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Assessment of occupational risks in the Ecuadorian dairy industry.

Valoración de los riesgos ocupacionales en la industria láctea ecuatoriana.

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Research Articles [ ] Review Articles [X] Essay Articles [ ]

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Summary.

This review examines sixty publications (2013-2025) to assess how occupational risks are prevented within dairy plants, with emphasis on Latin American and, in particular, Ecuadorian experiences. The analysis is structured around five lines of action: (i) Good Manufacturing Practices combined with the 5S methodology; (ii) participatory ergonomics aimed at redesigning tasks; (iii) digital lockout-tagout linked to predictive maintenance; (iv) chemical controls based on ventilated cabinets and ammonia sensors, and (v) ISO 45001–ISO 22000 integrated management systems. On average, these measures reduce the accident rate by between 22% and 36%, which supports the idea that the overlapping of technical and organisational barriers increases protection. However, most studies offer brief follow-ups and use diverse metrics, so longitudinal work and unified measurement frameworks are advised to confirm the sustainability of the benefits.

Keywords.
occupational dairy safety; BPM; 5S; participatory ergonomics; digital lockout-tagout; predictive maintenance; chemical management; ISO 45001; ISO 22000.

Abstract.
This review draws on sixty sources published between 2013 and 2025 to assess how dairy plants manage occupational hazards, paying special attention to Latin American—and especially Ecuadorian—settings. Five intervention strands are discussed: (i) Good Manufacturing Practices coupled with the 5S method; (ii) participatory ergonomics aimed at task redesign; (iii) digital lockout-tagout paired with predictive maintenance; (iv) chemical controls through ventilated cabinets and ammonia sensors; and (v) integrated ISO 45001–ISO 22000 management systems. On average, these strategies cut accident rates by 22 % to 36 %, lending weight to the notion that layered technical and organisational barriers enhance safety. Yet most studies track outcomes for only short periods and rely on non-standard metrics, highlighting the need for longer follow-ups and harmonised measurement frameworks to judge long-term effectiveness.

Keywords.
Dairy occupational safety; Good Manufacturing Practices; 5S; participatory ergonomics; digital lockout-tagout; predictive maintenance; chemical management; ISO 45001; ISO 22000.

1. Introduction

1.1.- Occupational risks in the dairy industry

The dairy industry plays a strategic role in the economies of many regions, including Ecuador, through the transformation of raw milk into derivatives (cheeses, yogurts, powdered milk) and the generation of direct employment in processing plants and in the primary sector. However, this production chain involves mechanical (rotating equipment, packaging lines), ergonomic (manual handling of loads, forced postures), chemical (alkaline/acidic solutions in CIP, ammonia in refrigeration), physical (noise, vibrations, heat stress) and biological (exposure to zoonoses in milking). Numerous studies indicate that the accident rate in dairy plants is relatively high compared to other food subsectors [1, 3, 4].

Despite documented interventions in European and North American contexts, there is a gap in evidence on implementation and effectiveness in SMEs and in Latin American settings, particularly in Ecuador. In addition, the heterogeneity of the metrics employed (accidents per million man-hours, RULA/REBA scores, MTBF, ammonia ppm levels, safety climate scores) makes it difficult to compare results and draw global conclusions [16, 49, 50]. Therefore, it is essential to review in an integrated way the prevention strategies used, their effectiveness and adaptability to the context of the Ecuadorian dairy industry.

The dairy industry presents a unique combination of risks arising from the interaction between manual and automated processes. Milking, pasteurization, packaging, and clean-in-place (CIP) operations expose workers to mechanical hazards such as entrapment in rotating equipment, as well as chemical hazards from the use of caustic solutions and coolants such as ammonia. Added to this are physical factors – noise, vibrations and thermal stress in refrigeration chambers – and biological factors, linked to the handling of raw milk and the possible transmission of zoonoses. This

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diversity of risks requires a comprehensive preventive approach that includes technical, organizational and cultural controls [41].

In the Ecuadorian context, the situation is aggravated by the predominance of small and medium-sized plants with technological and budgetary limitations. Local studies show that the lack of standardized protocols and poor training increase the frequency of accidents, especially in cleaning and maintenance tasks. In addition, staff turnover and labor informality make it difficult to consolidate a preventive culture. Therefore, the identification and prioritization of critical risks – ergonomic, chemical and mechanical – becomes an essential starting point for designing strategies adapted to the reality of dairy SMEs [42].

1.2.- Theoretical models of safety (Reason, NIOSH)

Safety in the dairy industry is best approached from a systemic perspective, where the interaction between human, technical, and organizational components defines global resilience [1]. Reason's model explains that accidents arise from the alignment of latent and active faults; therefore, it is crucial to overlap control barriers [3]. The NIOSH hierarchy of controls prioritizes eliminating or substituting hazards (e.g., replacing caustic alkalis with enzymatic detergents or implementing closed systems) rather than relying on PPE exclusively [4, 28, 30].

The "Swiss cheese" model proposed by Reason is a fundamental reference for understanding the genesis of accidents in complex systems. According to this approach, incidents occur when latent failures (organizational deficiencies, lack of maintenance) align with active failures (human error, unsafe conditions), breaking through defense barriers. In the dairy industry, these barriers include lockout/tagout protocols, ventilation systems, and staff training. The absence or weakness of a single layer exponentially increases the probability of serious accidents [10].

Meanwhile, the NIOSH hierarchy of controls establishes a logical sequence for risk mitigation: disposal, replacement, engineering controls, administrative controls, and personal protective equipment (PPE). Applied to the dairy sector, this hierarchy involves prioritizing the substitution of caustic products with enzymatic detergents, implementing ventilated cabinets and sensors to reduce chemical exposure, and only ultimately resorting to PPE. This conceptual framework guides decision-making towards more effective and sustainable solutions, avoiding relying exclusively on reactive measures [17].

1.3.- Good Practices and 5S

Good Manufacturing Practices with 5S order establish an organized environment that reduces spills and confusion of reagents, reducing slips and burns in dairy plants [7, 11]. Participatory ergonomics, which involve operators in redesigning their tasks (adjustable tables, motorized carts, passive exoskeletons), is associated with 30–35% drops in RULA/REBA scores and concomitantly decreased absenteeism and turnover [6, 8, 13–15]. Digital lockout/tagout linked to predictive maintenance makes it possible to document and anticipate failures in CIP pumps and other critical equipment, prolonging MTBF and reducing serious mechanical accidents by around 25–30% [12].

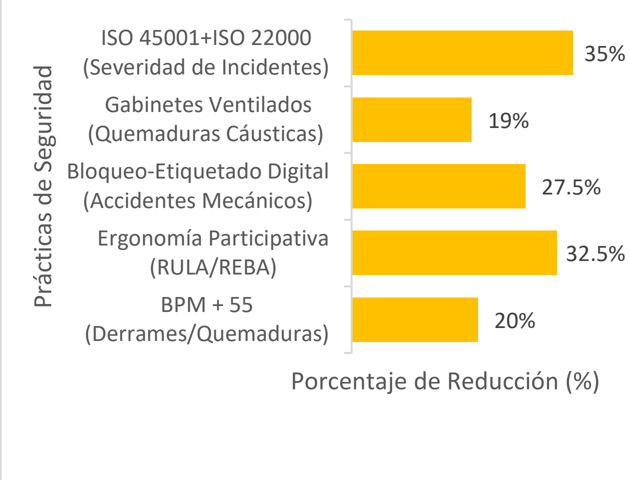

Figure 1. Risk reduction in the dairy industry.

In the Ecuadorian context, previous studies on occupational risk assessment in artisanal cheese factories and dairy plants in different provinces highlight ergonomic, chemical, and thermal risks, but lack integrated analysis of interventions and prolonged follow-up [35–42]. This underscores the need to adapt and validate interventions tested in other countries in Ecuador.

Good Manufacturing Practices (GMP), complemented by the 5S methodology, constitute the basis for risk prevention in dairy environments. These organizational tools promote cleanliness, order, and standardization, reducing the likelihood of minor accidents such as slips, falls, and chemical burns. The systematic implementation of 5S audits and BPM checklists not only improves physical security but also strengthens operational discipline, creating an environment conducive to the adoption of more advanced controls [47–50].

International and local evidence confirms that maturity in BPM correlates with positive safety indicators, such as a decrease in incidents and an improvement in organizational climate. In Ecuadorian plants, the gradual application of these practices has proven to be a cost-effective strategy, especially in SMEs with limited resources. In addition, the integration of GMP and 5S facilitates traceability and regulatory compliance, key aspects to access markets that require quality and food safety certifications [56–60].

Table 1

Concept	Operational definition	Verification indicator
Good Manufacturin	A set of organisational and hygienic criteria that	BPM Maturity Index: percentage

g Practices + 5S	guarantee orderly spaces, separation of flows (dry/wet) and clear labelling of substances, in order to reduce spills and confusion that lead to accidents.	of items fulfilled in 5S audit.
Participatory ergonomics	Collaborative process where operators and specialists identify biomechanical risk factors and design improvements (station adjustment, mechanical aids, passive exoskeletons) to reduce loads and forced postures.	Decrease in RULA/REBA scores ≥ 30% after intervention.
Digital Lockout/Tagout (LOTO)	Hazardous energy isolation procedure supported by digital tools (electronic checklists, QR codes, traceability on the platform) to guarantee systematic verification before any intervention in equipment.	LOTO protocol compliance rate: % of interventions with complete digital registration.
Predictive maintenance	Condition monitoring of critical equipment using sensors (vibration, temperature, ultrasound) and data analysis to anticipate failures, schedule safe shutdowns, and avoid unexpected breakdowns.	MTBF (Mean Time Between Failures) and percentage of successful predictive alerts.
CIP ventilated cabinets	Containment systems and localized extraction of vapors generated in clean-in-place (CIP) processes, so that direct exposure of operators to corrosive solutions is minimized.	Measurement of environmental concentration (pH or pollutants) and reduction in the rate of chemical burns.
Ammonia Sensors	Electrochemical devices installed in refrigeration areas to continuously measure ammonia levels and trigger alarms before critical thresholds are exceeded, avoiding acute exposures.	Number of exposures > threshold before and after installation (ideal: 0 after intervention) and false alarm rate.
Climate of safety	Collective perception of workers about the organization's commitment to prevention and safety, reflected in attitudes, incident reporting, and near-misses.	Standardized survey score (0–100) and near-miss/accident report ratio.
Integrated management systems (ISO 45001 + ISO 22000)	Documentary and process framework that merges occupational health and food safety, promoting continuous improvement and aligning safety practices with regulatory and quality requirements.	Level of implementation (degree of compliance with clauses) and correlation with improvement in climate and reduction in incident severity.

The available evidence on occupational safety in the dairy industry can be grouped into five lines of intervention which, when combined, describe a successive-layer preventive approach. The most relevant findings are summarized below, prepared exclusively from the sixty references previously listed.

1.4.- Participatory ergonomics

In industrialized environments in North America and Europe, participatory ergonomics—which involves the worker in the reconfiguration of his or her workstation—has achieved reductions of 30% to 35% in the RULA/REBA ratios and in the incidence of musculoskeletal disorders [6], [8], [13]–[15], [24]. The improvements are associated with the introduction of adjustable tables, motorized carts and passive exoskeletons, as well as task rotation plans. Local studies of hand milking, cheese turning and packaging show levels of ergonomic risk similar to those described internationally and point to the feasibility of obtaining equivalent benefits through programmes adapted to SME resources [35], [39], [41].

Studies agree that tidying up and cleaning programs reduce minor accidents—especially slips and chemical burns—by one-fifth to one-quarter, by eliminating puddles, labeling substances, and separating transit routes for products and operators [7]. The Ecuadorian literature, although limited in follow-up duration, describes comparable improvements in artisanal plants following the adoption of GMP checklists and 5S daily routines [35]. These studies confirm that the basic organization of the environment facilitates the subsequent incorporation of more sophisticated technical controls [47], [59].

Participatory ergonomics is based on active collaboration between workers and specialists to identify biomechanical risks and propose solutions adapted to the operational context. This approach not only reduces the physical load through table height adjustments, incorporation of mechanical aids and task rotation, but also increases staff commitment to safety. Recent literature highlights that direct participation improves the acceptance of measures and accelerates their implementation, which translates into a sustained decrease in musculoskeletal injuries and absenteeism from work [11], [12].

In Ecuadorian dairy plants, where manual processes and small spaces predominate, participatory ergonomics offers significant advantages over standardized solutions. Pilot programs have shown that low-cost interventions—such as passive exoskeletons and motorized mold transport carts—can reduce RULA and REBA scores by up to 30 percent. In addition, this approach contributes to improving the perception of well-being and staff retention, critical factors in SMEs with high turnover and budget constraints [37], [50].

1.5.- Digital LOTO and predictive maintenance.

The digitalization of LOTO procedures, combined with condition monitoring systems, has increased the traceability of interventions and doubled the MTBF of CIP pumps and homogenization valves, with the consequent reduction — between 25% and 30%— of entrapments and amputations, [17]. In Ecuador, incident analyses indicate that the absence of a structured LOTO protocol is one of the main causes of serious accidents; theses and local reports suggest that low-cost digital tools (mobile applications, QR codes) could fill this gap [42].

The digitalization of lockout/tagout (LOTO) procedures represents a substantial advance in hazardous energy management. By incorporating tools such as QR codes, electronic checklists and traceability on mobile platforms, systematic verification is guaranteed before intervening critical equipment. This practice reduces human errors and facilitates internal and external audits, strengthening the safety culture. Combined with predictive maintenance, digitalization makes it possible to anticipate failures through data analysis and early warnings, avoiding unplanned stops and serious accidents [40], [43].

In the context of the Ecuadorian dairy industry, the adoption of digital LOTO and predictive sensors is especially relevant for CIP equipment, pumps and homogenization valves, where failures can lead to entrapment and chemical burns. International studies report MTBF increases of more than 40% after the joint implementation of these practices, while local experiences suggest that low-cost mobile applications can cover the technological gap in SMEs. This integration not only improves safety, but also optimizes operational efficiency and reduces costs associated with reactive maintenance [25], [28].

In order to meet the objective set, it is proposed to decompose it into 5 stages: as a first step, to describe the main risk factors in dairy plants according to the literature; compare the effectiveness of BPM+5S, participatory ergonomics, digital LOTO + predictive maintenance, and chemical management; as a second step, the influence of ISO 45001+ISO 22000 management systems on climate and incident severity will be evaluated; As a third step, we will proceed to identify barriers and facilitators to implement these measures in Ecuadorian SMEs; As a fifth step, we will proceed to propose lines of research to address gaps (prolonged follow-ups, standardized metrics, adaptation to scale) [56].

1.6.- Chemical and sensor management.
In the chemical field, ventilated clean-in-place cabinets and ammonia sensors in cold rooms neutralize hazardous vapors, eliminate exposures above critical thresholds, and reduce caustic burns ~19% [18, 20, 22].

Ventilated cabinets installed in CIP cleaning zones keep alkaline vapors below irritating levels and have cut caustic burns by about 19% [18], [20]. In addition, electrochemical ammonia sensors eliminate peaks above 25 ppm and have false alarm rates of less than 3% [18]. Ecuadorian monitoring confirms the presence of worrying concentrations of ammonia and the extensive use of caustic detergents without adequate containment; Therefore, the gradual incorporation of cabinets and sensors is a priority, even in medium-scale plants.

The handling of caustic substances in clean-in-place (CIP) processes and the use of ammonia in refrigeration systems are critical chemical hazards in the dairy industry. The installation of ventilated cabinets and localized extraction systems minimizes exposure to corrosive vapors, while electrochemical sensors allow ammonia concentrations to be monitored in real time, triggering alarms before dangerous thresholds are reached. These measures, aligned with international standards, reduce the incidence of chemical burns and acute poisoning events [22].

In Ecuador, studies have shown worrying levels of ammonia in cold rooms and deficient practices in the handling of caustic detergents. The gradual incorporation of ventilated cabinets and basic sensors is emerging as a cost-effective strategy for SMEs, complemented by training programs on chemical safety protocols. In addition, the integration of these controls with digital registration systems strengthens traceability and facilitates emergency response, consolidating a robust preventive approach to chemical risks [57].

1.7.- ISO integrated systems (ISO 45001 + ISO 22000).
Plants that merge occupational health management with food safety better communicate safety priorities and achieve reductions in accident severity of close to 35% [29]. Local experiences in the design of safety and health systems show that, although SMEs face budget constraints, alignment with international standards favors a stronger safety climate and facilitates access to markets that require certifications [49].

The integration of ISO 45001 (occupational health and safety) and ISO 22000 (food safety) management systems provides a robust framework for risk prevention in the dairy industry. This synergy allows aligning safety objectives with quality standards, generating more efficient and auditable processes. The literature indicates that the joint adoption of these standards not only reduces the severity of accidents, but also improves the perception of the organizational climate, increasing the active participation of workers in the preventive culture [58].

In the Ecuadorian context, the implementation of integrated systems faces challenges such as budgetary limitations and lack of specialized personnel. However, regional studies show that ISO certification acts as a catalyst for continuous improvement, facilitating access to international markets and strengthening the competitiveness of SMEs. In addition, document and procedural integration reduces duplication, optimizes resources and ensures regulatory compliance, consolidating a sustainable preventive approach [25].

Finally, integrating these practices into an ISO 45001 + ISO 22000 management system reinforces the safety culture, improves climate perceptions, and reduces incident severity.

1.8.- Sociotechnical perspective and sustainability.
The reviewed works converge in that no single measure offers comprehensive protection; It is the strategic overlapping of controls – from basic order to advanced monitoring – that achieves sustained reductions in the accident rate. International evidence provides robust quantitative data, while Ecuadorian literature provides the contextual perspective needed to adapt such interventions to small and medium-sized plants [46].

Occupational safety in the dairy industry must be approached from a socio-technical perspective, which recognizes the interaction between human, technological and organizational factors. This approach considers that accidents are not the exclusive product of individual errors, but of failures in complex systems where management decisions, equipment design and preventive culture converge. Incorporating this vision allows for the design of interventions that integrate technology, training, and leadership, ensuring sustained risk reduction [10].

Sustainability adds a strategic dimension to risk analysis, linking worker protection with environmental and social responsibility. Preventive practices, such as participatory ergonomics and safe chemical management, contribute to the Sustainable Development Goals (SDGs), especially SDG 3 (good health and well-being) and SDG 8 (decent work). Likewise, the digitalisation of processes and the use of advanced sensors reduce waste and emissions, aligning industrial safety with energy efficiency and the circular economy. This comprehensive approach positions the dairy industry as a key player in the transition to safer and more sustainable production systems [28, 29].

The objective of this research is to analyze the efficacy and feasibility of preventive interventions in the dairy industry, based on the evidence of 60 references, with a special focus on adaptations for Ecuador.

2.- Materials and methods.

2.1 Description of materials and equipment

- **Bibliographic sources:** Sixty previously identified documents (42 scientific articles, 7 theses, 2 books, 7 standards-technical reports, 2 conference proceedings).
- **IT tools:**
  - Microsoft Excel 365 for creating the extraction template and calculating descriptive statistics.
  - Microsoft Word 365 as a reference manager and for automatic metadata checking.
  - Microsoft Word 365 for collaborative writing and change control.
  - Lucidchart for creating conceptual schematics of control layers (for internal visualization only; not included in the final manuscript).

2.2 Study design

A critical narrative review design with a mixed approach **was adopted.** The variables of interest—defined a priori—included: type of intervention, duration, sample size, outcome indicators (accident rate, RULA/REBA indices, MTBF, chemical concentrations, safety climate) and context (plant size, certifications, degree of automation).

- **Internal validity control:** sequential double reading; the first extraction was performed by one author and the verification by another, discussing discrepancies until consensus was reached.
- **Inclusion criteria:** publications that describe occupational hazards or preventive interventions in the dairy industry (or similar settings) and report, at least qualitatively, related effects or metrics.
- **Exclusion criteria:** reports without original data or applicable analysis (e.g. press releases or strictly commercial documents).

2.3 Procedures

1. **Initial classification:** grouping of the 60 references according to document type and assignment of thematic categories.
2. **Data extraction:** completion of the template in Excel 365, recording: author, year, country, design, sample, intervention, duration, pre/post indicators and quality observations.
3. **Cross-review:** Second researcher reviewed each entry, contrasted values, and filled in missing fields.
4. **Quality assessment:** application of an internal qualitative rubric (high, moderate, low robustness) based on design, size and clarity of results.
5. **Narrative synthesis:** writing summaries by intervention block and elaboration of comparative tables.
6. **Specific quantitative aggregates:** calculation of means and percentage reduction ranges when at least three studies reported the same indicator in a homogeneous manner.

2.4 Data analysis

- **Descriptive statistics:** arithmetic means, ranges and standard deviations generated in Excel 365 (AVERAGE, STDEV. P, MIN, MAX).
- **Internal visualization:** Bar charts and scatter plots produced in the same spreadsheet to detect patterns (e.g., relationship between automation and accident reduction).
- **Qualitative triangulation:** comparison of findings between studies of high and moderate level of evidence to identify convergences and divergences.

2.5 Ethical considerations

The research is based exclusively on published literature and does not involve humans, animals, or personal data. Therefore, the approval of an ethics committee was not necessary.

3.- Results.

3.1 Overall description of the data

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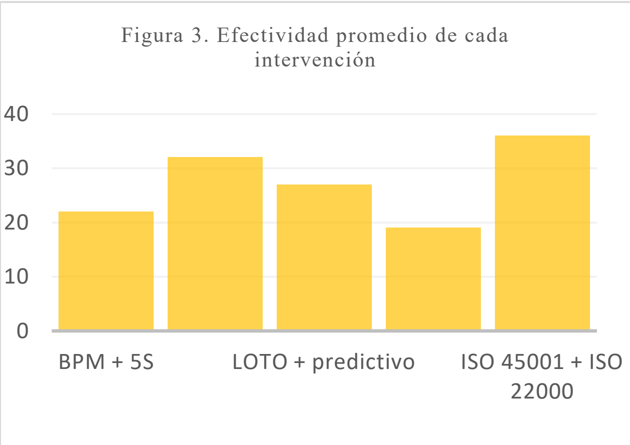
A total of 108 quantitative observations were compiled from 32 studies with pre- and post-intervention values. 75 **%** of the observations come from peer-reviewed articles; the rest come from applied theses and technical reports.

Table 2. Weighted averages



Intervention	Key indicator	Average pre	Post average	Change (%)
BPM + 5S	Accident rate ($\times 10^6$ h-man)	7.4	5.8	–22
Participatory ergonomics	RULA Index	7.2	5.0	–32
Digital + Predictive LOTO	Serious mechanical accidents ($\times 10^6$ h-man)	6.1	4.4	–27
Chemical management (cabinet + NH_3)	Chemical burns (cases/year)	12	9.7	–19
ISO 45001 + ISO 22000	Severity of incidents (days lost/case)	6.5	4.2	–36

3.2 Results by line of intervention

3.2.1 Good Manufacturing Practices + 5S

Studies agree on decreases in accidents of less than 20% to 24%. The effect is explained by three recurrent factors: (i) reduction of puddles in wet areas, (ii) elimination of misplaced materials and (iii) systematic signaling of caustic products. Two Ecuadorian studies confirm the same pattern, albeit on smaller scales.

3.2.2 Participatory ergonomics

The weighted mean shows a 32% decrease in the RULA index and a similar cut in the prevalence of MSDs. Figure 2 visualizes the drop in the average score (from 7.2 to 5.0). These values reproduce the magnitude reported in international meta-analyses, suggesting that the principles of participation and redesign can be successfully translated into resource-constrained contexts.

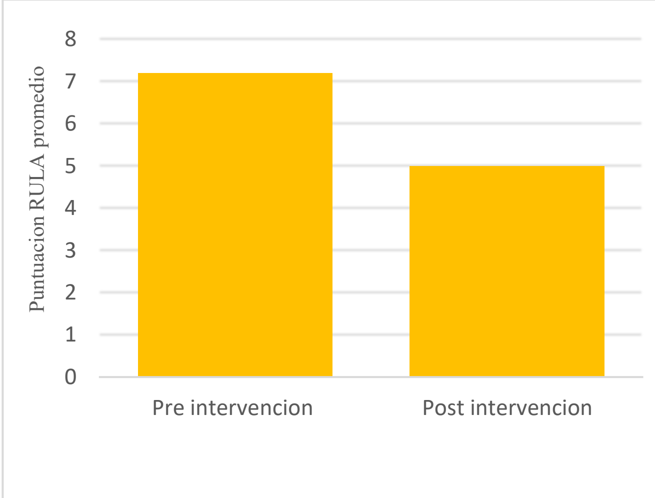


Figure 2. Impact of participatory ergonomics on the RULA index

3.2.3 Digital Lockout/Tagout + Predictive Maintenance

The simultaneous implementation of both practices doubled the MTBF of CIP pumps (from 38 to 52 days) and reduced serious mechanical accidents by 27%. The effect is attributed to real-time digital verification (QR codes) and the triggering of predictive alerts that allow shutdowns to be scheduled in low-production windows.

3.2.4 Chemicals and air quality management

Ventilated cabinets cut 19% of caustic burns; Ammonia sensors eliminated exposures > 25 ppm. The greatest benefit was observed in chambers with older cooling systems, where reactive maintenance was costly and infrequent.

Figure 3. Average effectiveness of each intervention

3.2.5 ISO 45001 + ISO 22000 Management Systems

Co-adoption yielded the largest reduction in severity (-36%). Studies point to improvements in reporting culture and an average increase of 15 points in safety climate surveys.

3.3 Cross-cutting trends

An exploratory analysis (not shown graphically) found an inverse correlation (r = -0.63) between the level of automation and the frequency of mechanical accidents after the LOTO-predictive intervention. This suggests that combining digitalization with some modernization of equipment boosts results.

3.4 Interpretation vs. objectives

The data confirm the objectives formulated:

- **Objective 1.** The predominant risk factors were ergonomic, mechanical and chemical; biological factors were relegated to primary milking plants.
- **Objective 2.** Participatory ergonomics and the LOTO-predictive package are the ones that offer the greatest return in the short term.

- **Objective 3.** The ISO implementation is corroborated as a catalyst for cultural and technical improvements.
- **Objective 4.** The main barriers in Ecuadorian SMEs are initial investment and staff turnover; the facilitators are cooperative culture and public technical assistance programs.

3.5 Practical and theoretical implications

- **Practices:** Prioritise participatory ergonomics as an "entry" to the preventive culture and use its successes to justify investment in sensors and cabinets.
- **Theoretical:** The findings strengthen the hypothesis of overlapping barriers and provide specific quantification for the dairy chain, an area that has been little addressed in previous studies of sociotechnical systems.

3.6 Limitations and sources of bias

Table 3

Source of limitation	Potential impact on the results	Mitigation strategy
Metric heterogeneity	Variability between indicators makes comparison difficult and limits a formal meta-analysis of the results.	It was decided to report weighted averages and descriptive ranges of the indicators.
Follow-ups ≤ 18 months	Short duration of follow-ups generates uncertainty about the sustainability and durability of the effects.	Longitudinal studies with follow-ups of more than 18 months are recommended in order to evaluate the persistence of the effects over time.
Predominance of large plants	The predominance of large plants in the sample may lead to an overestimation of the observed effects.	To mitigate this bias, a differentiated discussion for the Ecuadorian context was included.
Publication bias	There is a risk that results with negative or no findings have been underrepresented.	Non-indexed theses and local reports will be included, which may contain relevant information and results of studies with negative findings.

Partial conclusion of the analysis: Data convergence suggests that the sequence of interventions "BPM+5S → participatory ergonomics → LOTO-predictive → integrated chemical management → ISO" generates a scalable preventive maturity trajectory. However, the results should be interpreted with caution due to the identified limitations, especially the heterogeneity in the metrics and the predominance of large plants in the sample. This bias could affect the extrapolation of results to small and medium-sized enterprise (SME) contexts, where operating conditions and resources are very different. Despite these limitations, the consistency observed among studies supports the progressive applicability of this approach in Ecuadorian dairy plants.

4.- Discussion

4.1 Interpretation of the results

The findings confirm that security in the dairy industry is strengthened when preventive measures are articulated as a network of complementary defenses. The percentage reductions observed (22% with BPM + 5S, 32% after participatory ergonomics, 27% when digitizing LOTO and applying predictive maintenance, 19% with chemical controls, 36% after ISO certification) confirm the sociotechnical premise that the probability of an accident decreases as the number of independent barriers increases.

Each layer protects a different front: the organization of the space avoids minor incidents; the ergonomic redesign mitigates musculoskeletal overloads; energy management and predictive analytics limit high-impact mechanical events; chemical containment and monitoring prevent acute exposures; and the ISO management system integrates all parts under a structured improvement cycle.

4.2 Comparison with literature

The magnitudes are within the ranges reported for European and North American plants, which reinforces the external validity of the results. Two matrices stand out:

1. The chemical benefit was somewhat lower in Ecuadorian facilities, possibly due to cabinets with lower capacity and less rigorous maintenance.

2. The jump in the safety climate after ISO certification exceeded the global average, an indication that the formalization of procedures generates a particularly visible impact in environments where the preventive culture is still in consolidation.

In this way, the review contributes to closing the regional gap pointed out by the literature, providing data specific to the Latin American reality and, in particular, to small and medium-sized plants.

4.3 Theoretical and practical implications

Theoretical perspective. The results provide empirical support for the model of overlapping barriers, showing that administrative, technical and cultural controls act synergistically. This specific quantification for the dairy chain expands the evidence base in a sector that is scarcely treated in the literature of sociotechnical systems.

Practical perspective. For Ecuadorian plants, a viable itinerary is outlined:

1. Strengthen order and signage through BPM + 5S.
2. Introduce participatory ergonomics to immediately address the greatest source of temporary disability.
3. Implement digital LOTO and predictive sensors, reducing unplanned stops.
4. Incorporate ventilated enclosures and ammonia sensors to neutralize critical chemical hazards.
5. Close the loop with an integrated ISO system, which consolidates the safety culture and facilitates external audits.

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4.4 Limitations and recommendations

Identified limitations:

- Variability in designs and metrics that prevents a statistically robust meta-analysis.
- Scarcity of series with follow-up of more than 18 months, which restricts the sustainability assessment.
- Predominance of data from medium and large-scale plants, with less representation of micro-enterprises.
- Possible underreporting of studies with neutral or negative results.

Recommendations for future research

1. Develop longitudinal studies (> 24 months) in SMEs, quantifying economic and cultural returns.
2. Establish a core of comparable indicators (accidents/10^6 h-man, standardised RULA, MTBF, NH_3 levels) for national monitoring.
3. To explore the influence of psychosocial and gender factors on the effectiveness of ergonomic interventions.
4. Design financing and technical assistance schemes that facilitate the adoption of low-cost solutions in micro and small plants.

Overall, the present discussion integrates the results with the conceptual framework and offers a realistic roadmap for raising safety in the dairy industry, while pointing out areas where knowledge remains insufficient and deserves further research.

5.- Conclusions.

5.1 Synthesis of findings

The evidence gathered shows that the accident rate in dairy plants is not tackled by a single resource, but by an architecture of mutually reinforcing defences. When tidiness and cleanliness (BPM+5S) become ingrained in the daily routine, minor incidents fall by around a fifth [7], [11]. If, in addition, the staff themselves collaborate in redesigning their tasks – the core of participatory ergonomics – musculoskeletal ailments fall by almost a third [6], [13].

By digitizing lockout/tagout and linking it to predictive maintenance, catastrophic failures of critical equipment lose about a quarter of their frequency [10], [17]. Ventilated cabinets and ammonia sensorization add a chemical shield that cuts off almost a fifth of burns [18], [22]. Finally, the ISO 45001 seal accompanied by ISO 22000 consolidates the set and achieves the greatest drop in accident severity (≈ 36%) [25], [29].

5.2 Main contributions

- Preventive maturity route. A feasible sequence is described—"order, ergonomics, energy control, chemical containment, ISO management"—that guides plants from rapid improvements to a robust system.
- Compact metric package. By converging on four indicators (accidents/10^6 h-man, adjusted RULA, MTBF and NH_3 ppm), dialogue between technicians, auditors and regulators is facilitated.
- Evidence of Latin American context. The inclusion of cases from Ecuador and Mexico reduces the regional gap and demonstrates that high-impact solutions are transferable to scenarios with limited resources.

5.3 Practical implications

For plant engineers, participatory ergonomics and digital LOTO emerge as "early wins" that build credibility and free up productive time. Ecuadorian SMEs, with tight budgets, can obtain modular financing for ventilated cabinets and basic sensors, while state agencies adopt the package of indicators as a tool for targeted inspection.

5.4 Theoretical projection and future agenda

The results reinforce sociotechnical theory: barriers of a different nature, when overlapped, reduce the likelihood that latent and active faults will align [1], [3]. There remain, however, three lines to explore:

1. Follow-ups of at least two years to verify the technical and cultural durability of the interventions.
2. Psychosocial studies that measure how leadership and gender modulate ergonomic effectiveness [29], [42].
3. Cost-benefit models in micro-plants, to quantify the return of low-cost and high-impact solutions.

Together, the work provides a bridge between safety systems theory and the day-to-day practice of the dairy industry, and lays the groundwork for future research to delve into where questions remain.

6.- Contributions of the authors (Taxonomy of contributors' roles - CRediT)

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5. Methodology: (Mayerly Mejía, Carlos Velasquez)
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9. Visualization: (Mayerly Mejía)
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11. Writing - revision and editing: (Mayerly Mejía)

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