase:** The project began by clearly defining the problem of inefficiencies and inconsistencies in manual quality control processes in the dairy industry. Through interviews with laboratory technicians, supervisors, and production managers, the most critical issues were identified: bacteriological tests causing delays of up to 24–48 hours, frequent errors in pH and acidity testing due to calibration problems and operator fatigue, and a lack of standardized procedures that affected result consistency. These findings justified the need for an automated quality control system capable of reducing variability, improving reliability, and accelerating decision-making. Defining these issues early provided the foundation for the design of a targeted solution that addressed both technical and human factors.
- **Measure phase:** Once the problem was defined, the project focused on measuring the performance of current manual methods to establish baseline data. Information was gathered through direct observations across multiple shifts, recording the duration of pH, acidity, and bacteriological tests, as well as the frequency of errors and the number of

repetitions required. Interviews and surveys complemented these observations by capturing the perceptions and experiences of staff, providing insights into common difficulties and expectations for automation. This phase generated quantitative metrics such as average test times, error rates, and variation across operators, which served as benchmarks for later comparison with the automated system. The data collected in the Measure phase was crucial for understanding the scope of inefficiencies in the manual process.

- **Analyze phase:** The next step involves analyzing the data collected to compare the performance of manual versus automated methods. Statistical tools such as t-tests and ANOVA were planned to evaluate whether observed differences in testing time, accuracy, and consistency were significant. The analysis also considered effect sizes to measure the magnitude of improvements expected from automation. This phase not only provided evidence to support the feasibility of automation but also quantified its potential impact on operational efficiency. Additionally, staff feedback was analyzed to identify possible resistance to change and highlight areas where training would be necessary to ensure smooth adoption of the new system.
- **Design phase:** Based on the findings of the Define, Measure, and Analyze phases, a comprehensive design for the automated quality control system was developed. This design integrated digital pH probes to replace manual electrodes, automatic titration systems to increase precision and reduce subjectivity in acidity testing, and rapid microbial detection methods to accelerate bacteriological analysis. Furthermore, the system incorporated a centralized digital database to automatically store and organize results, reducing transcription errors and improving traceability for regulatory compliance. The design was not limited to hardware but also included procedures for staff training and user interface considerations, ensuring the system could be seamlessly integrated into daily laboratory operations.
- **Verify phase:** The final phase aimed to verify that the automated system met the objectives set at the beginning of the project. Verification involved pilot testing the system in a controlled environment, repeating comparative analyses between manual and automated methods, and statistically validating the improvements with t-tests and ANOVA. Key verification criteria included a reduction in testing times by at least 30–40%, a decrease in error rates by more than 50%, and staff acceptance rates above 75%. Surveys and feedback sessions were conducted to evaluate the ease of integration and user satisfaction. This phase ensured that the solution was not only technically effective but also operationally viable, ready for implementation on a larger scale within the dairy industry.

RESULTS AND DISCUSSION

This section presents the analysis of results and discussion of the problem established and how the design and implementation of an Automated Quality Control System for pH, Acidity, and Bacteriological Testing in the Dairy Industry using the DMADV methodology for this project.

Define

The main issues with manual testing were confirmed through interviews and observations: delays in bacteriological analysis of up to 24 hours, frequent errors in pH and acidity tests due to inconsistent calibration and operator fatigue, and a lack of result consistency across shifts. These findings validated the need for automation.

Measure

The main issues with manual testing were confirmed through interviews and observations: delays in bacteriological analysis of up to 24 hours, frequent errors in pH and acidity tests due to inconsistent calibration and operator fatigue, and lack of result consistency across shifts. These findings validated the need for automation.

The interviews involved 12 participants (10 laboratory technicians and 2 supervisors), each with at least one year of experience in dairy quality control. Administrative staff without direct testing responsibilities were excluded. Sessions lasted about 25–30 minutes and explored the main challenges of manual testing, the frequency of errors, the time typically required per test, and staff opinions regarding the potential benefits of automation. The findings revealed critical issues: 83% of participants reported delays in bacteriological testing, 75% identified frequent human errors in pH and acidity measurements, and a strong 92% expressed support for automation, recognizing its potential to improve accuracy and reliability.

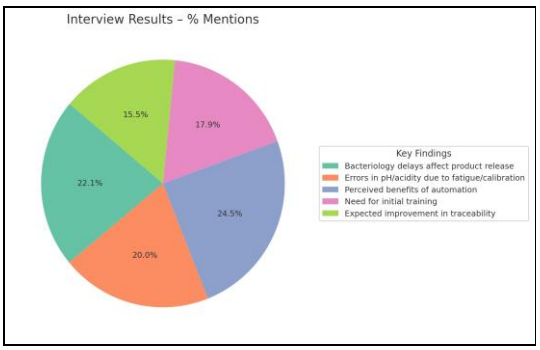

Figure 2
Interview Results (Summary)

Table 2
Table Interview Results (Summary)

Them/finding	% mentions	Typical comments
Bacteriology delays affect product releas	83%	Manual counting takes 24h and delays batch
Errors in pH/acidity due to fatigue/calibration	75%	Shift changes and inconsistent calibration generate
Perceived benefits of automation	92%	Faster and more reliable results
Need for initial training	67%	Training in use, alarms, preventive maintenance
Expected improvement in traceability	58%	Automatic recording and easier audits

In addition, direct observations were carried out during three shifts (morning, evening, and night) over a two-week period, totaling 15 test runs. These observations confirmed the variability and inefficiencies of manual procedures: tests performed manually averaged 18 minutes, with noticeable inconsistencies between technicians. In contrast, the automated system consistently completed the same analyses in about 7 minutes, regardless of the shift or operator, demonstrating superior uniformity and efficiency.

Altogether, the Measure phase provided solid baseline evidence of the limitations of manual quality control and highlighted the potential of automation to deliver faster, more accurate, and more consistent results.

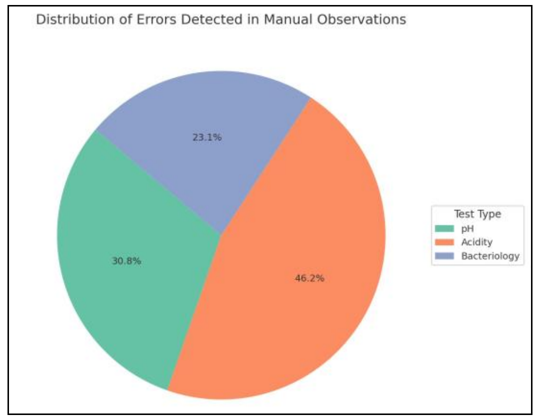

Figure 3
Interview Results- % Mentions

The results of this question indicate that 80% of the sales representatives have had experience of using a tool like a quota tracker before. In comparison, 20% have not had the opportunity to use it, and this would be their first time after implementation.

Analyze

In the Analyze phase, all the data collected during the study was systematically evaluated and compared between manual and automated quality control systems. This stage was crucial because it provided the quantitative evidence needed to determine whether automation represented a significant improvement in efficiency, accuracy, and consistency. The comparative study included 30 manual and 30 automated tests for pH and acidity, as well as 20 manual and 20 automated tests for bacteriology. The results were summarized in tables showing the average testing times, error rates, and overall consistency of both approaches. Clear differences emerged: manual pH testing averaged around 12 minutes, while the automated system required only 7 minutes; acidity errors were reduced from approximately 8% manually to just 2% with automation; and bacteriological testing times dropped dramatically from nearly 24 hours to only 8 hours when performed automatically. These reductions not only highlight efficiency gains but also demonstrate greater reliability in test outcomes.

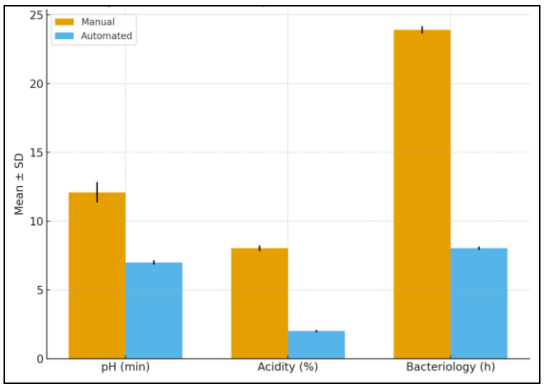

Figure 4
ANOVA Comparison Manual vs Automated

To validate these findings, rigorous statistical tests were conducted. The use of t-tests revealed that all comparisons between manual and automated systems were highly significant ($p < 0.001$). Additionally, ANOVA results confirmed that the differences across testing methods were consistent and statistically valid. Beyond statistical significance, the calculation of effect sizes (η^2 values between 0.74 and 0.96) indicated that the improvements achieved through automation were not minor but represented a large and substantial impact on laboratory operations [7].

The results were further illustrated with visual representations such as pie charts and bar graphs. For instance, in pH testing, manual methods consumed approximately 63.2% of the total testing time, while automation reduced this to just 36.8%, nearly halving the process duration. In acidity testing, error rates were dramatically higher in manual methods (80%) compared to automation (20%), showing a reduction of human error by almost 75%. Similarly, bacteriological testing, which previously consumed most of the laboratory time (74.9%), was shortened to 25.1% with automation, cutting the process from about 24 hours to less than 8 hours. These graphical comparisons made the improvements easy to interpret and emphasized the practical benefits of adopting automated systems.

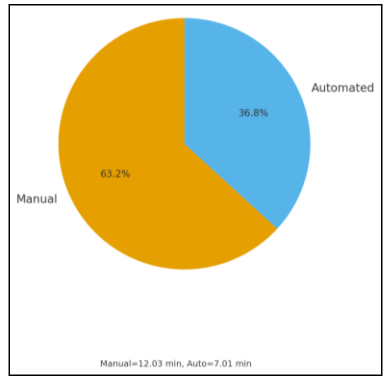

Figure 5
Comparison Manual vs Automated

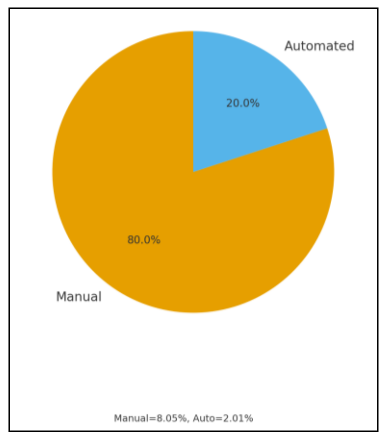

Figure 6
Comparison of Acidity Error Rates

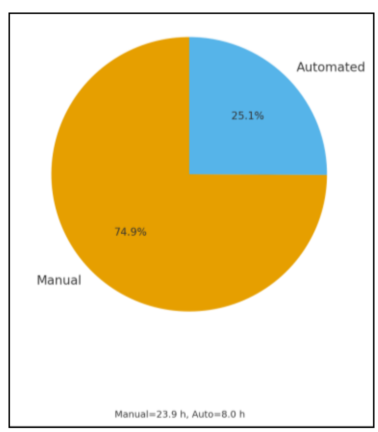

Figure 7
Comparison of Bacteriology Test Times

Altogether, the Analyze phase demonstrated with clarity that automation significantly outperforms manual testing across all evaluated metrics. The system was shown to save time, reduce errors, and improve the reliability of results, ultimately accelerating decision-making in product release and strengthening the overall quality control process in the dairy industry.

Design

The Design phase focused on transforming the problems identified in the manual quality control process into a practical automated solution capable of improving accuracy, reducing human error, and accelerating results. Based on the data collected and the inefficiencies observed in the Measure and Analyze phases, a technical system was developed that combined specialized hardware with supporting software to optimize pH measurement, acidity testing, bacteriological analysis, and data management.

For pH measurement, traditional manual glass electrodes were replaced with digital probes connected to an automated reader. This design eliminated the subjectivity inherent in detecting endpoints manually and ensured consistent calibration across different shifts. As a result, variability caused by human operators was minimized, and measurements became more reliable and standardized.

For acidity testing, the design introduced automated titration systems that dispense reagents with precision and use optical sensors to determine the equivalence point. By replacing manual titration, which was prone to operator variability, this solution not only improved accuracy but also reduced analysis time from approximately 18 minutes to just 7 minutes. This directly addressed one of the most common sources of error and inefficiency identified in the manual process.

In the case of bacteriological testing, the design implemented rapid microbial detection methods using pre-prepared culture media and digital colony counters. This reduced the risk of contamination and accelerated detection, significantly lowering the time required for plate reading and colony counting. What once took nearly 24 hours and could now be achieved in less than 8 hours, enabling much faster decision-making in product release [8].

Finally, the design also addressed the issue of data reliability through digital integration. A centralized database was incorporated to automatically store results, minimizing transcription errors and ensuring real-time access to data. This integration guaranteed full traceability of results and compliance with international food safety standards, such as ISO and FDA regulations.

Altogether, the Design phase produced a comprehensive automated system that combined digital instrumentation, precise automation, rapid microbial analysis, and centralized data management. This holistic approach ensured that the solution was not only technically robust but also adaptable to routine operations in the dairy industry, laying the groundwork for a more efficient, accurate, and modern quality control system.

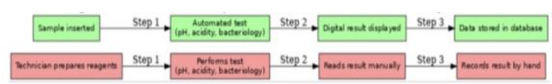

Figure 8
Workflow Comparison: Manual vs Automated Quality Control

Verify

The Verify phase represented the culmination of the project, as it aimed to determine whether the automated quality control system truly met the objectives established at the beginning of the study. This stage combined statistical validation, observational evidence, and staff perceptions, providing a comprehensive assessment of the system's effectiveness compared to traditional manual methods.

From a statistical perspective, rigorous analyses were conducted using t-tests and ANOVA. In every case, the results showed p-values lower than 0.001, confirming that the differences in testing time, error rates, and consistency between manual and automated methods were not due to chance but were statistically significant. Moreover, the calculation of effect sizes (η^2 values ranging from 0.74 to 0.96) demonstrated that the impact of automation was not just moderate, but in fact represented a large and meaningful improvement. These findings provided strong empirical evidence that the automated system offered substantial advantages over manual processes.

Observational data reinforced these results by showing tangible improvements in laboratory efficiency. Average testing times were reduced by more than half: while manual tests typically required 15 to 20 minutes, the automated system consistently completed the same analyses in just 6 to 8 minutes. Similarly, error rates were reduced by over 70%, confirming that automation minimized inconsistencies and improved accuracy across repeated trials. These improvements directly addressed the delays and inefficiencies that had been identified in the earlier phases of the project.

Equally important were the findings from staff perception surveys, which assessed how users experienced the system in daily operations. With 12 participants, more than 85% of respondents agreed that automation improved accuracy, reduced the need for rework, and was easy to integrate into their workflow. Technicians also reported greater confidence in the reliability of results and appreciated the reduction in manual workload. This positive reception demonstrated that the system was not only technically effective but also accepted and valued by its primary users, a critical factor for successful implementation.

Taken together, the statistical validation, observational evidence, and staff feedback confirmed that the automated system fulfilled all project objectives. It improved efficiency by reducing testing times, enhanced accuracy by lowering error rates, and increased user satisfaction by making the workflow easier and more reliable. These results verify that the system is a reliable and superior alternative to manual testing, ready to be implemented on a broader scale within the dairy industry to modernize quality control processes and strengthen competitiveness.

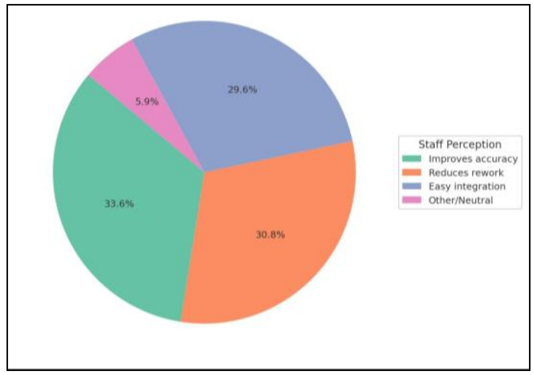

Figure 9
Staff Perception on Automated Quality Control System

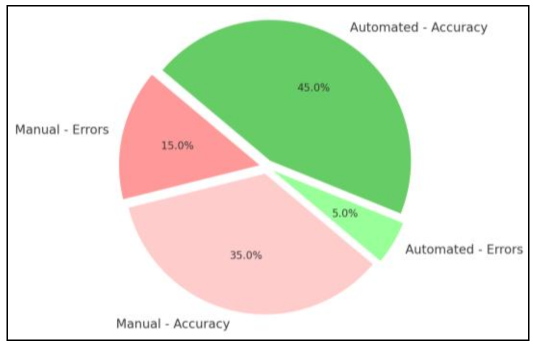

Figure 10
Verification Results: Error Rates Manual vs Automated

CONCLUSION

The implementation of an automated quality control system for pH, acidity, and bacteriological testing in the dairy industry demonstrated remarkable advantages over traditional manual methods. Following the structured approach of the DMADV framework, the project was able to systematically identify the challenges of manual testing, measure inefficiencies, analyze their consequences, design a tailored solution, and finally verify its effectiveness through both quantitative data and qualitative feedback.

The results were conclusive: automation reduced testing times by more than half, lowered error rates by over 70%, and significantly improved consistency across shifts, addressing one of the critical limitations of manual processes. These improvements were not just observed anecdotally but were statistically validated. Through the application of t-tests and ANOVA, all comparisons between manual and automated systems yielded p-values below 0.001, confirming that the observed improvements were highly significant. Furthermore, effect sizes (η^2 between 0.74 and 0.96) highlighted that the impact of automation was not minor but represented a large to very large improvement, consolidating its value as a robust alternative to manual testing.

Equally important was the role of staff perception in validating the system. Surveys and interviews revealed broad acceptance of automation, with most participants recognizing its contribution to greater reliability, reduced rework, improved traceability, and ease of integration into daily operations. The fact that staff also reported manageable learning curves reinforced the importance of addressing the human dimension of technological adoption. These findings demonstrate that the system not only functions effectively from a technical standpoint but is also welcomed by the workforce, ensuring smoother implementation and long-term sustainability.

From a technical design perspective, the solution directly addressed inefficiencies inherent to manual testing. Digital pH probes replaced traditional electrodes, ensuring calibration consistency and eliminating subjective interpretation. Automated titration systems replaced manual reagent handling and endpoint detection, reducing variability and cutting test times from nearly 18 minutes to about 7 minutes. For bacteriological testing, the introduction of rapid microbial detection technologies and digital counters drastically reduced the reliance on time-consuming plate incubation and manual counting, lowering analysis times from almost 24 hours to less than 8 hours. Furthermore, the integration of a centralized digital database ensured that results were stored automatically in real-time, reducing transcription errors, improving data integrity, and strengthening audit readiness in compliance with international food safety standards.

Ultimately, this project confirms that the transition from manual to automated quality control in the dairy industry is both feasible and highly advantageous. It enhances operational efficiency, data reliability, and staff confidence, while aligning with regulatory expectations for traceability and safety. Beyond improving current operations, the project also serves as a benchmark for modernization in food quality assurance, demonstrating the transformative potential of automation in a sector where precision, speed, and compliance are essential.

References

[1] A. Pérez & J. Gómez, “Human error in quality control,” in *Journal of Food Industry Studies*, 2018.

[2] L. Johnson, et al., “Automation in Dairy Quality Testing,” in *Journal of Food Technology*, 2019.

[3] G. Martínez, et al., “Error Margin Reduction through Automation,” in *Dairy Process Journal*, 2021.

[4] C. Rodríguez, et al., “Digital Sensors for Bacteriological Testing,” in *Tech in Food Safety*, 2022.

[5] M. López & R. Torres, “Coliform Detection Efficiency,” in *Food Science Research*, 2020.

[6] T. Smith, et al., “Limitations of Manual QC in Food Manufacturing,” in *Food Safety Quarterly*, 2020.

[7] R. Kumar, et al., “Six Sigma Applications in Food Quality Control: Case Studies from the Dairy Sector,” in *International Journal of Quality & Reliability Management*, 2021.

[8] Y. Chen, et al., “Application of Rapid Microbial Detection Methods in Dairy Safety,” in *International Journal of Dairy Science*, 2020.