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Integrating Injury Analytics and Failure Modes and Effects Analysis (FMEA) in Occupational Safety in the Testing, Inspection, and Certification (TIC) Sector

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ABSTRACT

This study examines workplace injuries in the Testing, Inspection, and Certification (TIC) sector to promote evidence-based improvements in occupational safety. Fifty-two incident reports from a TIC firm were analyzed using correlation methods, univariate and cross-tabulation analysis, and Failure Modes and Effects Analysis (FMEA) accompanied by the Hierarchy of Controls. Research indicates that hazardous situations, particularly chemical exposure during laboratory testing, were the primary cause of accidents (53.8%). Male employees experienced more severe injuries, particularly among those aged 20 to 29. The FMEA identified 10 failure modes, with the highest Risk Priority Numbers associated with exposure to caustic liquids, slips, trips, falls, and chemical ingestion. The findings highlight the imperative to improve control mechanisms, bolster safety training, and reinforce compliance with personal protective equipment (PPE) laws. This research offers practical insights for risk reduction and the development of proactive safety measures to improve the safety culture in the TIC sector.

Keywords: Testing; Inspection; and Certification (TIC) Industry; failure modes and effects analysis; occupational safety; laboratory safety; hierarchy of controls

INTRODUCTION

The Testing, Inspection, and Certification (TIC) industry is an autonomous sector that delivers conformity assessment services, including testing, validation, and declaration of conformity. These services encompass a broad spectrum of quality and safety controls such as supply chain certifications, industrial site inspections, product testing, management system audits, periodic vehicle inspections, pre-shipment inspections, and consignment-based conformity assessments. By strengthening consumer protection, enhancing governmental efficiency, enabling market oversight, and supporting manufacturers in meeting international regulatory requirements, the TIC sector plays an essential role in global economic systems and contributes significantly to public safety and product reliability (TIC Council 2022; Singapore Accreditation Council n.d.).

Demand for adherence to consumer standards, health and safety regulations, and environmental compliance has led TIC firms to collaborate closely with multiple sectors across the economy (Roberts, 2022). In the Philippines, the Philippine Accreditation Bureau–Department of Trade and Industry (PAB-DTI) accredited approximately 196 laboratory firms in 2024, the majority of which fall under the testing domain of the TIC sector (DTI-PAB 2023). The industry's operational activities testing, inspection, and certification span diverse environments including construction, manufacturing, food and agriculture, energy, and chemicals (Long 2023). Testing services involve product safety evaluations, analytical laboratory operations, and quality verification; inspection services include facility and supply chain inspections; and certification services involve conformance and management system assessments (Fortune Business Insights, 2022). Given this breadth, achieving and maintaining safe and healthy work environments requires specialized knowledge and consistent adherence to technical protocols (Taidi n.d.).

The primary objective of TIC organizations is to safeguard the well being of the technical professionals who conduct these activities laboratory analysts, technicians, inspectors, and auditors across both fixed and field based settings. These personnel routinely encounter varied hazards, emphasizing the importance of proactive safety strategies that protect workers while ensuring the accuracy and integrity of conformity assessment services. Testing, which holds the largest market share among the three service types (Fortune Business Insights 2022), is predominantly conducted in analytical laboratories where specialists perform experiments and analyses involving hazardous chemicals (Furr 2001), radiation emitting equipment, and complex procedures. Gopalaswami et al. report that chemical spills are the most frequent incident type in laboratory settings, followed by explosions and fires. Correspondingly, institutional laboratory safety programs must include hazard specific practices, equipment training, emergency procedures, workplace organization, and consistent use of personal protective equipment (Safe Science 2014).

Safety requirements in inspection and certification follow similar principles, adjusted for hazards inherent to field verification, operational assessments, and conformance auditing. Effective programs include employee training, the use of PPE, equipment maintenance, regulatory compliance, and the implementation of emergency response plans. These measures mitigate potential risks and maintain the reliability and integrity of inspection and certification processes.

Despite the TIC sector's strong commitment to ensuring product and service safety across industries, research on the internal occupational safety of TIC personnel remains limited. Existing studies predominantly examine academic or research laboratory settings. For example, Xu et al. (2023) identified unsafe human actions and weak safety culture as key contributors to laboratory incidents, while Nasrallah et al. (2023) applied Failure Mode and Effects Analysis (FMEA) to develop corrective and preventive actions in a public university laboratory. However, such studies seldom extend to TIC organizations, leaving a substantial knowledge gap regarding safety performance in this globally significant service sector.

This gap is driven by several structural factors. Industry analyses show that the TIC sector's analytical efforts and resources are primarily directed toward external risk mitigation for clients—including regulatory compliance, product safety, ESG verification, and AI related conformity assessments—rather than internal workforce safety (Grand View Research 2024; TIC Council 2024; Drazdou 2025).The sector's fragmentation further complicates systematic safety research: TIC staff operate across diverse environments such as industrial plants, construction sites, food facilities, and analytical laboratories, creating highly heterogeneous hazard profiles often subsumed within the safety statistics of host industries (Zion Market Research, 2024; MarketsandMarkets, 2024). Compounding this issue are persistent data collection challenges typical of service industries, including under reporting, variations in documentation standards across jurisdictions, and difficulties harmonizing injury classifications (ILO 2016; Perfect Data Entry 2024). These dynamics collectively contribute to the scarcity of empirical research on occupational safety within TIC operations, underscoring the need for focused analytical studies.

Systematic analyses of hazards, human factors, and failure modes within professional TIC organizations remain scarce, representing a critical research gap addressed by this study. Consequently, TIC safety practices largely rely on reactive, descriptive incident reviews, which often fail to capture latent risks. Recent advances in occupational safety research emphasize proactive, data driven approaches, including machine learning–based hazard prediction (Kim et al. 2022), human reliability analysis (Levine et al. 2024), and safety digitization via integrated safety information systems (Qiu & Li 2023). Innovations such as fuzzy logic–enhanced FMEA (Liu et al. 2014) and AI enabled predictive risk assessment (Gao & Sultan, 2022) further enhance hazard prioritization and failure anticipation. These developments underscore the potential to shift TIC occupational safety from retrospective incident analysis to predictive, system oriented risk management. To capitalize on this potential, the present study applies Failure Modes and Effects Analysis (FMEA) as a robust framework for capturing complex operational interactions, incorporating predictive insights from data driven safety analysis, and leveraging digital safety tools to identify high risk failure points within the heterogeneous TIC environment.

To address this gap, a comprehensive study was conducted in the Philippines to evaluate risk assessment methodologies applied in TIC work environments. The aim was to identify prevalent hazards and develop appropriate control mechanisms based on the hierarchy of controls. As defined by the Canadian Centre for Occupational Health and Safety (CCOHS), a hazard is any source of potential harm or adverse effect (Government of Canada 2025). Given that TIC organizations include both laboratory based testing facilities and off site inspection/audit settings, workers are routinely exposed to safety, biological, chemical, physical, and radiological hazards (Nasrallah et al. 2023; Michaels & Wagner 2020), which may result in chemical burns, lacerations, repetitive strain injuries, or dangerous exposures (Nasrallah et al. 2022).

Within occupational safety and health (OSH), risk is defined as the combination of the likelihood of an event and the severity of its consequences (Government of Canada 2025; ISO 2024). Risk assessment is therefore fundamental to an effective OSH management system. It involves hazard identification, risk evaluation, and appraisal of control measures to maintain risks at acceptable levels (HSE n.d.; Manuele 2014). In the TIC sector, where personnel operate across varied laboratory and field environments, structured risk assessment is essential to identifying hazards and tailoring mitigation strategies (Knegtering & Pasman, 2009). Without systematic risk identification and prioritization, even highly qualified personnel remain vulnerable to preventable injuries.

Failure Modes and Effects Analysis (FMEA) is a widely recognized proactive method for risk assessment, originally developed in aerospace and automotive contexts and now applied in healthcare, manufacturing, and certification services (Stamatis 2003; Bennett et al. 2017; IEC Commission 2018). FMEA systematically identifies potential failure modes, evaluates their consequences, and quantifies associated risks through severity, occurrence, and detectability scores, which are multiplied to generate a Risk Priority Number (RPN) (Carlson 2012). Unlike retrospective incident or root cause analysis, FMEA enables early identification of high risk failure points (Anjalee et al. 2021). Its effectiveness has been demonstrated in safety critical laboratory environments (Golkhani et al. 2018; Pourmadadkar et al. 2019; CDC n.d.), and it aligns closely with requirements for technical accuracy and process reliability in ISO/IEC 17025 and 17020 compliance assessments.

Effective risk mitigation following FMEA often relies on the Hierarchy of Controls, a widely used framework that ranks interventions from most to least effective starting with elimination and substitution, followed by engineering controls, administrative controls, and PPE (OSHA 2023). In TIC settings, this may include replacing hazardous chemicals (Substitution), employing automation to reduce exposure (Engineering Controls), or implementing rigorous training, procedures, and supervision (Administrative Controls). When used alongside FMEA, the hierarchy strengthens overall safety management by supporting the selection of controls with the greatest impact (Ajslev et al. 2022; Friend & Kohn 2018).

The purpose of this study is to systematically identify and assess the critical factors contributing to occupational injuries within a Philippines based TIC organization. Statistical techniques including cross tabulation, chi square tests, and phi coefficients were used to examine correlations among employee characteristics, worksite profiles, incident features, accident types, potential root causes, and affected body parts. Significant factors were subsequently evaluated through FMEA to determine key failure modes and their relative risk levels based on severity, occurrence, and detectability. Corresponding control measures were then proposed using the Hierarchy of Controls, emphasizing high level interventions such as elimination, substitution, and engineering controls where feasible. Through this integrated approach, the study aims to provide both analytical insight and actionable strategies for enhancing occupational safety within the TIC industry.

METHODOLOGY

STUDY DESIGN AND DATA COLLECTION

This study utilized incident data obtained from an anonymous Testing, Inspection, and Certification (TIC) firm in the Philippines. The company maintains an internal Incident Information System (IIS), which records all reported hazards and incidents since 2012. The IIS includes modules for various categories such as injury/illness, environment, property damage, fire/explosion, security, and transportation.

For this study, only incidents categorized under injury were considered. A total of 52 closed and validated reports recorded between October 2012 and December 2023 were extracted for analysis. Records that were incomplete, duplicated, or pending verification were excluded to ensure data accuracy and consistency. Each injury report contained detailed information on employee profile, location, incident characteristics, potential root causes, and affected body parts. The IIS structure facilitated systematic extraction and categorization of these data.

During the preliminary review, the injury type, mechanism, and affected body part variables showed numerous possible outcomes (over 20, 25, and 30 options, respectively). Categories with zero frequency were excluded, and low frequency categories (fewer than five cases) were consolidated to simplify analysis and improve interpretability. The revised classification scheme is presented in Tables 3 and 4.

To ensure comparability with prior research, classifications for variables such as gender, age, shift, location, injury severity, accident cause, and nature of injury were adapted from established literature. System generated attributes, including line of business, activity type, mechanism of injury, hours worked prior to incident, employee type, site type, and days lost, were also incorporated. Numerical codes were then assigned to each factor for statistical analysis.

All data were anonymized to protect both the company's confidentiality and the privacy of employees involved in the incidents. The researcher obtained formal permission from the company's management to use the dataset exclusively for academic purposes. The study adhered to internal data privacy protocols and applicable ethical standards throughout the analysis.

IDENTIFICATION OF SIGNIFICANT INJURY CORRELATES

For the method of analysis, descriptive and inferential statistics were utilized through the following programs: IBM SPSS Statistics 30.0.0, Microsoft Excel 365 version, and Minitab 22.4.0 software.

To address the research question regarding the relationship between employee demographics, work conditions, and injury characteristics, inferential statistics through the Chi square Test was performed to determine the association between categorical variables. The Chi square test was selected because the study variables (e.g., gender, age group, injury type, location, and activity type) were primarily categorical in nature, and the objective was to examine whether there were statistically significant associations between these factors and the occurrence or severity of injuries.

The strength of association between variables was evaluated using the Phi (φ) or Cramer's V coefficient along with the p value. A p value less than the significance level of 0.05 suggests that there is evidence of a statistically significant relationship or association between the variables (Minitab Manual). This analysis directly supports the research objective of identifying key factors influencing injury occurrence and patterns within the TIC industry.

Fisher–Freeman–Halton's exact test was used for variables and levels of factors with frequencies of less than five. After establishing an association between variables based on the p value, attention was directed to the Cramer's V outcome, which elucidates the intensity of the relationship between two variables. A Cramer's V value of 0 signifies no relationship, while a value of 1 indicates a perfect association (StatsTest 2020). A more concise relationship description was obtained through the Cramer's V Level of Association Table (Fletcher et al. 2018).

The Phi (φ) analysis was also facilitated for level factors with significance levels of less than 0.01 to further identify the association of level factors. The Phi (φ) coefficient, which is similar to the Pearson Correlation Coefficient, measures the association between two binary variables (at least one nominal variable or both dichotomous). It can have a value of –1 to 1, where 1 and –1 represent a perfect relationship and 0 indicates no relationship. Its inclusion was justified by the need to quantify associations between binary or limited level categorical factors, thereby offering a more precise understanding of relationships among injury related variables. Minitab's correlation module has been used to obtain the phi (φ) coefficient and the p value (Alexander 2021).

RISK ASSESSMENT USING FMEA

Significant factors from the correlation analysis were then evaluated and considered using Failure Mode and Effects Analysis (FMEA), a structured method for risk prioritization that has been widely adopted in industrial safety assessments (Carlson 2012). In order to identify the failure modes, root causes, and failure impacts for the risk assessment analysis, every injury incidence that was associated with the correlating factors was reevaluated and carefully examined. The FMEA was developed using historical information, and process owners from the audit, laboratory testing, and inspection domains were involved to gain an understanding of the TIC firm's operations.

The FMEA scoring system (Table 1) was adapted from established frameworks (Sellappan & Palanikumar, 2013; Rah et al. 2016; Bozdag et al. 2015, Nasrallah et al. 2023) and modified to align with the frequency and severity patterns observed in the TIC industry dataset. The 1–5 scale was retained for comparability with validated FMEA approaches, while descriptive thresholds (e.g., "Very Low," "Low," "Moderate") were refined based on the company's incident data distribution and expert judgment. Each identified failure mode was scored according to three criteria: occurrence (O), severity (S), and detectability (D). The occurrence score represents the likelihood of the failure mode based on historical injury data. The severity score reflects the potential impact on health and safety, derived from past incident records and their corresponding injury classifications, including first aid, minor/superficial, medical care, or lost time incidents. The detectability score was assessed through interviews with process owners, focusing on the ability to identify failure modes before they result in harm.

After determining the OSD scores for every failure scenario, the RPN was computed using the formula RPN = O x S x D. The RPN was between 1 and 125 on the scale specified in Table 2.

The range of risk acceptance was also computed. The RPN scores of each category were used to determine the priority of the most important potential FMs. Subsequently, the discovered FMs' intervention periodization was separated into three distinct zones (Lopez et al. 2010, Hatrwell 2022). Failure Modes with RPN ≥ 80 are highlighted in red, meaning that action must be taken to eliminate the risk; those with RPN ≥ 75, highlighted in yellow, require intervention to control or reduce the risk; and those with RPN < 20 are highlighted in green, meaning that they must be observed (accepted).

TABLE 1. FMEA OSD Scoring Matrix

Occurrence (% of the Time)		
Score	Description	Modified (Own Processing)
1	Rare (<10%)	Very Low (1 incident)
2	Unlikely (10 25%)	Low (2 incidents)
3	Possible (25 45%)	Moderate (3 incidents)
4	Likely (45% 65%)	High (4 incidents)
5	Almost Certain to Certain (64 90%)	Very High (5 incidents)
Severity		
Score	Description	Modified (Own Processing)
1	Insignificant	First Aid
2	Minor	Minor/Superficial
3	Moderate	Medical Treatment
4	Major	Lost Time
5	Catastrophic	Fatal
Detectability		
Score	Description	Modified (Own Processing)
1	Almost Certain	Easily detectable
2	High	Likely to detect with routine checks
3	Moderate	Can be detected with effort, some issues may go unnoticed
4	Low	Difficult to detect, may go unnoticed
5	Remote	Nearly impossible to detect, incidents go undetected

Source:(Sellappan & Palanikumar, 2013; Rah et al. 2016; Bozdag et al. 2015) [37,38,39]

TABLE 2. FMEA Risk Matrix Determination

S O x D	1	2	3	4	5
5	5	10	15	20	25
10	10	20	30	40	50
15	15	30	45	60	75
20	20	40	60	80	100
25	25	50	75	100	125

Low (Accept) Moderate (Control/Reduce) High (Eliminate)

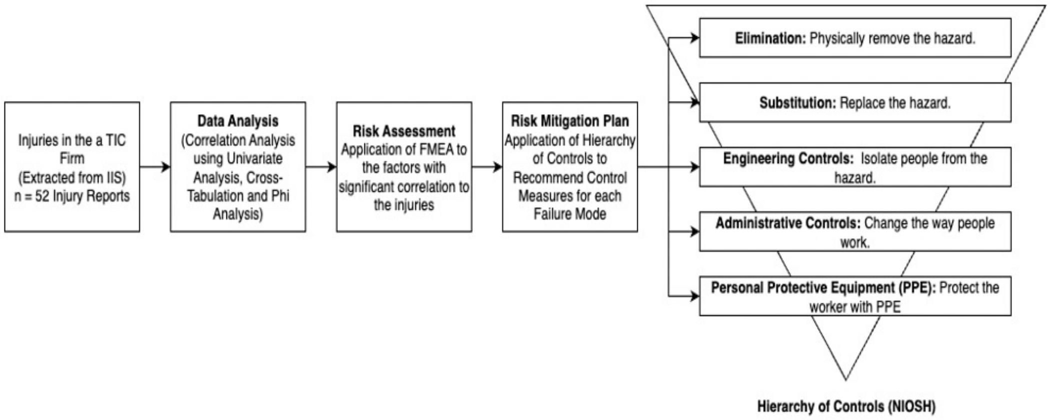

FIGURE 1. Injury Analytics and Risk Mitigation Framework for this Study

The Hierarchy of Controls was used to suggest control activities to improve the risk mitigation process after prioritizing the risks based on the RPN score at the conclusion of the risk assessment. One well known framework that the National Institute for Occupational Safety and Health recommends is the Hierarchy of Controls (Fletcher et al. 2018). Figure 1 described the study's methodology, which included the Hierarchy of Controls architecture and progressed from statistical analysis to risk assessment.

RESULTS AND DISCUSSION

EMPLOYEE CHARACTERISTICS

The analysis of employee characteristics revealed significant patterns in injury distribution within the TIC sector. Females accounted for 55.8% of injuries, while males represented 44.2%, as shown in Table 3. This aligns with previous studies suggesting that females may be more prone to certain injuries due to anatomical and task related factors (Redler & Sarig, 2023).

The 20 29 age group exhibited the highest injury rate (57.7%), consistent with research indicating that younger employees are more likely to be involved in high risk activities (Bensonch et al. 2022). This demographic, largely comprising Gen Z and Millennials, underscores the importance of targeted safety training for younger workers.

Regarding employment type, company personnel (88.5%) were more frequently injured compared to subcontractors (11.5%), highlighting the higher exposure risk for permanent staff. These findings emphasize the need for sector specific safety interventions and tailored training programs for both younger and permanent employees.

INCIDENT CHARACTERISTICS

The analysis of incident characteristics revealed that the majority of injuries occurred on company sites (67.3%), with laboratories being the most frequent location (61.5%), as shown in Table 4. This result is consistent with the high risk nature of laboratory activities, particularly testing and sampling operations, which expose workers to hazardous chemicals, equipment, and physical tasks. The risks associated with laboratory environments are well documented in the literature, with studies indicating that laboratory workers are especially vulnerable to both chemical and biological exposure (Papadopoli et al. 2020) and physical injuries. Similar findings were reported by Nasrallah et al. (2023), who identified laboratory settings as high risk environments for workplace injuries due to complex tasks involving hazardous materials and machinery.

Regarding the work relatedness of injuries, 92.3% were classified as work related, while the remaining 7.7% occurred during extracurricular activities, as indicated in Table 4. This high percentage of work related injuries emphasizes the need for safety protocols that specifically address risks encountered during routine occupational tasks.

Regarding injury severity, the majority of injuries were classified as first aid (54%) and minor injuries (31%), as illustrated in Table 4. This suggests that while the injuries were generally not severe enough to require extensive medical attention, they still had an impact on employee health and workplace productivity (Simpson et al. 2005). Injuries resulting in lost time were minimal, accounting for just 6%. The low percentage of lost time injuries indicates that these injuries generally did not lead to prolonged absences, though even minor injuries should be addressed to prevent future escalation.

TABLE 3. Frequency distribution of employee characteristics

Factor	Definition	Code	Level of Factor	N	%
Gender		1	Male	23	44.2%
		2	Female	29	55.8%
Age		1	20 29	30	57.7%
		2	30 39	15	28.8%
		3	40 49	5	9.6%
		4	50 and up	2	3.8%
Employee Type	Refers to the status of the employee.	1	Company Personnel	46	88.5%
		2	Subcontractor	6	11.5%
Line of Business	The organization's division that is based on the various lines of businesses that could either be the business' service or an internal operational entity or support groups.	1	Food, Agriculture and Healthcare Assurance	29	55.8%
		2	Government, Trade and Retail	8	15.4%
		3	Industries, Environment & Safety	7	13.5%
		4	Internal Support (Finance, Human Resources, Admin)	4	7.7%
		5	Energy and Resource	4	7.7%
Shift[a]			Day	52	100%

TABLE 4. Frequency distribution of incident characteristics

Factor	Definition	Code	Level of Factor	N	%
Location Type	Major location of where the incident occurred.	1	Company Site	35	67.3%
		2	Off Site	17	32.7%
Site Type	Specific sites where the incident happened.	1	Client Premises (Yard, Vessel, Warehouse, Laboratory)	10	19.2%
		2	Head Office	3	5.8%
		3	Laboratory	32	61.5%
		4	Off site Premises (Gym, Mixed use, Road, Residence)	7	13.5%
Is the injury Work related?	Determine if the specific injury is related to the activities of the organization or not.	1	Yes	48	92.3%
		2	No	4	7.7%
Activity Type	Refers to the activity performed by the employee during the occurrence of the incident.	1	Inspection, Audit & Certification	5	9.6%
		2	Testing/Sampling	35	67.3%
		3	Transit/Walking	8	15.4%
		4	Others (Office, Extracurricular Activities)	4	7.7%
Incident Cause	The classification to this factor has been obtained based on the IIS and safety guidelines of the organization which could either be an unsafe act or an unsafe condition. Unsafe act or behaviors are associated with human actions such as improper use of personal protective equipment (PPE), negligence or incorrect posture, whereas unsafe conditions are connected to the working environment, tools, or equipment.	1	Unsafe act	24	46.2%
		2	Unsafe condition	28	53.8%
Hours Work Prior to Incident	Refers to the length of hours of the employees prior to the incident.	1	Less than 8 Hours	33	63.5%
		2	8 24 hours	15	28.8%
		3	More than 24 hrs	4	7.7%

continue...

...cont.

Hours work within previous 14 days	Refers to the length of working hours of the employees 14 days prior to the incident	1	0 40	11	21.2%
		2	41 80	10	19.2%
		3	81 120	25	48.1%
		4	More than 120	6	11.5%
Days Lost	Refers to the days lost from lost time and restricted duty injury level	1	No Days Lost	47	90.4%
		2	1 20 Days Lost	5	9.6%
Nature of Injury	The specific type or description of harm or damage that the employee has experienced which helps in understanding the details and characteristics of the injury. The organization's IIS has more than 20 potential nature of injuries and has been reclassified in this study.	1	Burn Injuries	12	23%
		2	Eye and Vision Injuries	3	6%
		3	Other Injuries	13	25%
		4	Traumatic Injuries	24	46%
Affected Body Part	Specific area or part of the body that has been harmed or affected by an injury. This section has over 30 classification in the company's IIS and has been recategorized into four(4) in this study.	1	Head and Face	8	15%
		2	Lower Extremities	11	21%
		3	Torso and Back	4	8%
		4	Upper Extremities	29	56%
Mechanism of Injury	The way in which an injury occurred or the specific circumstances and forces that led to the harm. Originally with over 25 possibilities in the company's IIS, and reclassified further into five (5) categories.	1	Exposure Incidents	12	23%
		2	Fall and Slips	10	19%
		3	Mechanical Injuries	17	33%
		4	Physical Contact	2	4%
		5	Work Practice and Ergonomics	11	21%
Injury Severity Classification	Refers to the severity of the injury: First aid injuries that can be treated with first aid treatments, Minor/ Superficial minor injuries that can requires minor treatment measures and doesn't require extensive medical intervention, Medical Treatment injuries that require medical intervention beyond basic first aid, Lost Time injury that is severe enough that unable the employee to perform his regular work duties for a specific period, and Restricted Duty injury that limits an employee to perform his regular work duties but doesn't completely prevent him from working.	1	First Aid	28	54%
		2	Minor/Superficial	16	31%
		3	Medical Treatment	3	6%
		4	Lost Time	3	6%
		5	Restricted Duty	2	4%

TABLE 5. Frequency distribution of nature of injury

Factor	Level of Factor	N	%
Burn Injuries	Burn (Chemical)	9	17.31%
	Burn (Thermal)	3	5.77%
Eye and Vision Injuries	Eye Injury/Vision Impairment	3	5.77%
Other Injuries	Abrasion	6	11.54%
	Foreign Body	1	1.92%
	Swelling/Inflammation	6	11.54%
Traumatic Injuries	Contusion/Bruise	4	7.69%
	Crush	1	1.92%
	Fracture	2	3.85%
	Head Injury	1	1.92%
	Laceration/Avulsion	9	17.31%
	Puncture/Impalement	3	5.77%
	Sprain/Strain	4	7.69%

As shown in Table 5, burn injuries (chemical burns: 17.31%, thermal burns: 5.77%) were prevalent, primarily caused by exposure to hazardous materials or hot surfaces. This aligns with Kim et al. (2023), who identified chemical burns as a common injury in laboratory settings in Korea, emphasizing the need for effective PPE such as gloves and goggles to mitigate such risks. Eye injuries (5.77%) were mainly caused by chemical splashes or flying debris, supporting findings from Clark D.E. (2002) that eye protection is critical in high risk environments.

Other injuries included abrasions (11.54%) and swelling/inflammation (11.54%), often from friction or repetitive strain during tasks. These injuries highlight the importance of ergonomic interventions, as similarly noted by Hoe at al., 2018, which could reduce the risk of workers developing work related MSDs. Traumatic injuries, particularly lacerations/avulsions (17.31%) and punctures/ impalements (5.77%), were commonly caused by mishandling sharp objects or broken glassware, emphasizing the need for strict equipment handling protocols.

The nature of injuries revealed that mechanical injuries (33%) were the most common, followed by exposure incidents (23%), as obtained from Table 6. Mechanical injuries, such as lacerations, sprains, and fractures, are primarily caused by the improper handling of equipment or accidents involving faulty machinery. This is consistent with the study of Simmons et al. where findings showed that lacertaions were the most prevalent type, often resulting from glassware breaking during laboratory tasks. The primary causes of these injuries were identified as equipment, glassware, and blades, with 74.4% of glass related injuries linked to broken glassware during use. This underscores the need for better equipment maintenance, PPE compliance, and pre use inspection of glassware to prevent injuries.

The second most common injury type was chemical exposure (23%), highlighting the ongoing risks faced by employees in laboratory settings. As Nasrallah et al. (2023) and Xu et al. (2023) pointed out, laboratory workers are particularly vulnerable to exposure related injuries, emphasizing the need for rigorous PPE usage and adherence to chemical safety protocols to protect workers from harmful substances.

TABLE 6. Frequency distribution of mechanism of injury

Factor	Level of Factor	N	%
Exposure Incidents	Chemical Exposure (Body Contact)	9	17.31%
	Chemical Exposure (Inhalation)	1	1.92%
	Thermal Exposure	2	3.85%
Fall and Slips	Fall/Slip/Trip (Same Level or Less Than 2 metres)	10	19.23%
Mechanical Injuries	Laceration/Cut/ Puncture	12	23.08%
	Motor Vehicle Accident	3	5.77%
	Striking Stationary Object	2	3.85%
Physical Contact	Caught In/Between	1	1.92%
	Crush	1	1.92%
Work Practice and Ergonomics	PPE(Lack Of)/Incorrect Usage	6	11.54%
	Pushing/Pulling/ Other Incorrect Body Positioning	2	3.85%
	Repetitive Motion	3	5.77%

Table 7 identifies the primary root causes of injuries, categorized into unsafe conditions and unsafe acts. Unsafe conditions accounted for 70% of injuries, with poor equipment maintenance (25%) being the leading cause, contributing to mechanical injuries like lacerations. Chemical spills (15%) and inadequate PPE (13%) were significant contributors to chemical burns and eye injuries. Thermal exposures (10%) and poor work environment design (7%) also played a role in thermal burns and repetitive strain injuries.

Unsafe acts accounted for 30% of injuries, with negligence (20%) being the most prevalent cause, often leading to lacerations and abrasions. Other unsafe acts, such as rushing (5%) and inadequate training (5%), contributed to traumatic injuries like fractures and punctures.

These findings highlight the need for both engineering controls and behavioral interventions, focusing on equipment maintenance, PPE compliance, and safety training to reduce injury risks. Table 8 shows that the most commonly injured body parts were the Upper Extremities, specifically the hands and fingers (56%), followed by the lower extremities (21%), and the head and face (15%). Hands and fingers were predominantly injured due to mishandling sharp tools or broken glassware, highlighting the need for proper equipment handling and hand protection in laboratory settings. The high incidence of lower extremity injuries suggests that more attention is needed for ergonomic practices and floor safety. Head and face injuries (15%), although less frequent, underscore the importance of protective gear, such as face shields and goggles, to prevent exposure to flying debris or chemicals.

TABLE 7. Frequency distribution of root cause of incident

Factor	Level of Factor	N	%
Unsafe Act	Improper use or lack of PPE	7	13%
	Incorrect body positioning/posture	7	13%
	Lack of attention or negligence	12	23%
Unsafe Condition	Defective/Damaged tools, materials or equipment	6	12%
	Lack of Ergonomic Design	4	8%
	Poor ground/ladder conditions	7	13%
	Chemical spills, reaction, thermal exposure	9	17%

TABLE 8. Frequency distribution of affected body part

Factor	Level of Factor	N	%
Head and Face	Eye	3	5.77%
	Face	2	3.85%
	Head	2	3.85%
	Mouth	1	1.92%
Lower Extremities	Ankle	1	1.92%
	Foot	2	3.85%
	Knee	1	1.92%
	Leg(Lower)	5	9.62%
	Leg(Upper)	2	3.85%
Torso and Back	Back/Spine (Lower)	1	1.92%
	Back/Spine (Upper)	1	1.92%
	Buttocks	1	1.92%
	Chest (Thoracic)	1	1.92%
Upper Extremities	Arm(Lower)	2	3.85%
	Arm(Upper)	3	5.77%
	Finger (Other than Index)	6	11.54%
	Hand	11	21.15%
	Index Finger	3	5.77%
	Thumb	2	3.85%
	Wrist	2	3.85%

ASSOCIATION ANALYSIS

In the conduct of the association between factors in this research, cross tabulation through the IBM SPSS software has been executed. Furthermore, association was obtained through Pearson's chi square test indicating the significance of association with the p value at significance level of 0.05 and 0.01. The strength of the association was obtained through the Phi (φ) value for a 2 x 2 factor association test and Cramer's V value for a cross tabulation of more than the 2 x 2 grid at significance level of 0.05 and 0.01. Since chi square tests, phi, and Cramer's V values are applicable for variables with a frequency of 5 or more at each level, the Fisher Freeman Halton's exact test was employed to derive the p value using an exact iterative method. The precise relationship between associating variables using the Cramer's V value was established utilizing the Association Table proposed by Fletcher et al, shown in Table 9.

The cross tabulation analysis for the association of the factors can be found in Table 10, while Table 11 provides a summary of variables associated with a p value at significance level of 0.05, along with their corresponding Cramer's V value and the level of association.

A perfect relationship (Cramer's V = 1, $p < 0.001$) was observed between location type and site type, suggesting that the type of location in which work occurs (e.g., laboratory, company site) is intrinsically linked to the site type within that location (e.g., laboratory areas, office environments). This relationship reflects the higher injury risks in certain site types, particularly in laboratories and company sites, which are more likely to expose workers to chemical hazards, sharp equipment, and mechanical risks. This strong association indicates that site specific safety interventions may be needed to address the specific risks associated with each work environment.

TABLE 9. Cramer's v level of association (Fletcher et al. 2018)

Level of Association	Description	Comments
0	No relationship	Cannot predict the dependent variable from the independent variable
0 – 0.15	Very weak	Not acceptable
0.15 – 0.20	Weak	Slightly acceptable
0.20 – 0.25	Moderate	Acceptable
0.25 – 0.30	Moderately strong	Desirable
0.30 – 0.35	Strong	Very Desirable
0.35 – 0.40	Very Strong	Extremely desirable
0.40 – 0.50	Extremely strong	Extremely good relationship or the two variables are measuring the same concept
0.50 – 0.99	Redundant	The two variables are probably measuring the same concept
1	Perfect relationship	We can perfectly predict the dependent variable from the independent variable

Additionally, a perfect relationship (Cramer's V = 1, $p < 0.001$) was found between the classification of injury and days lost, underscoring that the severity of injuries directly correlates with the number of days lost due to the injury. Severe injuries, such as fractures or lacerations, naturally lead to higher days lost, affecting both productivity and workforce health. This emphasizes the importance of addressing both the severity and frequency of injuries, as these significantly impact work operations.

Furthermore, the association between accident cause and accident root cause showed a perfect relationship (Cramer's V = 1, $p < 0.001$). This indicates that the primary cause of accidents (e.g., chemical exposure, equipment failure) is strongly linked to the root cause (e.g., poor maintenance, lack of training). Identifying and addressing the root causes is crucial for preventing accidents, as the underlying factors must be corrected to mitigate recurrence.

The line of business also demonstrated significant associations with several key factors, as shown in Table 10. Location type (Cramer's V = 0.827, $p < 0.001$), site type (Cramer's V = 0.673, $p < 0.001$), and work relatedness (Cramer's V = 0.748, $p < 0.001$) were strongly associated with specific business sectors. For example, in the Agriculture, Life Sciences, and Healthcare Assurance, laboratory testing is integral to business operations, leading to increased exposure to chemical hazards and manual handling risks. These associations suggest that each line of business has unique site specific risks and activities that require tailored safety measures.

In addition, variables such as age group (Cramer's V = 0.347, $p < 0.01$), affected body part (Cramer's V = 0.401, $p < 0.01$), and length of work in the previous 14 days (Cramer's V = 0.357, $p < 0.05$) were found to have strong associations with the line of business. For example, younger employees (20 29 years) working in the Agriculture and Healthcare Assurance sectors may be more prone to exposure incidents, while older employees (40 49 years) in more physically demanding tasks may face increased risk of ergonomic injuries. These associations further highlight the need for age specific safety protocols in different business sectors.

The analysis of gender and injury classification revealed that male employees were more likely to sustain severe injuries requiring medical treatment, while female employees predominantly experienced minor injuries (Cramer's V = 0.566, $p < 0.001$). This suggests that gender based differences in injury types may be attributed to the nature of the tasks performed by each gender, with males engaging in more physically demanding work that increases the likelihood of serious injuries. Additionally, female employees may experience more minor injuries, potentially due to their involvement in less physically intensive roles. These findings indicate the need for gender sensitive safety protocols, such as PPE training for males handling sharp tools and ergonomic safety measures for females.

TABLE 10. Cross tabulation analysis for association of factors

Variables	Line of Business	Gender	Location Type	Site Type	Activity Type	Employee Type	Age Group	Work Related	Nature of Injury	Affected Body Part	Mechanism of Injury	Classification of Injury	Accident Cause	Accident Root Cause	Hours Worked Prior to Incident	No. of Hours Worked in Previous 14 Days
Gender	0.346															
	0.195															
Location Type	0.827	0.205														
	0.000	*0.234*														
Site Type	**0.673**	0.318	**1.000**													
	0.000	*0.172*	*0.000*													
Activity Type	**0.576**	0.254	**0.751**	**0.670**												
	0.000	*0.378*	*0.000*	***0.000***												
Employee Type	0.236	**0.406**	0.252	0.286	0.252											
	0.935	***0.005***	*0.161*	*0.397*	*0.687*											
Age Group	0.347	0.322	**0.556**	**0.429**	**0.471**	0.309										
	0.009	*0.146*	*0.000*	***0.000***	***0.000***	0.232										
Work Related	**0.748**	0.034	**0.414**	**0.732**	**0.538**	0.104	0.126									
	0.000	*1.000*	*0.009*	***0.000***	***0.000***	*1.000*	*1.000*									
Nature of Injury	0.268	0.065	0.314	0.317	0.275	0.283	0.232	0.312								
	0.632	1.000	0.141	0.069	0.208	0.362	0.567	0.267								
Affected Body Part	**0.401**	0.325	**0.457**	**0.342**	**0.385**	0.222	0.269	**0.388**	0.431							
	0.006	*0.160*	*0.006*	***0.007***	***0.000***	*0.818*	*0.229*	*0.032*	*0.000*							
Mechanism of Injury	0.308	0.134	**0.437**	**0.369**	**0.419**	0.407	**0.388**	0.378	**0.530**	0.529						
	0.065	*0.927*	*0.015*	***0.017***	***0.003***	*0.088*	***0.001***	*0.151*	*0.000*	0.000						
Classification of Injury	0.288	**0.566**	0.255	0.316	0.338	0.358	0.287	0.369	0.253	0.293	0.285					
	0.435	***0.000***	*0.388*	*0.261*	*0.156*	*0.076*	*0.278*	*0.116*	0.637	0.242	0.718					
Accident Cause	0.278	0.116	0.287	0.348	0.301	0.241	**0.411**	0.144	**0.386**	0.238	**0.586**	0.266				
	0.436	0.577	0.075	0.078	0.243	*0.191*	***0.030***	*0.610*	*0.049*	*0.411*	***0.000***	*0.564*				
Accident Root Cause	0.384	0.279	**0.526**	**0.494**	0.445	**0.492**	0.410	0.402	**0.613**	**0.459**	**0.688**	0.320	**1.000**			
	0.106	*0.718*	*0.014*	***0.004***	*0.220*	***0.042***	*0.051*	*0.175*	*0.000*	*0.011*	***0.000***	*0.750*	***0.000***			
Hours Worked Prior to Incident	0.350	**0.376**	**0.501**	**0.308**	**0.332**	0.184	0.241	0.296	0.269	0.169	0.277	0.539	0.043	**0.407**		
	0.057	***0.020***	*0.000*	***0.054***	***0.049***	*0.614*	*0.318*	*0.140*	*0.217*	*0.804*	*0.196*	*0.051*	*1.000*	***0.041***		
No. of Hours Worked in Previous 14 Days	**0.357**	0.254	0.293	0.265	0.213	0.299	0.250	0.244	0.157	0.186	0.232	0.202	0.351	0.323	0.236	
	0.046	*0.350*	*0.193*	*0.163*	*0.449*	0.207	0.336	0.438	0.892	0.892	0.801	0.919	0.096	0.637	0.286	
Days Lost	0.213	**0.366**	0.051	0.098	0.224	0.291	0.370	0.151	0.241	0.207	0.376	**1.000**	0.196	0.327	0.186	0.232
	0.738	***0.013***	*1.000*	*0.862*	*0.281*	*0.096*	*0.109*	*0.341*	*0.627*	*0.776*	*0.108*	***0.000***	*0.350*	*0.498*	*0.234*	*0.541*

TABLE 11. Variables Association Table (Cramer's V)

Variable X	Variable Y	Cramer's V	Association
Line of Business	Location Type*	0.827	Redundant
	Site Type*	0.673	Redundant
	Activity Type*	0.576	Redundant
	Age Group*	0.347	Strong
	Work Related	0.748	Redundant
	Affected Body Part*	0.401	Extremely Strong
	No. of Hours Worked in Previous 14 Days	0.357	Very Strong
Gender	Person Affected*	0.406	Extremely Strong
	Classification of Injury*[a]	0.566	Redundant
	Hours Worked Prior to Incident	0.376	Very Strong
	Days Lost	0.366	Very Strong
Location Type	Site Type*	1	Perfect Relationship
	Activity Type*	0.751	Redundant
	Age Group*	0.556	Redundant
	Work Related*	0.414	Extremely Strong
	Affected Body Part*[a]	0.457	Extremely Strong
	Mechanism of Injury*[a]	0.437	Extremely Strong
	Accident Root Cause	0.526	Redundant
	Hours Worked Prior to Incident	0.501	Redundant
Site Type	Activity Type	0.67	Redundant
	Age Group	0.429	Extremely Strong
	Work Related	0.732	Redundant
	Affected Body Part	0.342	Strong
	Mechanism of Injury	0.369	Very Strong
	Accident Root Cause	0.494	Extremely Strong
Activity Type	Age Group	0.471	Extremely Strong
	Work Related	0.538	Redundant
	Affected Body Part	0.385	Very Strong
	Mechanism of Injury[a]	0.419	Extremely Strong
	Hours Worked Prior to Incident	0.332	Strong
Person Affected	Accident Root Cause	0.492	Extremely Strong
Age Group	Mechanism of Injury*[a]	0.388	Very Strong
	Accident Cause[a]	0.411	Extremely Strong
Work Related	Affected Body Part	0.388	Very Strong

continue...

...cont.

Nature of Injury	Affected Body Part*[a]	0.431	Extremely Strong
	Mechanism of Injury*	0.53	Redundant
	Accident Cause	0.386	Very Strong
	Accident Root Cause*[a]	0.613	Redundant
Affected Body Part	Mechanism of Injury*	0.529	Redundant
	Accident Root Cause	0.459	Extremely Strong
Mechanism of Injury	Accident Cause*	0.586	Redundant
	Accident Root Cause*	0.688	Redundant
Classification of Injury	Days Lost *	1	Perfect Relationship
Accident Cause	Accident Root Cause*	1	Perfect Relationship
Accident Root Cause	Hours Worked Prior to Incident	0.401	Extremely Strong
	*with p value at 99% Confidence Level		
	[a] subject for further analysis through phi analysis		

Further analysis showed strong associations between gender and other factors, such as employee type (Cramer's V = 0.406, $p < 0.01$), hours worked prior to the incident (Cramer's V = 0.376, $p < 0.05$), and days lost (Cramer's V = 0.366, $p < 0.013$). This indicates that gender may influence work related fatigue and the severity of injuries, necessitating the development of safety programs tailored to the specific needs of male and female employees.

The association between location type and activity type (Cramer's V = 0.751, $p < 0.001$) showed that certain work activities are inherently linked to the location in which they are performed. For instance, laboratory testing and sampling activities were strongly associated with exposure incidents, while transit/walking activities were more likely to result in slips and falls. These findings emphasize the need for activity specific safety protocols, particularly in high risk environments such as laboratories where chemical exposure is common. Similarly, slips and falls during transit or walking activities highlight the need for improved workplace safety measures, such as clear pathways and proper footwear.The nature of injury was significantly associated with affected body part (Cramer's V = 0.431, $p < 0.001$), mechanism of injury (Cramer's V = 0.530, $p < 0.001$), and accident root cause (Cramer's V = 0.613, $p < 0.001$). For instance, burn injuries were strongly associated with chemical spills and thermal exposures (Phi = 0.715, $p < 0.001$), while eye injuries were linked to PPE noncompliance (Phi = 0.386, $p < 0.01$). The nature of injury analysis highlights the need for targeted safety measures, such as the proper use of PPE, particularly goggles and heat resistant gloves, to prevent injuries related to chemical exposure and thermal hazards.

The analysis also examined the relationship between age group and mechanism of injury, revealing significant associations with exposure incidents (Phi = 0.469, $p < 0.001$) for younger employees (20 29 years), and ergonomic injuries (Phi = 0.31, $p < 0.05$) for older employees (40 49 years). These findings suggest that younger workers are more likely to be exposed to chemicals in laboratory settings, while older employees face greater risks related to physical strain from repetitive tasks. The results point to the importance of age specific interventions, including ergonomic adjustments for older employees and chemical safety training for younger employees.

PHI (Φ) ANALYSIS

The association analysis presented in Table 10 and Table 11 identified several pairs of variables with significant associations, which were subsequently examined in greater detail through phi (φ) analysis to assess the strength of their associations. These pairs include: classification of injury and gender, location type and mechanism of injury, location type and affected body part, activity type and mechanism of injury, age group and mechanism of injury, accident cause and age group, nature of injury and accident root cause, and nature of injury and affected body part. These selected associations were deemed noteworthy, as they may have implications for the safety management strategies of the organization, given its operational characteristics. A summary of the findings from the phi analysis is provided in Table 12.

TABLE 12. Phi analysis association results

A. Classification Injury and Gender

Gender	Classification of Injury: Firs Aid	Lost Time	Medical Treatment	Minor/Superficial	Restricted Duty
Female	15	0	0	14	0
	0.048	0.278	0.278	0.426	0.225
	0.737	0.046	0.046	0.002	0.109
Male	13	3	3	2	2
	0.048	0.278	0.278	0.426	0.225
	0.737	0.046	0.046	0.002	0.109

B. Location Type and Mechanism of Injury

Location Type	Mechanism of Injury: Exposure Incidents	Fall and Slips	Mechanical Injuries	Physical Contact	Work Practice & Ergonomics
Company Site	12	5	12	1	5
	0.382	0.18	0.049	0.074	0.241
	0.005	0.202	0.732	0.603	0.085
Off Site	0	5	5	1	6
	0.382	0.18	0.049	0.074	0.241
	0.005	0.202	0.732	0.603	0.085

C. Location Type and Affected Body Part

Location Type	Affected Body Part: Head and Face	Lower Extremities	Torso and Back	Upper Extremities
Company Site	3	5	2	25
	0.271	0.241	0.107	0.452
	0.052	0.085	0.452	0.001
Off Site	5	6	2	4
	0.271	0.241	0.107	0.452
	0.052	0.085	0.452	0.001

D. Activity and Mechanism of Injury

Activity	Mechanism of Injury: Exposure Incidents	Fall and Slips	Mechanical Injuries	Physical Contact	Work Practice & Ergonomics
Inspection, Audit and Certification	0	2	1	0	2
	0.179	0.172	0.088	0.065	0.151
	0.205	0.223	0.534	0.646	0.287
Others (Office, Extracurricular Activities)	0	0	1	1	2
	0.158	0.141	0.047	0.318	0.204
	0.263	0.319	0.739	0.022	0.147
Testing/ Sampling	12	3	12	1	7
	0.382	0.388	0.049	0.074	0.041
	0.005	0.004	0.732	0.603	0.775
Transit/Walking	0	5	3	0	0
	0.234	0.468	0.044	0.085	0.221
	0.096	0	0.758	0.548	0.116

E. Age group and Mechanism of Injury

	Mechanism of Injury				
Age Group	Exposure Incidents	Fall and Slips	Mechanical Injuries	Physical Contact	Work Practice & Ergonomics
20–29	12	5	10	1	2
	0.469	0.076	0.016	0.031	0.414
	0.000	0.592	0.911	0.827	0.002
30–39	0	2	7	1	5
	0.349	0.095	0.19	0.093	0.19
	0.011	0.502	0.178	0.51	0.178
40–49	0	2	0	0	3
	0.179	0.172	0.227	0.065	0.31
	0.205	0.223	0.105	0.646	0.025
50 and up	0	1	0	0	1
	0.11	0.156	0.139	0.04	0.141
	0.439	0.269	0.324	0.778	0.318

F. Age Group and Accident Cause

	Age Group			
Accident Cause	20 29	30 39	40 49	50 and up
Unsafe Act	19	10	4	2
	0.389	0.212	0.196	0.2
	0.004	0.131	0.164	0.155
Unsafe Condition	20	5	1	0
	0.389	0.212	0.196	0.2
	0.004	0.131	0.164	0.155

G. Nature of Injury and Accident Root Cause

	Accident Root Cause						
Nature of Injury	Chemical spills, reaction, thermal exposure	Defective/ Damaged tools, materials or equipment	Improper use or lack of PPE	Incorrect body positioning/ posture	Lack of attention or negligence	Lack of Ergonomic Design	Poor ground/ ladder conditions
Burn Injuries	8	0	3	0	1	0	0
	0.715	0.198	0.185	0.216	0.192	0.158	0.216
	0.000	0.16	0.189	0.124	0.173	0.263	0.124
Eye and Vision Injuries	0	0	2	0	1	0	0
	0.113	0.089	0.386	0.098	0.06	0.071	0.098
	0.424	0.529	0.005	0.491	0.671	0.615	0.491
Other Injuries	1	1	1	1	2	1	6
	0.147	0.07	0.098	0.098	0.105	0.000	0.553
	0.299	0.624	0.491	0.491	0.457	1.000	0.000
Traumatric Injuries	0	5	1	6	8	3	1
	0.424	0.269	0.252	0.313	0.225	0.167	0.252
	0.002	0.053	0.071	0.024	0.108	0.237	0.071

H. Nature of Injury and Affected Body Part

	Affected Body Part			
Nature of Injury	Head and Face	Lower Extremities	Torso and Back	Upper Extremities
Burn Injuries	1	0	0	11
	0.107	0.284	0.158	0.396
	0.450	0.042	0.263	0.004

Eye and Vision Injuries	3	0	0	0
	0.580	0.128	0.071	0.278
	0.000	0.365	0.615	0.046
Other Injuries	1	6	1	5
	0.123	0.353	0.000	0.201
	0.385	0.01	1.000	0.153
Traumatic Injuries	3	5	3	13
	0.074	0.007	0.167	0.03
	0.602	0.959	0.237	0.833

First line is the frequency. Second line is the phi coefficient. Third line is the p value.
Bold stands for variables with significant correlation based on the p value and phi coefficient.

The results of the Phi (φ) analysis revealed several noteworthy associations that are key to understanding the risk factors influencing injury types. One significant finding was the moderate positive correlation between gender and injury classification (Phi = 0.426, $p < 0.01$), indicating that female employees are more likely to experience minor injuries, such as abrasions and bruises, while male employees tend to sustain more severe injuries, such as fractures and lacerations. This result highlights the need for gender specific safety protocols, particularly for male employees engaged in more hazardous tasks and female employees who may require different ergonomic considerations.Another critical association was between location type and mechanism of injury, with a moderate positive correlation (Phi = 0.437, $p < 0.05$). This finding suggests that laboratories, where employees engage with chemical materials and sharp tools, are associated with mechanical injuries and chemical burns. This aligns with the need for site specific safety measures, emphasizing the importance of improving equipment maintenance, chemical safety protocols, and PPE usage in such environments.

The analysis also revealed that age group significantly correlates with injury mechanism, with younger employees (20 29 years) more likely to experience exposure incidents (Phi = 0.469, $p < 0.001$), while older employees (40 49 years) were more prone to ergonomic injuries (Phi = 0.31, $p < 0.05$). This finding points to the need for age specific safety interventions, such as ergonomic adjustments for older workers and chemical safety training for younger employees, particularly those in laboratory settings.

Additionally, the relationship between activity type and injury outcome was highlighted, with testing and sampling activities strongly associated with exposure incidents (Phi = 0.382, $p < 0.01$), while transit and walking activities were linked to a higher incidence of slips and falls (Phi = 0.468, $p < 0.001$). This suggests that the activity specific risks in the workplace require targeted safety measures, such as slip resistant footwear for employees engaged in walking and chemical safety training for those involved in laboratory testing.

Finally, the analysis of the nature of injury and accident root cause showed a very strong positive correlation (Phi = 0.613, $p < 0.001$), particularly with burn injuries, which were most strongly associated with chemical spills and thermal exposure (Phi = 0.715, $p < 0.001$), and eye injuries, which were linked to PPE noncompliance (Phi = 0.386, $p < 0.01$). These findings underscore the importance of addressing root causes such as inadequate PPE usage, chemical handling errors, and equipment failures to prevent injuries in the workplace.

The Phi (φ) analysis reveals key associations between employee characteristics and injury outcomes, but it does not systematically identify the underlying failure modes. To address this, the next step is conducting a Failure Modes and Effects Analysis (FMEA).

The FMEA follows the Phi analysis to identify and prioritize the failure modes associated with these correlations. For instance, the Phi analysis highlighted the connection between location type and injuries like chemical burns and mechanical injuries in laboratories, suggesting that unsafe conditions, such as poor equipment maintenance or chemical exposure, contribute to injury risks. The FMEA helps assess these failure modes in terms of severity, probability, and detectability, enabling targeted interventions for the most critical risks.

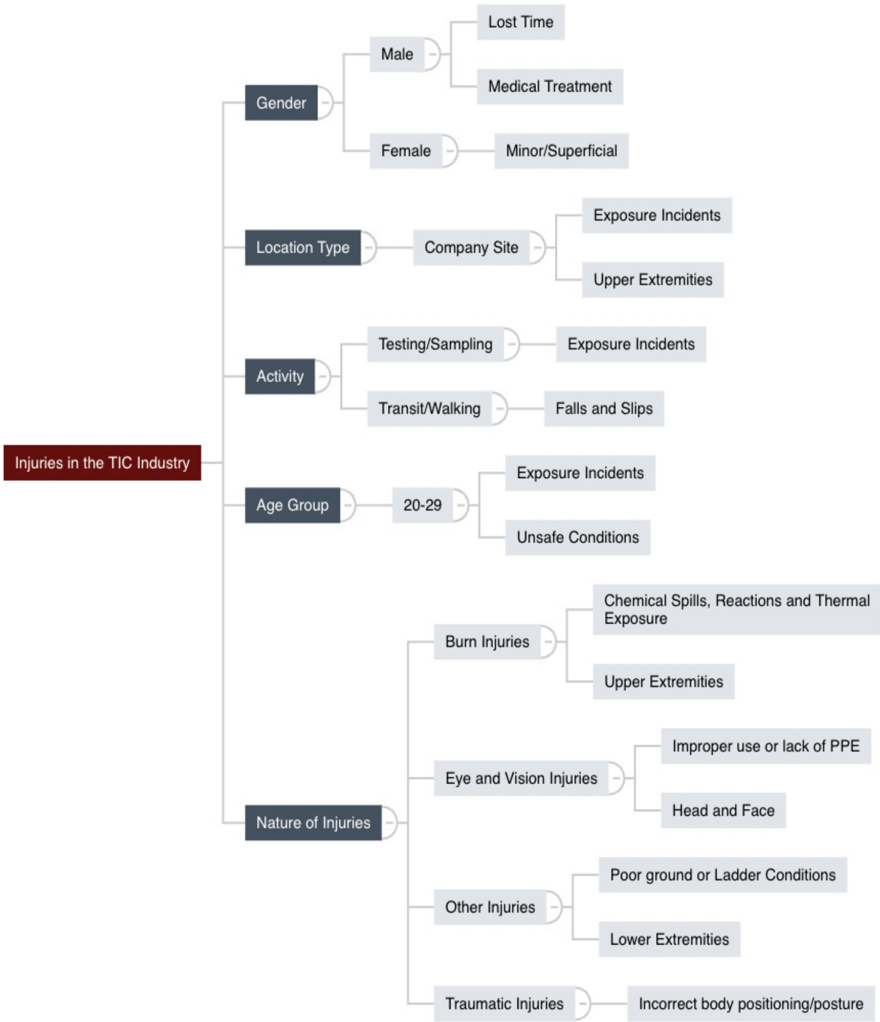

FIGURE 2. Tree Map of the Factors Correlating with the Injuries

Figure 2 lists the variables identified in the Phi (φ) analysis that were further assessed in the FMEA, showing strong correlations with injuries. This visual representation encapsulates how the insights derived from the Phi analysis guide the FMEA, systematically transforming statistical relationships into actionable risk management strategies. By conducting the FMEA after the Phi analysis, these insights inform the development of safety measures to mitigate the identified failure modes, ultimately improving workplace safety.

FAILURE MODES AND EFFECTS ANALYSIS (RISK ASSESSMENT APPROACH)

The 52 injury reports were carefully reviewed and analyzed in light of the insights gained from the Phi (φ) analysis, which is depicted in Figure 2, to develop a risk assessment strategy using the Failure Modes and Effects Analysis (FMEA) technique. Of the 52 reports, 26 injury records were identified as particularly relevant, characterized by the following traits: age range of 20 29 years, both male and female employees, and a predominant occurrence in company locations—specifically laboratories and offices. A summary of the FMEA risk assessment analysis is provided in Table 13.

From these 26 reports, 10 failure modes in the testing and inspection domain—primarily occurring within the company's laboratory and office environments—were identified. The affinity diagram technique was employed to stratify the failure possibilities, as shown in Table 13. The analysis revealed that 50% (5/10) of the failure modes were categorized with an RPN (Risk Priority Number) at the yellow level (indicating the need for risk control or reduction), while the remaining 50% (5/10) were classified at the green level (indicating the need for observation or acceptance).

The failure mode with the highest RPN of 36 was associated with exposure to highly corrosive or boiling liquids during heating or distillation processes, caused by insufficient personal protective equipment (PPE). This resulted in burn injuries to the upper extremities, typically classified as minor or superficial injuries. Such incidents were categorized as high priority due to the potential for more severe consequences in the absence of proper PPE, which is consistent with findings from Nasrallah et al. (2023). Chemical exposure in laboratory settings, accounting for approximately 73.7% of incidents at a public university in Lebanon, is a significant factor contributing to injury occurrence. The Hussain Gutierrez Law further supports this by identifying chemical burns and exposure injuries as frequent outcomes in laboratory environments where PPE is either improperly used or insufficient. These findings highlight the need for better PPE compliance in laboratory settings, particularly for tasks involving hazardous chemicals.

The second failure mode, with an RPN of 32, was related to trips, falls, and slips within both office and laboratory environments. The inadequate ground conditions and wet flooring were identified as the primary contributing factors. Slips, trips, and falls are well documented causes of occupational injuries worldwide. Chang et al. (2016) report that such incidents account for 32% of workplace injuries, often resulting in fractures or other significant injuries. The Health and Safety at Work report for 2022 2023 further emphasizes this issue, noting that slip related injuries are a substantial concern, particularly in environments where safety measures for flooring and ground conditions are insufficient. This failure mode, ranked second in the analysis, highlights the critical need for slip prevention measures, especially in high risk areas such as laboratories and office spaces.

In third place, the ingestion of chemicals due to improper use of PPE resulted in an RPN of 30. Though less frequent, such incidents can have dire consequences, including internal organ failure or death if exposure is prolonged. This type of injury, caused by the improper or insufficient use of PPE, is among the leading causes of laboratory injuries according to Hussain Gutierrez Law. As the risk associated with chemical ingestion is particularly high, this failure mode is classified as requiring immediate mitigation strategies to minimize the potential for exposure.

Another significant failure mode, with an RPN of 27, involved burn injuries caused by highly corrosive chemicals resulting from equipment spills or leaks. This failure mode was also categorized as requiring mitigation or risk control due to the potential for injury severity in the event of equipment malfunction or improper handling of hazardous materials.

Lacerations, cuts, and punctures, which result from accidents involving broken glassware or damaged equipment parts, were also identified as significant failure modes, with an RPN of 24. These injuries are commonly associated with laboratory environments and occur when equipment is mishandled or improperly maintained. The Phi (φ) analysis findings, particularly the strong correlation between location type and injury mechanism, support this observation, further suggesting that preventive maintenance and proper handling training are essential.

Further investigation revealed two failure modes related to chemical exposure in laboratory settings. One was caused by defective equipment, leading to chemical burns (RPN of 18), and another was attributed to an improper waste disposal system (RPN of 9), though these incidents were less frequent. While their occurrences are low, the potential for moderate to severe consequences remains significant, especially in the case of laboratory fires, which could lead to fatalities. Thus, the analysis indicates that regular equipment checks and appropriate waste disposal procedures should be prioritized to mitigate such risks.

The final two failure modes on the list involved eye injuries, caused by chemical splashes resulting from inadequate or improper PPE use. Despite the lower incidence of these injuries, they have been classified with an RPN of 12, reflecting their moderate severity and the potential for long term damage, such as permanent vision impairment. This finding aligns with previous studies highlighting the importance of proper eye protection, particularly in environments where chemical handling is prevalent.

Lastly, the failure modes involving traumatic injuries, such as lacerations, cuts, and punctures from sharp objects and broken glassware, were found to be infrequent but important. These injuries, though minor, often require immediate first aid and occur in the normal course of laboratory activities. Their low severity does not diminish the need for careful handling and the consistent application of safety protocols to prevent recurrence.

The findings from the FMEA underscore the importance of developing comprehensive risk mitigation strategies for each of the identified failure modes, utilizing the Hierarchy of Controls. The strategies include measures for engineering controls (e.g., improving equipment safety), administrative controls (e.g., training and work procedures), and the use of personal protective equipment (PPE) to reduce exposure to hazards. By addressing these failure modes through targeted interventions, the risk of injury in the workplace can be significantly minimized.

TABLE 13. FMEA Risk Assessment for Injuries in the TIC sector

Activity/ Process	Failure Mode	Root Cause	Failure Effect	Injury Classification based on the Response	Historical Frequency	Occurences in a Year	Severity	Occurrence	Existing Controls	Detectability	Risk Level (SxO)	RPN (SxOxD)
Laboratory Testing Process (Testing Domain)	Exposure from highly corrosive or boiling liquids during heating or distillation process	Insufficient PPEs for extreme heat and chemical reaction	Burn injuries in the Upper Extremities	Minor/Superficial Medical Treatment	4	1 occurences in a year	3	4	Safety Toolbox Meetings, Monitoring of PPEs, Existence of Integrated Management System (9001, 45001, 17025)	3	12	36
Laboratory Testing & Inspection Process (Laboratory & Office Location)	Injuries obtains from falls, trips and slips	Wet floor condition and poor ground condition (uneven flooring)	Abrasion in the Lower Extremities	Minor/Superficial Lost Time	4	1 occurrence in a year	4	4	Hazard Reporting, 5S Implementation and Audit, Safety Toolbox Meeting	2	16	32
Laboratory Testing Process (Testing Domain)	Ingestion of chemicals	Improper use or insufficient PPEs	Breathing difficulty, inflammation of affected area, vomiting, organ failure	Minor/Superficial Medical Treatment, Worst Lost Time/ Fatality in Long Exposure	2	1 occurences in a year	5	2	Safety Toolbox Meetings, Monitoring of PPEs, Existence of Integrated Management System (9001, 45001, 17025)	3	10	30
Laboratory Testing Process (Testing Domain)	Exposure from highly corrosive chemical spilling from equipment	Contact with chemicals leaking from equipment	Burn in the Upper Extremities	Minor/Superficial Medical Treatment	3	1 occurences in a year	3	3	Technical Training of the personnel, Reporting of unsafe act and unsafe conditions, Monitoring of the supervisors in the area, Monthly Equipment Monitoring and Preventive Maintenance, Existence of Integrated Management System (9001, 45001, 17025)	3	9	27
Laboratory Testing Process (Testing Domain)	Injuries from accidental encounter of broken glassware or equipment parts	Accidental contact with broken glassware or equipment parts when washing or testing	Laceration/ Cut/Puncture in the Upper Extremities	First Aid Minor/ Superficial	4	1 occurrence in a year	2	4	5S Implementation and Good Housekeeping, Technical Training to Personnel, Monitoring of Supervisors in the Area	3	8	24

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Laboratory Testing Process (Testing Domain)	Exposure from highly corrosive or boiling liquids during heating or distillation process	Conduct of testing despite of defective equipment; Improper use or maintenance of equipment	Burn injuries in the Upper Extremities	Minor/Superficial Medical Treatment	2	2 occurences in a year	3	2	Technical Training of the personnel, Reporting of unsafe act and unsafe conditions, Monitoring of the supervisors in the area, Monthly Equipment Monitoring and Preventive Maintenance, Existence of ISO Standards (9001, 45001, 17025)	3	6	18
Laboratory Testing Process (Testing Domain)	Injuries from splashing of chemicals to the eyes	Improper use or insufficient PPEs	Eye and Vision Injuries	Minor/Superficial Medical Treatment	2	1 occurrence in a year	3	2	Safety Toolbox Meetings, Monitoring of PPEs, Existence of Integrated Management System (9001, 45001, 17025), Eye wash and showers in place	2	6	12
Laboratory Testing Process (Testing Domain)	Exposure from reactive chemical disposed in the waste bins	Improper waste disposal system	Burn injuries in the Upper or Lower Extremities	Minor/Superficial Medical Treatment	1	1 occurrence in a year	3	1	5S Implementation and Good Housekeeping, Technical Training to Personnel, Monitoring of Supervisors in the Area	3	3	9
Laboratory Testing & Inspection Process (Laboratory & Office Location)	Injuries from contact with sharp objects or edges	Accidental contact with sharp edges like door frames	Puncture, Laceration, Avulsion	First Aid	2	1 occurrence in a year	1	2	Hazard Reporting, 5S Implementation and Audit, Safety Toolbox Meeting	3	2	6
Laboratory Testing Process (Testing Domain)	Injuries from contact with broken glasswares or equipment	Lack of attention during testing	Laceration/ Cut/Puncture in the Upper Extremities	First Aid	2	1 occurrence in a year	1	2	5S Implementation and Good Housekeeping, Technical Training to Personnel, Monitoring of Supervisors in the Area	2	2	4

DESIGN OF CONTROL MEASURES (HIERARCHY OF CONTROLS)

The Failure Modes and Effects Analysis (FMEA) performed in the TIC industry identified significant failure modes with high Risk Priority Numbers (RPNs), mainly due to substandard equipment conditions, incorrect chemical management, and human error in laboratory testing and inspection. These dangers were particularly prevalent in laboratory and office settings. In light of these findings, the Hierarchy of Controls (HOC) framework was utilized to suggest a systematic array of actions designed to reduce these risks, particularly focusing on engineering solutions appropriate for laboratory environments. The suggested control measures, detailed in Table 14, adopt a systematic methodology, encompassing elimination and substitution, alongside the deployment of personal protective equipment (PPE), thereby ensuring that engineering solutions and organizational procedures collaboratively enhance safety in the TIC sector. A thorough set of control measures is provided in Annex A.

Elimination and substitution were recognized as the most efficacious ways for mitigating risk in laboratory settings, but these interventions frequently pose implementation challenges. The FMEA results indicated that chemical exposure and associated injuries might be markedly diminished by substituting hazardous compounds with safer alternatives. For example, replacing highly corrosive chemicals with less dangerous substances immediately reduces the risk of burns and accidents during processes like as heating and distillation (Nasrallah et al. 2023). Moreover, the implementation of automation in sample preparation and testing diminishes dependence on manual handling, thereby reducing human error and the risk of inadvertent exposure (Hussain Gutierrez Law, 2024). The implementation of automation necessitates significant investments in laboratory equipment and technology. This integration must be meticulously orchestrated to guarantee compatibility with current laboratory infrastructure and adherence to applicable safety regulations (Ajslev et al. 2022). Furthermore, these automated systems require continuous maintenance and optimization to ensure their sustained efficacy, necessitating a cooperative effort between engineers and laboratory managers (Bennett et al. 2017).

Engineering controls are crucial for mitigating failure modes associated with chemical exposure, physical injury, and environmental risks. Implementing spill containment systems, fume hoods, and shatterproof materials in laboratory settings can significantly mitigate the hazards of chemical burns, toxic fume inhalation, and injuries from shattered glassware (OSHA 2023). Furthermore, advancements in laboratory flooring, such as the implementation of anti slip surfaces and the optimization of drainage systems, can significantly reduce slip related risks, especially in zones susceptible to moisture or chemical spills (Morrison 2024). These engineering solutions aim to mitigate the most significant hazards identified in the FMEA, including chemical exposure burns and slips and falls in laboratory settings. Implementing these technical controls necessitates a comprehensive evaluation of the laboratory's current infrastructure to guarantee the efficient integration of these safety elements (Sehsah et al. 2020). The procedure entails the reconfiguration of workspaces to integrate safety equipment, such fume hoods, spill trays, and anti slip flooring, while guaranteeing their effective installation. Consistent maintenance and inspection are essential for preserving the efficacy of these systems over time. The efficacy of these engineering solutions depends significantly on the dependability and ongoing enhancement of the equipment and environmental design, which must be routinely assessed to comply with the changing safety standards (Kim et al. 2022).

Administrative controls are essential in strengthening engineering measures and guaranteeing compliance with specified safety regulations. The FMEA indicated that younger employees were especially susceptible to chemical exposure, underscoring the need for specialized training programs (Papadopoli et al. 2020). Administrative techniques, including standardized chemical handling procedures, routine safety audits, and duty rotation schedules, mitigate fatigue and ensure laboratory personnel remain vigilant to possible hazards (Xu et al. 2023). Furthermore, the execution of safety drills and ongoing behavioral surveillance enhances danger awareness and fosters compliance with safe practices (Bensonch et al. 2022). Administrative controls function as an auxiliary reinforcement for engineering solutions, guaranteeing that personnel are adequately trained and constantly adhere to safety regulations. The formulation and implementation of these controls necessitate meticulous cooperation among safety officers, human resources, and engineering teams to guarantee that all people are adequately prepared to manage any hazards. These controls are especially efficacious in scenarios where engineering solutions cannot completely eradicate risks, guaranteeing that safety precautions are uniformly implemented throughout all laboratory operations (Golkhani et al. 2018; SafeScience 2014).

PPE, while seen as the final tier in the hierarchy, is an essential element in reducing injury risks. The FMEA identified multiple occurrences when poor PPE usage resulted in burns, lacerations, and ocular injuries due to insufficient protection during hazardous activities (Hussain

Gutierrez Law 2024). Personal protective equipment (PPE), such as gloves, lab coats, goggles, and respirators, serves as an essential barrier against exposure to hazardous chemicals and physical injuries (Sehsah et al. 2020). Ensuring the sufficiency, availability, and comfort of PPE is crucial for reducing the risk of harm, especially during high risk procedures (Nasrallah et al. 2023). Laboratory design must emphasize the convenient accessibility of personal protective equipment, while adequate storage options are essential to preserve the integrity of protective gear (Gao & Sultan 2023). Moreover, consistent oversight of PPE adherence, together with thorough training initiatives, is essential to guarantee that this ultimate safeguard is employed effectively when alternative controls fail to completely mitigate risk. The engineering considerations of PPE entail guaranteeing that protective equipment is suitably built for certain laboratory duties, readily accessible when required, and in optimal condition for utilization. Intensive cooperation between engineering teams and safety officials is essential to guarantee that personal protective equipment (PPE) is properly maintained, replaced as needed, and utilized consistently in alignment with safety regulations (SafeScience 2014; Hussain Gutierrez Law 2024).

The implementation of the Hierarchy of Controls (HOC) framework, informed by the findings of the Failure Modes and Effects Analysis (FMEA), offers a thorough approach to mitigating high RPN hazards in TIC laboratories. Engineering controls, including automation, spill containment systems, and anti slip flooring, effectively diminish the probability of hazardous exposures and injuries. Administrative controls augment these engineering measures by assuring adherence to safety protocols and enhancing hazard awareness among laboratory personnel (Gopalaswami & Han, 2020). Personal protective equipment (PPE) serves as an essential final barrier, providing safety when alternative measures fail to completely mitigate danger. The incorporation of these safeguards, bolstered by ongoing training, periodic audits, and enhancements to infrastructure, markedly diminishes injury rates and improves laboratory safety (Michaels & Wagner, 2020). This comprehensive strategy cultivates a safety oriented culture within the TIC business and encourages the establishment of sustainable safety standards, crucial for mitigating risks and safeguarding the welfare of laboratory personnel (Friend & Kohn, 2018).

PRACTICAL AND THEORETICAL IMPLICATIONS

The integration of statistical injury analytics with Failure Modes and Effects Analysis (FMEA) substantially enhances safety priorities in the TIC industry. This method integrates empirical injury data with a systematic risk assessment technique, facilitating the more efficient identification, evaluation, and mitigation of critical hazards, hence offering a more defined framework for safety measures. This has significant theoretical and practical ramifications, especially for ISO 45001 risk management systems and ISO/IEC 17025 laboratory accreditation standards, as well as for the future of predictive safety analytics in TIC companies.

This study's findings highlight the importance of integrating FMEA with injury analytics to prioritize risks based on quantitative data, in alignment with ISO 45001's emphasis on a risk based approach to occupational health and safety. This integration enhances the hazard identification and risk assessment elements of ISO 45001, facilitating more informed decision making and resource allocation. By recognizing high risk failure modes, including chemical exposure and slip and fall incidents, TIC firms can execute specific safety interventions at the engineering, administrative, and PPE levels, thereby enhancing compliance and promoting a continuous improvement cycle (Ajslev et al. 2022; Bensonch et al. 2022).

Within the framework of ISO/IEC 17025, which regulates laboratory competence and safety, the application of predictive analytics via FMEA can improve safety management by preemptively mitigating hazards prior to their occurrence. This predictive methodology conforms to the framework's stipulations for risk management and quality assurance, allowing laboratories to fulfill safety criteria while enhancing operational efficiency and safety performance. By utilizing FMEA in conjunction with injury data, laboratories can implement preventative measures and oversee safety processes to improve both efficacy and dependability (Nasrallah et al. 2023; Golkhani et al. 2018).

TIC firms can employ predictive safety analytics to mitigate the recurrence of identified failure modes. By employing data driven algorithms to predict possible safety hazards, such as chemical exposure or equipment malfunction, companies can take preemptive measures to avert catastrophes. This methodology not only conforms to the continuous improvement tenets of ISO 45001 but also facilitates more accurate safety protocols, diminishing dependence on reactive measures and augmenting the general safety culture (Sehsah et al. 2020; Friend & Kohn, 2018). The implementation of predictive models enables TIC organizations to anticipate potential risks, enhancing safety processes and ensuring compliance with ISO/IEC 17025 standards for laboratory safety (Levine et al. 2024; Gao & Sultan 2023).

TABLE 14. Hierarchy of Controls for Identified Failure Modes

Activity/ Process	Failure Mode	Root Cause	Failure Effect	Recommended Hierarchy of Controls
Laboratory Testing Process (Testing Domain)	Exposure from highly corrosive or boiling liquids during heating or distillation process	Insufficient PPEs for extreme heat and chemical reaction	Burn injuries in the Upper Extremities	Elimination: Replace hazardous chemicals with safer alternatives to reduce the need for protective gear. Substitution: Use less corrosive chemicals to minimize burn risks. Engineering: Install ventilation systems like fume hoods to capture chemical fumes. Administrative: Conduct regular PPE training and safety audits to ensure compliance. PPE: Provide gloves, goggles, and face shields to protect against exposure.
Laboratory Testing & Inspection Process (Laboratory & Office Location)	Injuries obtains from falls, trips and slips	Wet floor condition and poor ground condition (uneven flooring)	Abrasion in the Lower Extremities	Elimination: Remove obstacles such as cords or debris to clear walkways. Substitution: Replace slippery flooring with slip resistant materials to reduce fall risk. Engineering: Install proper drainage systems to avoid water accumulation. Administrative: Implement regular cleaning protocols and inspections for floor hazards. PPE: Require slip resistant footwear to protect employees from falls.
Laboratory Testing Process (Testing Domain)	Ingestion of chemicals	Improper use or insufficient PPEs	Breathing difficulty, inflammation of affected area, vomiting, organ failure	Elimination: Remove toxic chemicals from the laboratory process to avoid ingestion. Substitution: Replace hazardous substances with non toxic alternatives. Engineering: Use automated chemical dispensers and closed systems to limit exposure. Administrative: Enforce strict safety procedures for chemical handling. PPE: Provide full face shields, respirators, and gloves to prevent ingestion.
Laboratory Testing Process (Testing Domain)	Exposure from highly corrosive chemical spilling from equipment	Contact with chemicals leaking from equipment	Burn in the Upper Extremities	Elimination: Replace faulty equipment to prevent leaks. Substitution: Use safer materials less prone to leakage. Engineering: Install leak detection systems and automatic shutoff valves. Administrative: Conduct regular maintenance checks and safety training. PPE: Provide chemical resistant gloves and suits to prevent exposure.
Laboratory Testing Process (Testing Domain)	Injuries from accidental encounter of broken glassware or equipment parts	Accidental contact with broken glassware or equipment parts when washing or testing	Laceration/Cut/ Puncture in the Upper Extremities	Elimination: Use shatterproof alternatives to reduce the risk of glass breakage. Substitution: Replace glassware with durable plastic options. Engineering: Implement safe handling equipment to secure glassware during testing. Administrative: Provide training on proper handling techniques for fragile equipment. PPE: Supply cut resistant gloves to protect workers from sharp objects.

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Laboratory Testing Process (Testing Domain)	Exposure from highly corrosive or boiling liquids during heating or distillation process	Conduct of testing despite of defective equipment; Improper use or maintenance of equipment	Burn injuries in the Upper Extremities	Elimination: Use safer, non toxic chemicals during heating or distillation. Substitution: Replace volatile chemicals with safer alternatives. Engineering: Implement containment systems to prevent spills and exposure. Administrative: Offer comprehensive chemical handling training for staff. PPE: Provide chemical resistant gloves and full body suits for protection.
Laboratory Testing Process (Testing Domain)	Injuries from splashing of chemicals to the eyes	Improper use or insufficient PPEs	Eye and Vision Injuries	Elimination: Remove outdated or malfunctioning equipment that could cause splashes. Substitution: Replace hazardous equipment with safer, modern alternatives. Engineering: Install safety switches and grounding systems to prevent malfunctions. Administrative: Regularly check and ensure that all safety equipment is functional. PPE: Ensure the use of goggles or face shields to protect eyes from splashes.
Laboratory Testing Process (Testing Domain)	Exposure from reactive chemical disposed in the waste bins	Improper waste disposal system	Burn injuries in the Upper or Lower Extremities	Elimination: Use non reactive chemicals that do not pose disposal risks. Substitution: Replace hazardous chemicals with safer disposal options. Engineering: Implement fire suppression systems and proper waste containment strategies. Administrative: Train staff on safe waste disposal practices and fire drills. PPE: Provide flame retardant clothing for workers handling chemical waste.
Laboratory Testing & Inspection Process (Laboratory & Office Location)	Injuries from contact with sharp objects or edges	Accidental contact with sharp edges like door frames	Puncture, Laceration, Avulsion	Elimination: Remove or modify sharp edges to prevent injuries. Substitution: Use rounded or padded edges on furniture and equipment. Engineering: Install edge guards and safety barriers around sharp objects. Administrative: Establish safe working procedures and conduct safety audits. PPE: Provide cut resistant gloves to reduce the risk of injury.
Laboratory Testing Process (Testing Domain)	Injuries from contact with broken glasswares or equipment	Lack of attention during testing	Laceration/Cut/ Puncture in the Upper Extremities	Elimination: Use safer, non breakable materials for testing. Substitution: Replace glassware with plastic or other durable materials. Engineering: Install protective equipment such as safety shields. Administrative: Enforce SOPs for careful handling and ensure supervision during critical tasks. PPE: Provide cut resistant gloves to protect workers from injuries caused by glassware.

Sources: (Government of Canada, 2025; CDC, n.d.; OSHA, 2023; OSHA, n.d.; NAP, n.d.; Engineering Controls for Laboratory Safety, n.d.; EHS, 2024; Lab Safety Hazard, n.d.; Science Equip, n.d.; Goldone, n.d.; Carey et al. 2018, Elder et al. n.d.; Trevor Henderson, n.d.; National Research Council (US), 2011; Laboratory Chemical Waste Management, n.d.)

CONCLUSION

This study advances occupational safety analytics by demonstrating that coupling statistical injury correlations with FMEA based prioritization yields a more proactive risk management model for TIC laboratories. It underscores the importance of integrating empirical injury data with established risk assessment frameworks to enhance safety measures in the Testing, Inspection, and Certification (TIC) industry. Unlike previous studies, this research focuses specifically on the safety challenges within TIC laboratories, offering valuable insights into the characteristics of injuries, their root causes, and the contributing factors behind unsafe conditions in the workplace.

The analysis of 52 injury cases reveals that female employees predominantly experience minor injuries, while male employees are more likely to suffer injuries that result in lost time and require medical attention. Moreover, the study highlights that employees aged 20 29 are more susceptible to injuries, particularly those caused by exposure incidents in laboratory environments. Unsafe conditions, especially those involving chemical spills, reactions, and thermal exposures, are identified as the primary contributors to injury incidents. Additionally, improper use or lack of personal protective equipment (PPE) accounts for significant eye injuries, while poor posture and body positioning contribute to traumatic injuries. These findings emphasize the critical role of a robust laboratory safety management program and the need for improved risk mitigation strategies, including enhanced PPE usage and heightened employee awareness of workplace hazards.

This study makes a significant contribution to the field by integrating statistical injury data with the Failure Modes and Effects Analysis (FMEA), providing a more data driven and systematic approach to safety prioritization in the TIC industry. The application of the Hierarchy of Controls to the identified failure modes offers practical recommendations for mitigating risks and enhancing safety protocols, with a particular focus on engineering controls, administrative measures, and the consistent use of PPE.

Future research could enhance this study by incorporating machine learning techniques to forecast injury trends and detect upcoming safety issues using historical data. Furthermore, multi site validation of the findings would augment the generalizability of the data and offer a more comprehensive understanding of safety concerns among diverse TIC organizations. Integrating ergonomic considerations into future investigations may enhance safety measures by tackling concerns associated with personnel posture and equipment design. These research paths will enhance safety models and aid in the advancement of proactive, data driven safety policies within the TIC industry.

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DECLARATION OF COMPETING INTEREST

None.

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