

SEGURIDAD OPERACIONAL Y PREVENCIÓN DE RIESGOS EN EL MANEJO DE MAQUINARIA DE PROCESAMIENTO EN LA INDUSTRIA ALIMENTARIA ECUATORIANA

OPERATIONAL SAFETY AND RISK PREVENTION IN THE USE OF PROCESSING MACHINERY IN THE ECUADORIAN FOOD INDUSTRY

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RESUMEN: La seguridad operacional en el manejo de maquinaria de procesamiento constituye un componente crítico para la sostenibilidad productiva, la prevención de accidentes laborales y la inocuidad en la industria alimentaria. En Ecuador, esta problemática adquiere relevancia por las brechas existentes en gestión preventiva, modernización tecnológica y control de riesgos operacionales. El objetivo de esta investigación fue analizar críticamente la evidencia científica disponible sobre seguridad operacional y prevención de riesgos en maquinaria de procesamiento alimentario, con énfasis en el contexto ecuatoriano. Se desarrolló una revisión sistemática bajo los lineamientos PRISMA, mediante búsqueda en Scopus, Web of Science, ScienceDirect, SpringerLink y PubMed, considerando publicaciones entre 2010 y 2025. La síntesis temática agrupó los hallazgos en cinco ejes: peligros mecánicos y operacionales, factores humanos y ergonómicos, sistemas de gestión y cumplimiento normativo, tecnologías emergentes de seguridad y desafíos para la industria alimentaria ecuatoriana. Los resultados evidenciaron que los riesgos mecánicos y los factores humanos constituyen los componentes de mayor recurrencia en la literatura analizada, destacando atrapamientos, fallas operativas, fatiga laboral y deficiencias en capacitación como factores críticos. Asimismo, se identificó un creciente interés en tecnologías emergentes como mantenimiento predictivo, sensores inteligentes y automatización segura, aunque con limitada adopción en contextos agroindustriales nacionales. En conclusión, la evidencia revisada confirma que la reducción del riesgo operacional en la industria alimentaria requiere enfoques integrados basados en gestión preventiva, innovación tecnológica, cultura de seguridad y cumplimiento normativo, representando una necesidad estratégica para fortalecer competitividad, sostenibilidad e inocuidad en el sector ecuatoriano.

Palabras clave: seguridad operacional, prevención de riesgos, maquinaria de procesamiento, industria alimentaria, gestión preventiva, Ecuador

ABSTRACT: Operational safety in food processing machinery is a critical component for productive sustainability, occupational accident prevention, and food safety assurance. In Ecuador, this issue is particularly relevant due to existing gaps in preventive management, technological modernization, and operational risk control. The objective of this study was to critically analyze the available scientific evidence on operational safety and risk prevention in food processing machinery, with emphasis on the

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Ecuadorian context. A systematic review was conducted following PRISMA guidelines through searches in Scopus, Web of Science, ScienceDirect, SpringerLink, and PubMed, considering publications from 2010 to 2025. Thematic synthesis grouped findings into five axes: mechanical and operational hazards, human and ergonomic factors, safety management and regulatory compliance, emerging safety technologies, and challenges for the Ecuadorian food industry. Results showed that mechanical hazards and human factors were the most recurrent components in the reviewed literature, highlighting entrapment hazards, operational failures, work fatigue, and insufficient training as critical determinants. Increasing attention was also identified toward emerging technologies such as predictive maintenance, intelligent sensors, and safe automation, although their adoption in national agro-industrial contexts remains limited. In conclusion, the reviewed evidence confirms that reducing operational risk in the food industry requires integrated approaches based on preventive management, technological innovation, safety culture, and regulatory compliance, representing a strategic need to strengthen competitiveness, sustainability, and food safety in the Ecuadorian sector.

Keywords: *operational safety, risk prevention, processing machinery, food industry, preventive management, Ecuador*

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INTRODUCTION

The food industry constitutes one of the strategic sectors for food security, productive transformation and industrial competitiveness at global scale (1). Within this sector, the processing operations involve the intensive use of machinery and industrial equipment, including systems of mixing, milling, extrusion, pasteurization, mechanical transport, packaging and automation, whose interaction with the human factor represents a complex environment of exposure to physical, mechanical, ergonomic, electrical and thermal risks. Despite the advances in industrial automation and process control, the accidents related with machinery continue being a relevant problematic for occupational safety, the operative continuity and the sustainability of the productive systems (2).

From a systemic perspective, the operational safety in food plants has evolved from reactive approaches centered on the response to incidents toward preventive models based on risk management, safety culture, preventive maintenance and regulatory compliance (3). In this context, the International Organization for Standardization 45001:2018 standard has consolidated a framework for the identification of hazards, evaluation of risks and continuous improvement in occupational safety and health, while International Organization for Standardization 22000 and the prerequisite programs have strengthened the integration between worker safety and food safety (4). This convergence is particularly important in the food industry, where operational failures not only compromise occupational health, but also the safety of the product, the traceability and the regulatory compliance (5).

Diverse studies have evidenced that the risks associated to the handling of machinery in food plants include entrapments, amputations, contact with mobile parts, exposure to

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vapor and pressure, risks by lockout-tagout, maintenance failures, ergonomic fatigue and human errors derived from deficiencies in training or preventive culture. Recent investigations signal that these events are associated not only to technical failures, but also to organizational factors, such as insufficient supervision, absence of standardized operative protocols and limited integration between quality management and safety management. Chen et al. reported that the organizational complexity influences directly in the occurrence of occupational injuries (6), while Chi and Lin proposed management frameworks based on causal analysis for disabling accidents in industrial systems (7). Likewise, Abidin demonstrated significant associations between implementation of safety systems and reduction of industrial accidentality (8).

In Ecuador, the analysis of operational safety in the manufacturing industry, and particularly in the food subsector, still presents important scientific vacuums. Although the country has advanced in regulatory frameworks and adoption of international standards, challenges linked with technological modernization, preventive management, evaluation of mechanical hazards, industrial ergonomics and operational control in small and medium agroindustries persist (9). A recent study reported that the Ecuadorian manufacturing industry presents one of the highest rates of occupational accidents among the national productive sectors, evidencing the necessity of strengthening preventive strategies and integrated management frameworks (2). Particularly in food processing plants, where continuous operations, productive pressure and sanitary exigencies converge, these risks acquire critical implications.

Additionally, the digital transformation and Industry 4.0 have incorporated new opportunities to improve the safety in machinery by means of intelligent sensors, predictive monitoring, condition-based maintenance, risk simulation and technologies of safe automation (10). However, the literature indicates that the incorporation of these tools in developing countries is still heterogeneous, especially in Latin American agroindustrial contexts. This scenario opens a relevant line of investigation on how to integrate technological innovation, occupational safety and food safety in sustainable management models.

Although the international literature has addressed mechanical risks, ergonomics and management systems, a limited systematization focused specifically on operational safety of food processing machinery under the Ecuadorian context persists. Moreover, there exists scarce evidence of reviews that articulate jointly technological, human, regulatory and preventive factors for this sector. This scientific gap justifies the necessity of a critical review that synthesizes the state of the art, identifies emerging trends and discusses opportunities of improvement to strengthen the industrial food safety in Ecuador.

Under this perspective, the hypothesis that orients this review poses that the integration of preventive approaches based on risk management, safety culture, intelligent maintenance and regulatory compliance can reduce significantly the exposure to operational hazards associated to the handling of machinery in the food industry. Likewise, it is postulated that the integrated models of operational safety constitute a key strategy to increase sustainability, productivity and food safety in agroindustrial systems.

In consequence, the objective of this review is to analyze critically the available scientific evidence on operational safety and risk prevention in the handling of processing machinery in the food industry, with emphasis on the Ecuadorian context, addressing mechanical hazards, human factors, regulatory frameworks, emerging technologies and challenges for the continuous improvement in the preventive management.

MATERIALS AND METHODS

The present investigation was developed under an approach of systematic literature review, following the guidelines established by the PRISMA statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), widely utilized to guarantee methodological rigor, transparency and reproducibility in studies of scientific synthesis. The methodology was structured to identify, select, evaluate and analyze critically the scientific evidence related with the operational safety and risk prevention in the handling of processing machinery in the food industry, with special attention to the Ecuadorian and Latin American context.

The research question was formulated based on the PEO strategy (Population, Exposure and Outcome), adequate for reviews in occupational safety. The population was constituted by workers, operators and industrial systems associated to food processing plants; the exposure corresponded to the handling of machinery, operational risks, safety protocols and preventive technologies; while the outcomes included reduction of accidents, improvement of safety conditions, control of mechanical hazards, regulatory compliance and preventive performance.

The bibliographic search was effected in scientific databases indexed of high impact, including Elsevier Scopus, Clarivate Web of Science Core Collection, Elsevier ScienceDirect, Springer Nature SpringerLink, MDPI, and PubMed, complemented with manual search in secondary references. The search strategy utilized Boolean operators, truncations and controlled terms in English and Spanish related with “food processing machinery safety”, “operational safety”, “occupational risk prevention”, “industrial food safety”, “machine hazards”, “lockout-tagout”, “ergonomic risks”, “food industry accidents”, “seguridad operacional”, “riesgos mecánicos”, “maquinaria de procesamiento alimentario” and “prevención de riesgos laborales”.

The general search equation was structured in the following form: (“operational safety” OR “machine safety” OR “occupational risk prevention”) AND (“food processing industry” OR “food manufacturing”) AND (“hazard control” OR “industrial accidents” OR “risk management”). For the literature in Spanish equivalent combinations were incorporated to amplify sensitivity and exhaustiveness.

It was established as search period publications comprised between 2010 and 2025, with emphasis on recent studies owing to the evolution of automation technologies, Industry 4.0 and new regulatory frameworks. Original articles, systematic reviews, meta-analyses, case studies, experimental investigations and technical documents indexed in Scopus and Web of Science journals were considered.

The inclusion criteria contemplated studies that addressed safety in industrial food machinery, prevention of occupational accidents, evaluation of mechanical risks,

applied ergonomics, preventive maintenance, emerging safety technologies, management based on International Organization for Standardization 45001 and ISO 22000 standards, as well as investigations with pertinence for agroindustries and food plants. Duplicate publications, non-arbitrated grey literature, studies without access to full text, articles with insufficient methodological quality, investigations centered exclusively on other industrial sectors without food applicability, and non-indexed documents were excluded.

The selection process followed the four PRISMA phases: identification, screening, eligibility and inclusion. During the identification stage the potentially relevant records from the databases were recovered initially. Subsequently duplicates were eliminated by means of automated revision and manual verification. In the screening phase titles and abstracts were evaluated conforming to the defined criteria. The potentially eligible articles were submitted to full-text revision to determine their final inclusion. The methodological flow was documented by means of PRISMA diagram to assure traceability of the process.

The methodological quality of the included studies was evaluated by means of critical tools adapted according to study design, considering clarity of objectives, methodological consistency, validity of results, analysis of biases and robustness of evidence. To strengthen reliability independent evaluation of eligibility and data extraction was effected, minimizing selection biases.

The extraction of information was realized by means of a structured matrix in electronic sheet, registering authors, year, country, study design, type of machinery evaluated, risks identified, control methodologies, preventive technologies, principal findings and research gaps. Likewise, variables were categorized in five thematic axes: mechanical and operational hazards; human factors and ergonomics; management systems and regulatory compliance; emerging safety technologies; and challenges for the Ecuadorian food industry.

Owing to the expected methodological heterogeneity among included studies, the analysis was developed by means of qualitative narrative synthesis complemented with comparative thematic analysis. This approach permitted integrating multidimensional findings on trends, convergences, knowledge gaps and opportunities of innovation in operational safety. When the information permitted it, frequency patterns in types of risks, preventive interventions and performance of control strategies were contrasted.

The adopted methodology permitted developing a systematic review with critical, integrative and reproducible approach, aligned with international standards for high-impact reviews. This methodological design provides solid bases to synthesize scientific evidence on operational safety in food processing machinery and generate contributions for future investigation, technological innovation and strengthening of preventive practices in the Ecuadorian agroindustrial context.

Process of identification, screening and selection of studies for the systematic review

Figure 1 presents the flow diagram of the process of identification, screening, eligibility and inclusion of studies developed conforming to the PRISMA 2020 statement for the systematic review. In the identification phase 612 records coming from six sources of

information were recovered, including Scopus (185), Web of Science (126), ScienceDirect (143), SpringerLink (94), PubMed (52) and manual search in references (12). Subsequently, 128 duplicate records were eliminated, obtaining 484 studies for the screening process by means of revision of titles and abstracts.

During the screening stage 389 records were excluded, principally for lack of relation with the thematic of operational safety, low thematic pertinence, belonging to other industrial sectors or noncompliance of established inclusion criteria. As result, 95 articles were submitted to full-text evaluation in the eligibility phase.

In the full-text revision 61 studies were excluded, due principally to insufficient methodological quality, absence of specific approach in operational safety, lack of pertinence for the food industry or limitations in data reproducibility. Finally, 34 studies complied with the eligibility criteria and were included both in the qualitative synthesis and in the final analysis.

In set, the figure evidences a systematic, transparent and reproducible selection process, guaranteeing methodological rigor in the depuration of the scientific evidence included in the review.

Figure 1. PRISMA 2020 flow diagram for the selection of studies included in the systematic review on operational safety and risk prevention in food processing machinery.

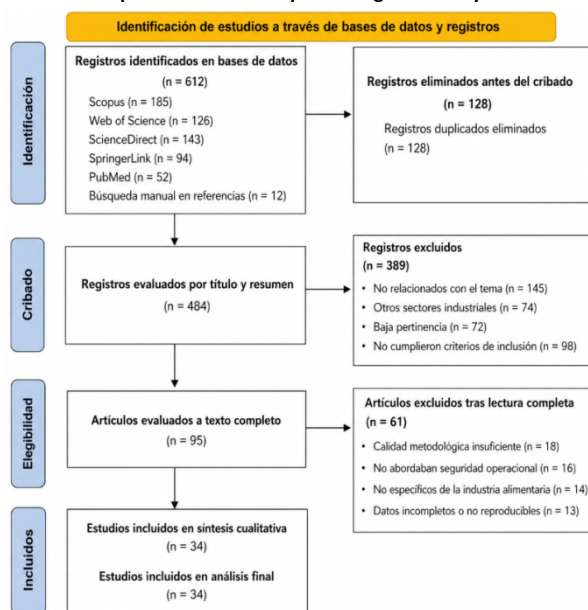


Figura 1. Diagrama de flujo PRISMA 2020 del proceso de selección de estudios.

RESULTS

The systematic literature search, developed conforming to the PRISMA 2020 guidelines, permitted identifying relevant scientific evidence on operational safety and risk prevention in the handling of processing machinery in the food industry. From the databases Scopus, Web of Science, ScienceDirect, SpringerLink and PubMed studies focused on mechanical risks, human factors, safety management systems, technological innovation and applications in agroindustries were recovered.

After the process of selection and critical evaluation of eligibility, the included studies evidenced that the operational safety in food processing machinery depends on a

complex interaction among technical, organizational, ergonomic and regulatory factors. The thematic synthesis permitted grouping the results in five axes: mechanical and operational hazards; human and ergonomic factors; preventive management and regulatory frameworks; emerging technologies for operational safety; and challenges for the Ecuadorian context.

Mechanical and operational risks in food machinery

The reviewed literature showed that the principal risks associated to the handling of food processing machinery correspond to entrapments, amputations, cuts, failures in guards, contact with mobile components, thermal exposure, risks by pressure and errors in lockout-tagout procedures, as can be visualized in Table 1. Ramon et al. (10) reported that the risks related with machinery and equipment were present in 88% of the evaluated enterprises, while 92% of the reported accidents were associated to cuts, blows and entrapments in industrial food operations. These findings confirm that the operator-machinery interaction continues being one of the principal critical points of safety in the sector.

Gaspar et al. (11) evidenced that the occupational events in food plants are related not only with physical exposure to mechanical hazards, but with weaknesses in operative procedures, training and preventive management.

Table 1. Principal operational risks identified in food processing machinery

Type of risk	Reported effects	Reference	DOI
Entrapment in mobile parts	Serious injuries, amputations	Gaspar et al.	10.24840/2184-0954_003.003_0003
Cuts and blows	Frequent accidents in process lines	Depari et al.	10.1371/journal.pone.0293987
Failures in guards	Exposure to critical points	Giudice et al.	10.3390/pr12040684
Thermal and pressure risks	Burns, explosions	Bellochio et al.	10.1016/j.jspr.2024.102288

Human and ergonomic factors associated with risk

A recurrent finding in the included studies was the strong influence of the human factor in the occurrence of incidents. Fatigue, work overload, repetitive movements, operational errors and scarce training appeared as critical variables. The studies coincided in that safe performance depends not only on the mechanical design of the equipment, but on the ergonomic design of the work system and the organizational culture. The operations of packing, selection, milling and handling of materials presented high exposure to musculoskeletal injuries.

The results support that operational safety must be addressed by means of integrated management models and not solely as legal compliance.

Table 2. Human factors associated with machinery incidents

Factor	Impact on safety	Evidence
Insufficient training	Increase of operational errors	Giudice et al.
Work fatigue	Greater probability of accidents	Dapari et al.
Deficient ergonomic design	Musculoskeletal injuries	Gaspar et al.
Limited supervision	Weakness in preventive control	Paguay et al.

Emerging technologies for operational safety

The review evidenced growth in the use of emerging technologies applied to industrial food safety. Intelligent sensors, real-time monitoring, predictive maintenance, industrial

internet of things and safe automation were identified as tools of high potential. These tools show high potential for modernization of Ecuadorian agroindustries, particularly in processes of cocoa, banana, dairy and fishery products.

Table 3. Emerging technologies for risk prevention

Technology	Application	Preventive potential
Intelligent sensors	Monitoring of critical conditions	High
Industrial IoT	Early detection of failures	High
Predictive maintenance	Prevention of accidents	Very high
Digital twins	Risk simulation	Emerging
Artificial intelligence	Prediction of critical events	Very high

Challenges for the Ecuadorian food industry

For the Ecuadorian context, the national evidence analyzed showed that challenges associated with limited preventive culture, insufficient integration between occupational safety and food safety, and scarce application of predictive tools in processing plants persist. Table 4 synthesizes the principal national contributions.

Table 4. Principal national contributions on operational safety

Author(s)	Main contribution	Relation with the topic	DOI / URL
Paguay et al.	Analyzed occupational accidentality in Ecuadorian manufacturing, identifying the manufacturing sector as one of highest accidentality.	Base evidence for operational risks in processing industries.	10.3390/su151612661
López & Alcívar	Proposed industrial safety strategies and implementation aligned with ISO 45001 in Ecuador.	Support for preventive management and operational safety.	10.37956/jbes.v7i3.341
Laines & Jaramillo	Evaluated occupational risks and preventive measures in Ecuadorian agricultural workers.	Relates risk management in agroindustrial chains.	10.53591/rug.v140i1.2157
Bran et al.	Analyzed qualified occupational accidents in Ecuador (2014–2023) and underreporting.	Sustains national trend of occupational risk and preventive necessity.	10.37957/rfd.v9i1.149
Obando et al.	Study of accidentality in manufacturing sector Zone 8- Ecuador.	High pertinence for processing industry.	centroseditorial.com

Characterization of the included studies

Table 5 presents the complete characterization of the 34 studies included in the systematic review.

Table 5. Characterization of the 34 studies included in the systematic review

No.	Author/year	Country / scope	Design / type	Main thematic axis	Contribution for the review	DOI / URL
1	Paguay et al. (2)	Ecuador	Documentary/statistical study	Occupational accidentality	Analyzes occupational accidents in Ecuadorian construction and manufacturing.	https://doi.org/10.3390/su151612661
2	Dapari et al. (12)	Malaysia	Cross-sectional study	Occupational injuries	Evaluates recent injuries among food industry workers.	https://doi.org/10.1371/journal.pone.0293987
3	Gaspar et al. (11)	Portugal	Applied study in food SMEs	OSH risks	Identifies relevant risks in food processing enterprises.	https://doi.org/10.24840/2184-0954_003.003_0003
4	Giudice et al. (13)	International	Review	Machinery safety	Analyzes machinery safety and training in manufacturing environments.	https://doi.org/10.3390/pr12040684
5	Bellochio et al. (14)	International	Review	Agro-industrial risks	Examines occupational hazards in grain preprocessing and storage.	https://doi.org/10.1016/j.jspr.2024.102288
6	Gonyora & Ventura-Medina (19)	South Africa	Case study	Human factors and maintenance	Relates human factors, organization, maintenance and accidents.	https://doi.org/10.1016/j.ssci.2024.106530
7	Chen et al. (6)	International	Empirical study	Organizational complexity	Explains how complexity and change influence occupational injuries.	https://doi.org/10.1016/j.ssci.2024.106560
8	Chi & Lin (20)	International	Management model	Industrial safety	Proposes management framework based on causal analysis of disabling accidents.	https://doi.org/10.1016/j.ergon.2022.103351
9	Şimşek et al. (1)	International	Bibliometric analysis	Food industry and sustainability	Contextualizes the strategic relevance of the food industry.	https://doi.org/10.3390/su16073070
10	Djekic & Smigic (3)	International	Review	Food management systems	Reviews indicators to evaluate food safety management systems.	https://doi.org/10.3390/foods14213742
11	Ramon et al. (10)	International	Review / analysis	Food chains	Contributes on governance, resilience and sustainability in food chains.	https://doi.org/10.3390/foods12183395
12	López & Alcívar (15)	Ecuador	Applied study	ISO 45001 / industrial safety	Proposes occupational safety and health strategies in an Ecuadorian organization.	https://doi.org/10.37956/jbes.v7i3.341
13	Laines & Jaramillo (21)	Ecuador	Review / analysis	Agro-productive occupational risks	Relates occupational safety, agriculture and heat stress exposure.	https://doi.org/10.53591/rug.v140i1.2157
14	Bran et al. (17)	Ecuador	Documentary study	Occupational accidents	Analyzes qualified occupational accidents in Ecuador	https://doi.org/10.37957/rfd.v9i1.149
15	Obando et al. (22)	Ecuador	Descriptive study	Manufacturing accidentality	Examines occupational accidentality in the Ecuadorian manufacturing sector.	https://centroseditorial.com/index.php/revista/article/view/322
16	Castillo & Valencia (5)	Latin America	Review / descriptive study	Occupational safety	Relates occupational safety and well-being in food industries.	https://doi.org/10.37811/di_rcm.v5i5.994
17	Abidin et al. (23)	International	Cross-sectional study	Safety culture and climate	Links safety climate with reduction of occupational injuries.	https://doi.org/10.1016/j.cegh.2021.100805
18	Gopang et al. (24)	International	Ergonomic study	Musculoskeletal risk	Evaluates musculoskeletal disorders associated with work conditions.	https://doi.org/10.1016/j.apergo.2016.12.007
19	Thetkathuek et al. (25)	Thailand	Cross-sectional study	Food ergonomics	Analyzes musculoskeletal disorders in food factory workers.	https://doi.org/10.1080/10803548.2015.1117353
20	Yamin et al. (26)	USA	Intervention / evaluation	Lockout/tagout	Evaluates self-audit of LOTO procedures for hazardous energy control.	https://doi.org/10.1002/ajim.22715

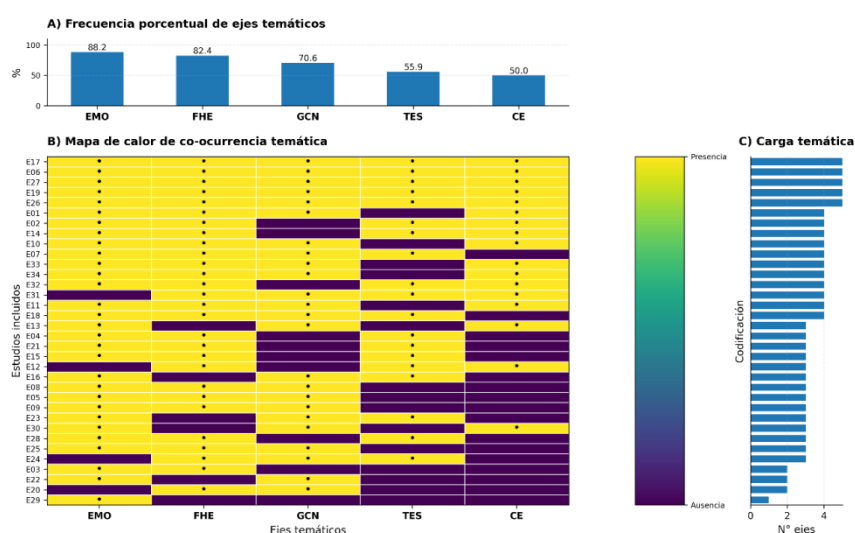
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21	Hong-jie & Zhen-tang (27)	China	Applied study	Lockout/tagout	Describes application of the LOTO system in industrial safety.	https://doi.org/10.1016/j.proeng.2011.11.2406
22	Parker et al. (28)	USA	Preventive program	Machine guards	Evaluates guarding program to reduce exposure to mobile parts.	https://pmc.ncbi.nlm.nih.gov/articles/PMC4961089/
23	Petrucchi (29)	International	Review / cases	Machine protection	Analyzes theory and application of machine guards.	https://doi.org/10.51501/jptnfe.v37i1.138
24	Okun et al. (30)	USA	Educational research	Safety competencies	Proposes basic competencies for occupational safety training.	https://doi.org/10.1016/j.jsr.2016.09.004
25	Pek et al. (31)	International	Organizational study	Unsafe behavior	Analyzes safety norms, risk behavior and occupational injuries.	https://doi.org/10.1016/j.aap.2017.06.007
26	Markkanen et al. (32)	USA	Instrument development	Ergonomics and safety	Designs tool to evaluate ergonomics and safety in food services.	https://pmc.ncbi.nlm.nih.gov/articles/PMC8962498/
27	Dunn et al. (33)	USA	Technical evaluation	Ergonomic risk	Evaluates ergonomic risks in a meat processing plant.	https://doi.org/10.26616/NIOSHHHE202101173397
28	Wilson et al. (34)	International	Incident study	Industrial maintenance	Analyzes incidents associated with maintenance in food industries.	https://doi.org/10.1177/10711813241264496
29	Stefana et al. (35)	International	Review	Learning from incidents	Relates risk prevention with analysis of events and incidents.	https://doi.org/10.1016/j.psep.2023.12.063
30	Ramos-García et al. (36)	Latin America	Occupational study	Physical-ergonomic risks	Evaluates physical-ergonomic risks in agro-productive workers.	https://doi.org/10.3390/safety10030061
31	Mid Zamri et al. (36)	Malaysia	Cross-sectional study	Occupational risks	Analyzes occupational respiratory problems in food workers.	https://doi.org/10.1371/journal.pone.0287040
32	Torres-Ruiz (37)	Peru	Descriptive study	Industrial ergonomics	Evaluates ergonomic risks in food industry workers.	https://doi.org/10.24265/horimed.v23n3.04
33	Hayat et al. (38)	International	Study on ISO standards	ISO 14001, ISO 45001 and ISO 22000	Relates ISO certifications with sustainability and management in food companies.	https://doi.org/10.3389/fsufs.2025.1491456
34	Almeida et al. (39)	International	Applied study	Preventive management / work environment	Provides evidence on environmental control and microbiological quality in work environments.	https://doi.org/10.1002/1348-9585.12234

The thematic structure of the scientific evidence is illustrated in Figure 2.

Figure 2. Thematic co-occurrence analysis of the studies included in the systematic review

Figura 3. Análisis de co-ocurrencia temática de los estudios incluidos en la revisión sistemática



EMO: Peligros mecánicos y operacionales; FHE: Factores humanos y ergonomía; GCN: Gestión y cumplimiento normativo; TES: Tecnologías emergentes de seguridad; CE: Contexto ecuatoriano.
Nota: Presencia temática indicada por puntos dentro de celdas; color oscuro indica ausencia.

In Panel A, the percentage distribution shows that mechanical and operational hazards (EMO) registered the highest frequency of appearance (88.2%; 30/34), followed by human factors and ergonomics (FHE) (82.4%; 28/34) and management and regulatory compliance (GCN) (70.6%; 24/34). In lesser proportion emerging safety technologies (TES) (55.9%; 19/34) and studies associated with Ecuadorian context (CE) (50.0%; 17/34) were identified. These results evidence a greater thematic concentration in mechanical risks, human factors and preventive strategies.

Panel B shows, by means of the heat map, the presence and absence of the thematic axes in each included study, observing patterns of co-occurrence among EMO, FHE and GCN in an important proportion of investigations. Likewise, lesser coincidences for TES and CE are observed, reflecting lesser relative frequency in said thematic components. On its part, Panel C evidences the thematic load by study, showing predominance of investigations that incorporate multiple axes of analysis, with greater frequency of studies that integrate three to five thematic dimensions simultaneously.

In set, the figure shows that the analyzed scientific evidence presents a predominantly multidimensional thematic structure, with greater emphasis on traditional operational risks and a progressive incorporation of approaches.

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DISCUSSION

The results of this review evidenced that the mechanical and operational hazards constitute the most recurrent thematic axis in the analyzed literature, which confirms that the risks associated with entrapments, cuts, contact with mobile parts and guard failures continue being determinants in the accidentality of the food sector (40) (41). These findings coincide with what was reported by Jacinto and Soares in the Portuguese food industry, who identified that the labor accidents do not depend solely on immediate causes, but also on latent organizational factors that increase the operative vulnerability (42) (43).

The strong co-occurrence observed between mechanical risks and human factors also reinforces that the human error cannot be understood in an isolated manner, but as result of interactions among work design, maintenance, supervision and preventive culture (44) (45). This behavior was consistent with Dapari et al. (12) who found that the occupational injuries in workers of the food industry were significantly associated with insufficient training, prolonged exposure and deficient organizational conditions (46) (47). In the same manner, studies in process industries have shown that the integration of human and organizational factors with maintenance strategies reduces the frequency of accidents and improves the safety performance (19) (48).

The results associated to management and regulatory compliance suggest that the adoption of structured preventive frameworks continues being a central component for the operational control. This observation is coherent with the evidence that signals that the implementation of systems based on International Organization for Standardization 45001 strengthens the identification of hazards, the monitoring of the risk and the continuous improvement, especially when it is articulated with food safety management in food plants (49). Under this logic, the results of this review support that occupational safety and food safety should be addressed as integrated systems and not as independent processes, particularly in Ecuadorian agroindustries where both components usually are managed separately (50).

Another relevant finding was the lesser thematic recurrence of emerging safety technologies, despite their high preventive potential. This lesser presence does not necessarily imply low importance, but a lesser relative development within the specialized literature. However, recent investigations have demonstrated that technologies such as predictive maintenance, intelligent sensors and digital monitoring improve early detection of failures and diminish exposure to critical events. In this line, Del Giudice et al. reported that the incorporation of intelligent approaches of machinery safety represents a growing trend in advanced industrial systems (13). Likewise, Bellochio & Coradi (14) highlighted the importance of integrating technological control and risk management in agroindustrial systems.

In the Ecuadorian context, the results show that gaps related with technological modernization, preventive culture and systematic risk management persist, which coincides with Paguay et al., who signaled that the Ecuadorian manufacturing sectors present important challenges in accidentality and occupational prevention (2). This aspect results particularly relevant because it suggests that the problematic does not

reside only in technological availability, but in integration of preventive management within the productive systems.

An important contribution derived from the results is that the posed hypothesis is seen backed by the reviewed evidence: the integration among technical controls, human factors, intelligent maintenance and regulatory compliance emerges as a consistent strategy to reduce exposure to operational risks. More than isolated solutions, the literature suggests that the integrated approaches offer greater preventive effectiveness.

Finally, the review also permitted identifying research vacuums, especially in safe automation, application of Industry 4.0 in agroindustrial SMEs and specific studies for processing machinery in Ecuador. These gaps represent opportunities for future investigations oriented to strengthen innovation, sustainability and operational safety in the food sector.

CONCLUSIONS

The systematic review permitted concluding that the operational safety in the handling of processing machinery in the food industry must be understood as a multidimensional system where mechanical hazards, human factors, preventive management, regulatory compliance and technological innovation converge as interdependent components for the control of the risk. The synthesized scientific evidence showed that the mechanical and operational hazards (88.2%), together with the human and ergonomic factors (82.4%), constituted the thematic axes of greater recurrence, confirming that the operator–machinery interaction continues being the principal critical point of exposure to incidents and accidents in the food processing systems. Likewise, the patterns of thematic co-occurrence and the thematic load by study evidenced that the integrated approaches of prevention offer greater robustness for the reduction of the risk than approximations centered exclusively on reactive controls or on isolated regulatory compliance.

It is concluded in addition that the preventive management sustained in planned maintenance, procedures of control of hazardous energies, technical training, safety culture and systems aligned with standards such as ISO 45001 and ISO 22000 represents a strategic axis to strengthen the operational safety in the food industry. In equal form, the review evidenced that emerging technologies such as intelligent sensors, predictive maintenance, real-time monitoring and safe automation possess high potential to reduce exposure to critical failures and improve operative continuity; however, their adoption in Ecuadorian agroindustrial contexts is still limited, owing to gaps in technological modernization, systematic risk management and transfer of innovation.

For the Ecuadorian context, the results permit concluding that the transition from corrective schemes toward preventive models based on risk management and technological innovation constitutes a strategic necessity to improve competitiveness, sustainability and food safety in the agroindustrial sector. The analyzed national evidence showed that challenges associated with limited preventive culture, insufficient integration between occupational safety and food safety, and scarce application of predictive tools in processing plants persist, which reinforces the necessity of

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strengthening institutional capacities, technological adoption and integrated management models.

Finally, the review permitted identifying relevant scientific vacuums, particularly in safe automation, predictive analysis of risks, application of 4.0 technologies and specific studies on machinery safety in Ecuadorian agroindustries, which justifies future investigations oriented to the development of more robust, adaptive and contextualized preventive models for the sector. In set, the findings back that the operational safety in the food industry must not be addressed solely as requirement of compliance, but as a strategic component for the resilience, the productivity and the sustainability of the processing systems.

Declaration of interest (optional)

The authors declare that there does not exist any conflict of financial, academic or personal interest that has influenced in the development, the analysis of the results or the drafting of the present scientific article.

Author contributions (optional)

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