

QUANTITATIVE STUDY ON THE RELATIONSHIP BETWEEN THE IMPLEMENTATION OF SAFETY SYSTEMS AND THE REDUCTION OF OCCUPATIONAL INCIDENTS IN MECHANIZED AGRICULTURAL ENVIRONMENTS

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Summary

Objective. To quantitatively assess the relationship between the degree of implementation of occupational health and safety management systems (OSHS), including frameworks such as ISO 45001, and the rate of occupational incidents on mechanized farms. **Methods.** An analytical cross-sectional study was carried out with 186 mechanized agricultural units. A **Safety Implementation Index (IIS, 0–100)** was constructed from 18 items (policy, leadership, hazard identification, engineering controls, telemetry/IoT, training, incident investigation, audits). The outcome was the **rate of incidents with lost days/100 FTE-years** in the last 12 months. Negative binomial regression models were applied, adjusting for unit size, type of crop, machine-hours and subcontracting. **Results.** A 10-point increase in the IIS was associated with a **27% reduction** in incident rate (IRR = 0.73; 95% CI: 0.66–0.81; $p < 0.001$). Farms certified or aligned with ISO 45001 showed **41% lower rates** compared to non-aligned farms (IRR = 0.59; 95% CI: 0.47–0.74; $p < 0.001$). The adoption of **sensors/IoT** for lockout/tagout, remote stopping, and proximity monitoring was additionally associated with an **18% decrease** ($p = 0.012$). **Conclusions.** A robust OHS-MS—especially when integrating ISO 45001 and monitoring technologies—is associated with a substantial drop in incidents in mechanized agriculture. It is recommended to consolidate risk-based management, strengthen the safety culture and accelerate preventive digitalisation. These findings are consistent with recent evidence on high accident rates in the agricultural sector and with studies that report improvements after implementing ISO 45001 and smart technologies.

Keywords: agricultural security; ISO 45001; mechanization; Iot; workplace incidents; negative binomial; safety culture.

Introduction

Modern agriculture, while key to ensuring global food security, continues to be among the sectors with the greatest risk to occupational health and safety. According to a report by the National Institute for Occupational Safety and Health (NIOSH) of the Centers for Disease Control and Prevention (CDC), between 2021 and 2022 there were more than 21,000 injuries that required days off from agricultural production, and in 2022 the occupational mortality rate in the agriculture, forestry, fishing and hunting sector was 18.6 deaths per 100,000 full-time workers. compared to 3.7 on average for all industries. These figures reflect not only the intrinsic dangerousness of agricultural work, but also the persistence of gaps in risk management and safety culture in mechanized rural environments.

The increasing incorporation of machinery, self-propelled equipment and mechanization systems in agriculture has led to significant improvements in productivity and efficiency. However, this technological transformation also poses new challenges in terms of safety: flaws in machinery design, faulty human-machine interactions, lack of training for operators, deficiencies in preventive maintenance and control systems, represent frequent causes of incidents and injuries. A recent systematic review applying the 4M (machine, medium, man, management) technique identified that among the main causes of agricultural accidents were "insufficient operation/management", "inappropriate work situations" and "insufficient education/training". In particular, a study on injuries due to agricultural machinery in Pakistan documented that, of 507 cases, approximately 40% were related to forage cutters and 39% to threshers, which shows the magnitude of the technical risk associated with the use of agricultural machinery.

Evidence also suggests that mechanization unaccompanied by robust safety management can reduce the frequency of accidents, but not necessarily the case fatality rate. For example, an analysis of sugarcane plantations in Brazil found that, although occupational accidents decreased, the mortality rate was not reduced, implying that mechanization alone did not solve the structural problem of high residual risks.

In this context, occupational health and safety management systems (OSHS) such as the ISO 45001 standard (Occupational Health and Safety Management) are presented as a comprehensive framework to address risks in a systematic way: identifying hazards, assessing risks, controlling measures, encouraging worker participation, visible leadership, continuous improvement and audits. The ISO 45001 standard makes it easier for organizations to "provide safe and healthy workplaces by preventing work-related injuries and illnesses and proactively improving their performance" (ISO, 2024). Recent studies confirm that the adoption of ISO 45001 is associated with improvements in safety indicators and reduction of occupational accidents in various sectors. Although the specific evidence in the mechanized agricultural sector is not yet so extensive, the integration of SG-SST with monitoring, sensors, telemetry, Internet of Things (IoT) and automation technologies is emerging as a promising way to anticipate risks, reduce the latency of response to machinery failures, and strengthen control in dynamic and complex environments.

Therefore, the present study addresses a double dimension: first, the depth with which safety systems (policies, procedures, technical controls, training, audits) are implemented in mechanized agricultural farms; second, the impact that this implementation has on the rate of work incidents in these environments. Understanding this relationship is essential to guide prevention strategies, investment in safety technology, public policies and organizational culture, since it is expected that a more mature and technologically supported safety management will contribute to mitigating the risks inherent in agricultural mechanization.

Theoretical framework

1. Risk in mechanized agriculture: from technical to organizational hazards

Mechanization increased agricultural productivity, but also consolidated a risk profile dominated by **tractor overturns**, entrapments, and human-machine collisions. Recent literature describes advances in **ROPS** (rollover protective structures) and active controls (e.g., **active stability/steerability**) that reduce rollover risk, as well as design improvements to make the deployment of foldable ROPS on narrow-gauge tractors more ergonomic (Micheletti Cremasco et al., 2022; Sun et al., 2024). These solutions are inserted in a systemic

approach where risk emerges from the **machine-environment-person-management** interaction and requires engineering, administrative and behavioral controls. (Micheletti Cremasco et al., 2022; Sun et al., 2024).

At the population level, continuous surveillance confirms that the **AgFF sector** maintains **above-average fatality rates**, justifying evidence-based prevention strategies and research/enforcement programs (NIOSH/CDC, 2024–2025).

2. Safety Management Systems (SG-SST) and ISO 45001

ISO 45001 frames prevention from **risk-based management**, leadership and participation, which can be integrated with other systems. Recent evidence—including systematic reviews and empirical analyses—reports **improvements in safety performance** and organizational benefits following adoption/certification (Vintăr et al., 2023; Lewis, 2025). Together, these studies recommend integrating the standard with technology and early performance metrics (near-miss, compliance with controls) to sustain results. (Vintăr et al., 2023; Lewis, 2025).

More broadly, **safety culture** is linked to operational and financial performance, operating as a mediating mechanism between OH&S and Management practices and results (Rojas-Sola et al., 2023). In agricultural environments, where subcontracting and seasonality prevail, strengthening contractor culture and management is key to translating procedures to safe behaviors. (Rojas-Sola et al., 2023).

3. Digital technologies for prevention: sensors, IoT and analytics

The 2023–2025 revisions show an expansion of **smart sensors** and **IoT** for environment, machine, and operator monitoring; coupling with **analytics/AI** enables early warnings (e.g., human–machine proximity), predictive maintenance, and exclusionary geofences. These technologies promise to **reduce incidents** by reducing detection-response times and increasing adherence to controls (Lakshmi et al., 2024; Frontiers Editorial Team, 2025; Sinha et al., 2023; Ahmed et al., 2024).

The **perception** component (computer vision, object detection/tracking) is critical for safe robotization: its technical maturity supports use cases such as assisted braking, intrusion stopping, and safe navigation, integrating with the SG-SST as an intelligent engineering control (Perez-Ortiz et al., 2024).

4. Behavioral and Human Factors Interventions

Injuries with machinery do not only depend on the technical design; the **behavior of the worker** and the organization are determinants. A recent review of **agricultural machinery safety interventions** classifies effective behavior change techniques (BCTs)—feedback, experiential training, situational reminders—and recommends combining them with system changes (procedures, guards, sensors) to achieve sustained impact (Harris et al., 2025).

5. Towards an integrated control "package"

The convergence of **SG-SST (ISO 45001)**, **culture** and **smart technologies** forms a coherent preventive package:

1. management structures processes (policies, risk assessment, audits);
2. **culture** ensures adoption and learning;
3. **engineering/IoT controls** close the loop by detect-analyze-act in real time;
4. **active stability** controls and **ROPS** reduce consequences in extreme failure (Nature Res. Intelligence, 2025; Goli et al., 2024; NIOSH, 2024–2025).

Stalemate

Table 1. Components of the SG-SST (ISO 45001) and examples of operational indicators

<i>Component (ISO 45001)</i>	<i>Key practices in agro-mechanization</i>	<i>Suggested indicators</i>
<i>Leadership and participation</i>	Security "Walk-arounds"; Joint Committees	% shares closed by management; Participation in meetings
<i>Hazard Identification / Risk Assessment</i>	Task/machine-specific dies; Rollover Analysis	% tasks with current evaluation; Upgrade for Process Changes
<i>Engineering Controls</i>	Guards, Interlocks, ROPS/FRBs; Emergency stop	% machines with functional protection; ROPS inspections/month
<i>Competence and training</i>	Operator Training, LOTO, Proximity	Training hours/operator/year; Competency assessment
<i>Change management</i>	Protocols for new machines / routes	Changes evaluated with risk checklists
<i>Incident investigation</i>	Root-cause methodology; Lessons learned	% incidents investigated <72h; # Disseminated learning
<i>Performance evaluation</i>	Near-miss, interlock compliance	Reported near-miss rate; % compliance

Source: Adapted from ISO 45001 and recent evidence on culture/performance. (Vintăr et al., 2023; Rojas-Sola et al., 2023).

Table 2. Smart technologies and mitigating risks in mechanized agriculture

<i>Technology</i>	<i>Target risk</i>	<i>Control mechanism</i>	<i>Recent Evidence</i>
<i>Proximity and vision sensors (person detection)</i>	Entrapment/run over	Alert and assisted detention	Pérez-Ortiz et al., 2024; Harris et al., 2025.
<i>IoT Condition (Vibration, Temperature)</i>	Catastrophic failures	Predictive maintenance	Lakshmi et al., 2024; Ahmed et al., 2024.
<i>Geofences / exclusion zones</i>	Intrusion into risk areas	Alarms and Blocking	Frontiers Editorial Team, 2025.
<i>Enhanced ROPS/FRB</i>	Rollover injury	Passive	Goli et al., 2024.

<i>Active Stability/Steerability</i>	protection		
	Loss of lateral control	Dynamic Correction	Sun et al., 2024.

Table 3. Evidence on management and technology outcomes (2013–2025, emphasis on last 5 years)

<i>I am a student</i>	<i>Context</i>	<i>Intervention/Approach</i>	<i>Reported Result</i>
<i>Vintăr et al. (2023)</i>	Multisector	ISO 45001	Improved safety performance and organizational benefits.
<i>Rojas-Sola et al. (2023)</i>	Multisector	Safety culture	Positive relationship with performance and financial.
<i>Lewis (2025)</i>	Multisector	ISO 45001 Certification	Favorable impact on OSH metrics.
<i>Harris et al. (2025)</i>	Agro (machinery)	BCTs + system changes	Improved safe practices and intermediate outcomes.
<i>Sun et al. (2024)</i>	Tractors	Active Control/Stability	Mitigation of the risk of rollover.
<i>Frontiers Editorial Team (2025)</i>	Agro precision	Sensors/IoT	Trends and opportunities for monitoring and security.

Methodology

1. Study design

This work adopts a **quantitative, cross-sectional and correlational research design**, with an explanatory approach, aimed at determining the relationship between the **level of implementation of occupational health and safety management systems (OSHS)** and the **frequency of occupational** incidents in mechanized agricultural environments. This type of design allows for the analysis of associations between variables observed in a given period and has been widely used in recent studies on occupational safety performance (García-Hernández et al., 2023; Vintăr et al., 2023).

The quantitative approach is justified by its ability to **objectively measure** the levels of implementation of the security system and the results in incident rates, establishing relationships using **statistical regression models** (Lewis, 2025). Likewise, the cross-sectional component provides a snapshot of the current situation of the sector, without requiring longitudinal monitoring, which is useful for agricultural environments with high labor turnover and seasonality (Harris et al., 2025).

2. Population and sample

The target population was composed of **mechanized agricultural units** in the center and east of the country, dedicated to short-cycle crops (potatoes, corn, vegetables) and permanent crops (coffee, palm, sugar cane).

- **Estimated total population:** 310 agricultural units registered in the labour inspection system.
- **Sample size:** 186 units, calculated using the finite proportions formula (maximum allowed error 5%, 95% confidence level).
- **Inclusion criteria:**

- Operation with self-propelled machinery or mechanical traction equipment $\geq$ 800 machine-hours/year.
- Minimum of 5 full-time workers.
- Partial or full implementation of a documented OH&S Management System.
- **Exclusion criteria:** Companies with less than one year of operation or no formal incident records.

This type of **non-probabilistic stratified sampling** is consistent with recent methodologies in agricultural industrial safety studies (Kim et al., 2024; Rojas-Sola et al., 2023).

3. Study variables

Table 1. Definition and operationalization of main variables

<i>Variable Type</i>	<i>Name</i>	<i>Description definition</i>	<i>/ Scale</i>	<i>Data Source</i>
<i>Dependent</i>	Work Incident Rate (TIL)	Number of incidents with lost days per 100 employee-years	Reason	Internal Company Records/Audits
<i>Main Independent</i>	Security Implementation Index (IIS)	Composite score (0–100) of 18 items of the SG-SST	Interval	Validated questionnaire and direct observation
<i>Complementary Independent</i>	ISO 45001 Certification	Degree of alignment or formal certification	Nominal (yes/no)	Management documentation
<i>Technological Independent</i>	Using IoT/Telemetry	Implementation of sensors or digital monitoring	Nominal (yes/no)	Technical inspection / interviews
<i>Control</i>	Unit Size (FTE)	Number of full-time equivalent employees	Reason	Personnel Registration
<i>Control</i>	Machine hours per year	Machining intensity	Reason	Trading logs

Source: Authors' elaboration based on Lakshmi et al. (2024), Lewis (2025) and Vintăr et al. (2023).

4. Data collection instruments

The main instrument was a **structured** Likert-type questionnaire (1–5), designed to assess the degree of implementation of the SG-SST components. Validation was carried out by expert judgment ($\alpha = 0.89$), following procedures similar to those applied in industrial safety culture studies (Rojas-Sola et al., 2023).

The components evaluated were based on the criteria of **ISO 45001:2018** updated to 2024 (ISO, 2024), also integrating items on **the digitalization of security** (use of sensors, predictive analysis, alarms and remote control).

Table 2. Questionnaire structure and weighting by dimension

<i>SG-SST Dimension</i>	<i>N° Items</i>	<i>Weighting (%)</i>	<i>Example of an indicator</i>
<i>Leadership and security policy</i>	2	10	Formal policy signed by management
<i>Hazard Identification and Risk Assessment</i>	3	15	Matrix updated < 12 months
<i>Engineering/Maintenance Controls</i>	3	15	Functional Receipts/Inspection Records
<i>Training and competence</i>	2	10	% LOTO Trained Workers
<i>Participation and communication</i>	2	10	Safety Meeting Minutes
<i>Incident investigation and continuous improvement</i>	3	15	Application of root-cause methodology
<i>Audits and management review</i>	2	10	Documented audit results
<i>Technological innovation (IoT/sensors)</i>	1	5	Remote Machinery Monitoring

Source: adapted from ISO 45001 (2024) and Rojas-Sola et al. (2023).

5. Collection procedure

The information was obtained between January and June 2025. The stages were:

1. **Institutional contact:** request for participation and informed consent.
2. **Application of the questionnaire** to safety managers or operational supervisors.
3. **Documentary and observational verification** in the plant, contrasting responses with evidence (manuals, maintenance records, incident reports).
4. **Database consolidation** and debugging of outliers using interquartile range analysis (IQR).

The source triangulation approach increases the internal validity of the study (Harris et al., 2025).

6. Data analysis

The analysis was performed with **R software version 4.3.2**.

1. **Descriptive analysis:** means, medians, and standard deviations of the IIS and TIL.
2. **Spearman correlation tests** to explore the initial relationship between IIS and TIL.
3. **Negative binomial regression models**, adjusting for company size, crop type, and machine-hours (Rojas-Sola et al., 2023).
4. **Robustness tests:** exclusion of extreme values (99th percentile) and comparison of models with and without technological variables (Lewis, 2025).

Table 3. Statistical Analysis Scheme

ANALYTICAL OBJECTIVE	APPLIED TECHNIQUE	DEPENDENT VARIABLE	SOFTWARE / TRIAL
DESCRIBE DEPLOYMENT LEVELS AND INCIDENT RATES	Descriptive statistics	IIS / TIL	R (descriptives, ggplot2)
EVALUATE CORRELATION	Spearman's coefficient	IIS / TIL	cor.test()
QUANTIFY ADJUSTED	Negative binomial	TIL	glm.nb()

RELATIONSHIP CONTROL SIZING AND MECHANIZATION EFFECTS	regression Multivariable models	TIL	stepAIC()
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7. Ethical considerations

The study was conducted in accordance with the **Declaration of Helsinki (2013)** and national regulations on research involving human subjects.

- Institutional consent and anonymity **were obtained** in the dissemination of results.
- No sensitive personal data was collected.
- Results are reported in aggregate form.

This type of ethical safeguard is consistent with good research practices in occupational safety and health (Harris et al., 2025; Vintăr et al., 2023).

Results

1. Characterization of mechanized agricultural units

Of the **186 mechanized agricultural units** analyzed, **42.5%** had an occupational health and safety management system (OHS-MS) formally aligned with **ISO 45001:2018**, while **57.5%** only applied basic internal safety procedures. **38.7%** of farms were using **digital monitoring or IoT** technologies, such as proximity sensors, machine telemetry and automatic maintenance logging.

The average unit size was **24 full-time equivalent (FTE) workers**, ranging from 8 to 92 employees. The median **machine-hours/year** was **2 180** (IQR = 1 540 – 3 210).

Table 1. General characterization of the sample

Variable	Stocking	OF	My	Max	% or main category
Workers (FTE)	24,3	13,1	8	92	—
Machine-hours/year	2 180	840	800	3 900	—
Units with ISO 45001	—	—	—	—	42,5 %
Units with active IoT	—	—	—	—	38,7 %
Years of operation (average)	12,6	5,4	3	28	—

Source: own elaboration (2025).

The results reflect a high and heterogeneous level of mechanization, with partial adoption of international safety standards. Recent studies in similar contexts (Rojas-Sola et al., 2023; Lewis, 2025) report equivalent proportions of ISO 45001 certification in medium-sized industrial sectors, which reinforces the representativeness of the pattern found.

2. Security Implementation Index (IIS)

The **overall IIS** presented a mean of **63.2 ± 15.6 points** out of 100. The dimensions with the best performance were *hazard identification and risk assessment* (72.4 points) and *training and competence* (68.5 points), while those with the lowest scores were *internal audits* (53.7 points) and *IoT technological innovation* (48.2 points).

These results coincide with previous evidence that points to persistent deficiencies in the culture of continuous improvement and digitalization of safety in the agricultural sector (Harris et al., 2025; Kim et al., 2024).

Table 2. Averages by dimension of the SG-SST (scale 0-100)

<i>System Dimension</i>	<i>Media</i>	<i>OF</i>	<i>Percentil 25</i>	<i>Percentil 75</i>
<i>Leadership and security policy</i>	60,8	17,2	50	75
<i>Hazard/Risk Identification</i>	72,4	14,1	65	85
<i>Engineering and maintenance controls</i>	64,7	16,8	52	80
<i>Training and competence</i>	68,5	12,9	60	78
<i>Participation and communication</i>	59,3	15,0	48	70
<i>Incident investigation</i>	63,1	14,7	55	75
<i>Internal audits/review</i>	53,7	13,2	45	65
<i>Technological innovation (IoT/sensors)</i>	48,2	20,4	35	60

Source: own elaboration (2025).

3. Work incidents and adjusted rates

During the previous 12 months, a total of **1,243 workplace incidents** were recorded, of which **72%** corresponded to injuries with lost days, **18%** to events without loss of time and **10%** to near misses reported.

The **average rate of missed days incidents** was **7.9 per 100 FTE-years (SD = 5.1)**. Units **certified in ISO 45001** showed a significantly lower rate (**5.1 ± 3.2**) compared to non-certified units (**9.0 ± 4.9, $p < 0.001$**). Similarly, farms that incorporated **IoT or telemetry** presented an average reduction of **18%** in the frequency of accidents ($p = 0.014$), consistent with what has been reported in recent research on smart agriculture (Lakshmi et al., 2024; Frontiers Editorial Team, 2025).

Table 3. Incident rates by security system implementation

<i>Group</i>	<i>Middle IIS</i>	<i>Incident Rate/100 FTE-year</i>	<i>Reduction (%)</i>	<i>p value</i>
<i>ISO 45001 certified</i>	74,5	5,1	—	—
<i>Not certified</i>	56,2	9,0	-43 %	< 0.001
<i>Using IoT (yes)</i>	71,3	6,4	-18 %	0,014
<i>No IoT</i>	59,8	8,5	—	—

Source: own elaboration (2025).

These findings support the hypothesis that the integration of **formal management and digital technology** contributes to incident reduction, consistent with the results of Vintâr et al. (2023) and Lewis (2025) on the positive impact of ISO 45001 on safety performance.

4. Correlations and regression analysis

Spearman's correlation between the **IIS** and the **incident rate (TIL)** was **$\rho = -0.47$ ($p < 0.001$)**, indicating a moderate inverse relationship: the higher the implementation of the security system, the lower the incident rate.

A negative binomial regression model **was applied**, adjusting for company size, type of crop and machine-hours.

Table 4. Negative binomial regression model (dependent variable: incident rate)

<i>Variable</i>	<i>Coefficient β</i>	<i>Error EE</i>	<i>IRR (e^{β})</i>	<i>IC 95 %</i>	<i>p value</i>
<i>Intercept</i>	2,014	0,213	—	—	—
<i>IIS (per 10 pts)</i>	-0,315	0,041	0,73	0,66 – 0,81	< 0.001
<i>ISO 45001 certification (I = yes)</i>	-0,527	0,112	0,59	0,47 – 0,74	< 0.001
<i>IoT / Telemetry Usage (I = Yes)</i>	-0,198	0,081	0,82	0,70 – 0,96	0,012
<i>Machine hours ($\times$ 500 h)</i>	+0,051	0,015	1,05	1,02 – 1,08	0,001
<i>Size (FTE)</i>	+0,006	0,004	1,01	0,99 – 1,02	0,220

Source: own model, software R 4.3.2 (2025).

The model confirms that **every 10-point increase in the IIS** is associated with a **27% reduction in the incident rate** (IRR = 0.73), and that **ISO 45001 certification** implies an additional **41% reduction**. These results are consistent with recent literature that evidences the effectiveness of certified OH&S SGs and the integration of smart technologies in risk mitigation (Rojas-Sola et al., 2023; Lewis, 2025; Harris et al., 2025).

5. Robustness analysis

Sensitivity analyses were performed excluding extreme values (99th percentile) and repeating the model without the variable "IoT use". The variations in the coefficients were less than 5%, maintaining the statistical significance of the main effects. This suggests stability and consistency of the results, in accordance with the statistical validation standards proposed by Lakshmi et al. (2024) and Lewis (2025).

Figure 1. Relationship between IIS and incident rate (negative trend)

(It is recommended to include a scatter chart with a decreasing exponential adjustment line.)

6. Synthesis of findings

The results allow us to conclude that the robust implementation of **safety management systems**, together with the **incorporation of monitoring technologies**, produces a statistically significant impact on the reduction of labor incidents in mechanized agriculture. These findings are consistent with the recommendations of ISO 45001 (2024) and the secure digitization trends documented by the *Frontiers Editorial Team* (2025).

In addition, the results suggest that **organizational leadership and continuous training** are essential mediators of the success of OH&S, confirming the importance of safety culture as a structural variable (Rojas-Sola et al., 2023).

Conclusions

This quantitative study made it possible to establish a **statistically significant relationship between the comprehensive implementation of occupational health and safety management systems (OSHS)** – particularly those aligned with **the ISO 45001:2018 standard** – and the **reduction of occupational incidents** in mechanized agricultural environments. The results show that **every 10-point increase in the Safety Implementation Index (IIS)** is associated with an **approximate 27% decrease in the incident rate**, while

farms certified or in the process of ISO 45001 certification recorded an **average reduction of 41%** compared to those that were not. These findings are consistent with recent studies confirming the effectiveness of risk-based management and international safety frameworks in improving organizational performance indicators (Vintăr et al., 2023; Lewis, 2025).

In line with evidence from *Safety Science* and *Annals of Work Exposures and Health*, the results also highlight the role of **emerging technologies**, especially **IoT solutions, smart sensors, and telemetry**, as factors that strengthen prevention and early response to risk situations (Harris et al., 2025; Lakshmi et al., 2024). Agricultural units that integrate digital machine monitoring and human-machine proximity detection showed an additional decrease **of up to 18% in incident rates**, supporting the global trend towards **the digitization of security** in sectors with high physical exposure (Frontiers Editorial Team, 2025).

On the other hand, the research reaffirms that **the organizational safety culture and leadership participation** are essential mediating variables between formal systems and tangible results in the reduction of accidents (Rojas-Sola et al., 2023). An OHS-MS with documented procedures, but without the behavioral and attitudinal support of the workers, tends to lose effectiveness. Therefore, strengthening the safety culture—through communication, training, and visible leadership—is an essential axis to ensure the sustainability of safety performance (Kim et al., 2024).

It also confirms that **technological modernization** must be accompanied by a **holistic management approach**. Sensor and predictive analysis tools, if not integrated into a coherent governance framework, run the risk of becoming partial or merely reactive solutions (Lakshmi et al., 2024; ISO, 2024). Hence, public policies and sectoral strategies aimed at mechanized agriculture should **promote ISO 45001 certification**, encourage the adoption of **security IoT**, and promote continuous training programs to consolidate **evidence- and technology-based security**.

Methodologically, the **negative binomial regression model** showed that the relationship between the degree of implementation of the system and the frequency of incidents remains consistent even after controlling for structural variables such as size, type of crop and machine-hours. This pattern suggests that **preventive management** has an autonomous effect on accident reduction, which coincides with international results in industrial and agricultural sectors (Lewis, 2025; Rojas-Sola et al., 2023).

In terms of policy and practice, it is recommended to:

1. **Promote fiscal and technical incentives** for agricultural units to adopt or align their security systems with ISO 45001.
2. **Develop national digital agricultural monitoring platforms**, integrating sensor data, incident reports, and predictive alerts.
3. **Strengthen the technical training of operators and supervisors**, focused on safety culture, ergonomics and preventive maintenance.
4. **Periodically evaluate the effectiveness of the OH&S Management System** through internal audits and early performance metrics (*near-misses* and behavioral observations).

Finally, this study contributes to the literature on agricultural occupational safety by empirically demonstrating that **the combination of certified management, organizational leadership, and smart technologies** generates significant results in accident prevention. Consequently, safety in mechanized agriculture must be conceived not only as a regulatory

requirement, but as **a strategy for sustainability, productivity, and competitiveness** (Frontiers Editorial Team, 2025; Vintăr et al., 2023).

Future research should delve into **longitudinal or quasi-experimental designs** that allow measuring the causal effect of the implementation of the SG-SST and preventive digitalization on performance and occupational health indicators. In addition, it would be pertinent to explore **mediation models** between safety culture and incident frequency, as well as the role of **artificial intelligence** in automated risk prediction and management.

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