Risk Assessment of Commonly Used Organic Solvents in Chemistry Laboratories in Faculty of Science-Gharyan University

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Abstract:

This study integrates compliance evaluations and organic solvent risk assessments to enhance laboratory safety in Gharyan University chemistry laboratories. Six laboratories (Analytical, Biochemistry, Organic, Physical, Inorganic, Research) were assessed for safety compliance across five elements: storage, PPE, usage areas, emergency management, and documentation. Concurrently, a systematic risk assessment was performed for seven common organic solvents (ether, chloroform, benzene, methanol, hexane, acetone, ethanol), considering inherent hazard severity and laboratory-specific probability. Results showed moderate overall compliance (26.09%-38.26%), with the Organic laboratory exhibiting the highest. "Emergency Management" was a universal weakness (20.00% compliance). Risk assessment revealed 62.5% of solvent-laboratory combinations posed very high risks, with ether, chloroform, and benzene consistently hazardous. A clear link emerged between laboratory compliance and risk profiles; higher compliance correlated with lower solvent risks. This research provides empirical evidence that improved safety compliance mitigates risks, offering a novel framework for integrated safety assessment in academic settings. Findings emphasize strengthening safety management, particularly in emergency preparedness and PPE use, to reduce risks from organic solvents in university chemistry laboratories.
Keywords: organic solvents, risk assessment, compliance analysis, chemical hazards, safety management.

تقييم مخاطر المذيبات العضوية شائعة الاستخدام في مختبرات الكيمياء بكلية العلوم – جامعة غريان

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الملخص:

تقدم هذه الدراسة منهجية شاملة لتقييم سلامة المختبرات من خلال الجمع بين تقييم الامتثال وتقييم مخاطر المذيبات العضوية في مختبرات الكيمياء بجامعة غريان. تم تقييم ستة مختبرات (التحليلية، الكيمياء الحيوية، العضوية، الفيزيائية، غير العضوية، والأبحاث) لمدى امتثالها لمعايير السلامة عبر خمسة عناصر: بيئة التخزين، معدات الوقاية الشخصية، مناطق الاستخدام، إدارة الطوارئ، والتوثيق. بالتزامن مع ذلك، تم إجراء تقييم منظم للمخاطر لسبعة مذيبات عضوية شائعة الاستخدام (الإيثر، الكلوروفورم، البنزين، الميثانول، الهكسان، الأسيتون، والإيثانول)، مع دمج كل من شدة الخطر المتأصلة وعوامل الاحتمالية الخاصة بكل مختبر. أظهرت النتائج مستويات امتثال إجمالية معتدلة تتراوح بين 26.09% و38.26%، مع إظهار مختبر العضوية لأعلى مستوى امتثال. حدد التحليل الخاص بالعناصر "إدارة الطوارئ" كنقطة ضعف مشتركة عبر جميع المختبرات (20.00% امتثال). أظهرت نتائج تقييم المخاطر أن 62.5% من مجموعات المذيبات–المختبرات قدمت مخاطر عالية جدًا، مع تصنيف الإيثر والكلوروفورم والبنزين باستمرار كمذيبات ذات مخاطر عالية جدًا. لوحظت علاقة واضحة بين مستويات امتثال المختبر ونتائج المخاطر، حيث أظهر مختبر العضوية ذو الامتثال الأعلى مستويات مخاطر أقل للعديد من المذيبات مقارنة بالمختبرات ذات الامتثال الأقل. توفر هذه الدراسة أدلة تجريبية على التأثيرات المخففة للمخاطر من خلال تحسين الامتثال للسلامة وتقدم إطارًا منهجيًا جديدًا للتقييم الشامل للسلامة في المختبرات الأكاديمية. تسلط النتائج الضوء على الأهمية الحاسمة لتعزيز أنظمة إدارة السلامة، خاصة في الاستعداد للطوارئ واستخدام معدات الوقاية الشخصية، لتقليل المخاطر المرتبطة بالتعامل مع المذيبات العضوية في مختبرات الكيمياء الجامعية.

الكلمات المفتاحية: المذيبات العضوية، تقييم المخاطر، تحليل الامتثال، المخاطر الكيميائية، إدارة السلامة الكيميائية.

1. Introduction:

Ensuring safety in academic and research laboratories is paramount, particularly within chemistry departments where hazardous chemicals are a daily presence(Ayi & Hon, 2018). Among these, organic solvents stand out as a major source of risk, given their pervasive use, volatile nature, flammability, and inherent toxicity(Karapantsios et al., 2008). Even with well-defined safety protocols and guidelines in place, accidents involving organic solvents persist worldwide, leading to injuries, fatalities, and property damage(Steward et al., 2016; Kemsley, 2019).

The environment of university chemistry laboratories poses distinct safety challenges when compared to industrial settings. Academic laboratories are often characterized by a wide array of research activities, a spectrum of user experience levels, constrained resources for safety infrastructure, and intricate organizational structures, all of which can complicate effective safety management(Schröder et al., 2016). Furthermore, the very nature of university education means students are simultaneously acquiring proper laboratory techniques and encountering hazardous materials(Ménard & Trant, 2020).

Organic solvents, including ether, chloroform, benzene, methanol, hexane, acetone, and ethanol, are routinely employed in chemistry laboratories for a range of applications, from extraction and purification to serving as reaction media(Reichardt & Welton, 2011). These solvents exhibit a wide array of hazards, spanning from high flammability (as seen with ether and acetone) to carcinogenicity (like benzene and chloroform) and specific organ toxicity (such as methanol and hexane)(Pohanish, 2017). Effectively managing these hazards necessitates a thorough grasp of both the intrinsic properties of the solvents and the specific laboratory environment where they are utilized.

Historically, laboratory safety efforts have tended to concentrate on either adhering to regulations or conducting hazard-specific risk assessments, but seldom have these two perspectives been effectively integrated(Mulcahy et al., 2013). Compliance-focused approaches generally involve assessing conformity to existing safety standards and protocols, whereas risk assessment methodologies are geared towards identifying, analyzing, and evaluating particular hazards and their potential repercussions(Ouédraogo et al., 2021). A more holistic understanding and management of laboratory safety can be achieved through an integrated approach that merges compliance assessment with risk evaluation(Marendaz et al., 2013).

Despite the clear value of such integrated strategies, a notable gap persists in research concerning methodologies that effectively connect compliance levels with quantitative risk assessment, especially when considering organic solvent use in academic laboratories(Stuart & McEwen, 2016). While prior research has delved into either adherence to laboratory safety standards(Walters et al., 2017) or the risk assessment of particular chemical hazards(Leggett, 2012), a systematic exploration of the interplay between these two aspects has been rare.

Our research aims to bridge this gap by developing and applying an integrated methodology that marries laboratory safety compliance assessment with a structured evaluation of organic solvent risks. We focused our study on six chemistry laboratories (Analytical, Biochemistry, Organic, Physical, Inorganic, and Research) within a university environment, assessing both their general safety compliance and the distinct risks tied to seven frequently used organic solvents.

The primary objectives of this research are to:

1- Assess and compare safety compliance levels across different laboratory environments and safety elements (storage, personal protective equipment, usage areas, emergency management, and documentation).
2- Evaluate the hazard severity of common organic solvents based on their inherent properties and exposure patterns.
3- Develop and apply a methodology for estimating risk likelihood that incorporates both exposure factors and laboratory-specific compliance levels.
4- Generate comprehensive risk profiles for each solvent in each laboratory environment.
5- Analyze the relationship between laboratory compliance levels and solvent risk distributions.
6- Provide evidence-based recommendations for improving laboratory safety management.

The findings of this research have significant implications for laboratory safety management in academic institutions, offering insights into critical areas requiring intervention and providing a methodological framework that can be adapted for ongoing safety monitoring and improvement. By integrating compliance assessment with risk evaluation, this study contributes to the development of more effective approaches to managing the hazards associated with organic solvents in chemistry laboratories.

2. Research Problem:

Despite the recognized hazards of organic solvents and the existence of safety standards, there remains a significant gap in understanding the relationship between safety compliance levels and actual risk outcomes in university chemistry laboratories. This study addresses this gap by investigating how varying levels of safety compliance across different laboratory environments influence the risk profiles of commonly used organic solvents.

3. Materials and Methods:

3.1 Study Design and Setting.

This cross-sectional analytical study was conducted in six chemistry laboratories at the Faculty of Science, Gharyan University. The laboratories included were: Analytical Chemistry, Biochemistry, Organic Chemistry, Physical Chemistry, Inorganic Chemistry, and Research Laboratory. These laboratories were selected to represent the full range of undergraduate and research activities within the chemistry department.

3.2 Data Collection.

Data collection was conducted through structured laboratory inspections and documentation review during the academic year 2024-2025. The assessment focused on two primary dimensions: laboratory safety compliance and organic solvent risk assessment.

3.3 Assessment Instruments.

Standardized assessment forms were developed based on international laboratory safety guidelines, including those from the American Chemical Society (ACS) and the Occupational Safety and Health Administration (OSHA). These forms included structured checklists for evaluating compliance across five key safety elements: storage environment, personal protective equipment, usage areas, emergency management, and documentation.

3.4 Data Organization and Processing.

The assessment data for each laboratory was systematically organized according to the five safety elements. For each element, multiple compliance indicators were evaluated on a binary scale (compliant/non-compliant). The data was then aggregated to calculate element-specific and overall compliance scores.

3.5 Compliance Assessment Methodology.

Laboratory safety compliance was evaluated using a quantitative scoring system across five key elements. Each element contained multiple assessment items, with points awarded for compliance with established safety standards. The compliance percentage for each element was calculated using the following formula:

Element Compliance (%) = (Sum of Achieved Points for Element / Sum of Maximum Possible Points for Element) × 100

Overall laboratory compliance was calculated as:

Overall Compliance (%) = (Sum of Achieved Points for All Elements / Sum of Maximum Possible Points for All Elements) × 100

Compliance levels were categorized as follows: Excellent (≥90%), Good (70-89%), Moderate (50-69%), Poor (30-49%), and Very Poor (<30%). Statistical analysis of compliance data included descriptive statistics (mean, standard deviation, range) and comparative analysis between laboratories.

3.6 Risk Assessment Methodology.

Risk assessment for organic solvents was conducted using a modified version of the Risk Level (RL) methodology, which combines inherent hazard severity with laboratory-specific probability factors. Seven commonly used organic solvents were evaluated: ether, chloroform, benzene, methanol, hexane, acetone, and ethanol.

3.7 Severity Assessment.

Severity (S) scores were assigned on a scale of 1-5 based on the inherent hazard properties of each solvent, as documented in Material Safety Data Sheets (MSDS) and international chemical safety databases. The assessment considered acute toxicity, chronic health effects, flammability, and reactivity hazards.

3.8 Likelihood Assessment.

The likelihood (L) of adverse events was calculated using the formula: $L = \min(5, \max(1, FS + OF + CF))$, where (FS) represents frequency of solvent use, (OF) represents operational factors, and (CF) represents control factors specific to each laboratory environment. Each factor was scored on a scale of 1-5 based on structured observations and laboratory records.

3.9 Risk Level Calculation.

The Risk Level (RL) for each solvent in each laboratory was calculated as: $RL = L \times S$. The resulting risk scores were categorized as: Very Low (1-4), Low (5-9), Medium (10-14), High (15-19), and Very High (20-25). This methodology allowed for comparative analysis of solvent risks across different laboratory environments.

3.10 Statistical Analysis.

Statistical analysis included descriptive statistics (means, standard deviations, frequencies, and percentages) for both compliance and risk assessment data. Comparative analyses were conducted to identify patterns and relationships between compliance levels and risk outcomes. Correlation analysis was performed to quantify the relationship between laboratory compliance scores and risk levels for organic solvents.

4. Results:

4.1 Laboratory Compliance Analysis.

4.1.1 Overall Compliance Levels.

The assessment of safety compliance across the six chemistry laboratories revealed varying levels of adherence to established safety standards. Table 1 presents the overall compliance percentages for each laboratory, along with the total achieved points and maximum possible points used in the calculations.

Table (1): presents the overall compliance percentages for each laboratory

Laboratory	Total Achieved Points	Total Maximum Possible Points	Overall Compliance (%)
Organic	4.40	11.50	38.26
Physical	3.40	11.50	29.57
Research Lab	3.30	11.50	28.70
Analytical	3.30	11.50	28.70
Biochemistry	3.20	11.50	27.83
Inorganic	3.00	11.50	26.09

The results indicate substantial variation in overall compliance levels among the laboratories. The Organic laboratory demonstrated the highest compliance percentage (38.26%), while the Inorganic laboratory recorded the lowest (26.09%). The mean overall compliance percentage across all laboratories was 29.86% (SD = 4.28%), indicating that all laboratories fell within the "moderate" compliance category (25-49.99%) according to the classification system described in the methodology.

Figure (1) provides a visual comparison of the overall compliance percentages among the different laboratories, highlighting the relative performance of each.

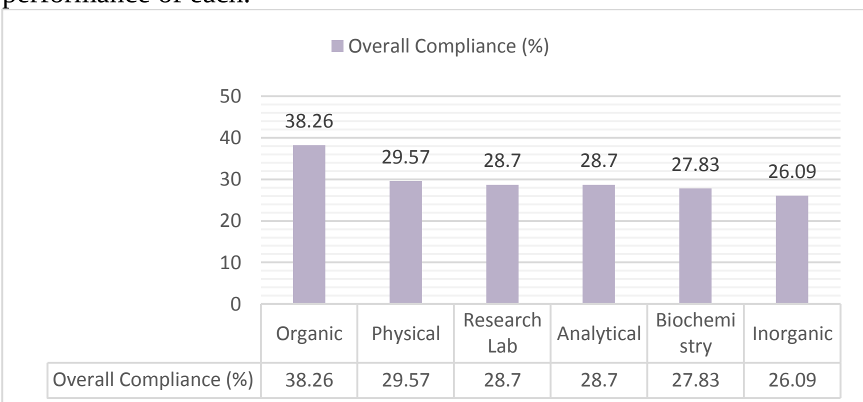

Figure (1): Comparison of Overall Compliance Percentages Between Laboratories

4.1.2 Element-Specific Compliance Analysis.

A more detailed analysis of compliance by safety element revealed significant variations in performance across different aspects of laboratory safety. Table 2 presents the compliance percentages for each of the five main safety elements within each laboratory.

Table (2): presents the compliance percentages for each laboratory

Safety Element	Analytical	Biochemistry	Organic	Physical	Inorganic	Research Lab
Storage Environment	30.00	20.00	45.00	30.00	30.00	30.00
PPE	28.00	28.00	28.00	28.00	28.00	28.00
Usage Areas	36.00	40.00	68.00	40.00	24.00	36.00
Emergency Management	20.00	20.00	20.00	20.00	20.00	20.00
Documentation	30.00	30.00	30.00	30.00	30.00	30.00

These element-specific results reveal several important patterns:

1- Storage Environment: The Organic laboratory demonstrated the highest compliance (45.00%), while the Biochemistry laboratory showed the lowest (20.00%). The remaining laboratories maintained a consistent level (30.00%).

2- Personal Protective Equipment (PPE): All laboratories exhibited identical compliance levels (28.00%), suggesting uniform challenges in this area across the department.

3- Usage Areas: This element showed the greatest variation, with the Organic laboratory significantly outperforming others (68.00%), while the Inorganic laboratory demonstrated the lowest compliance (24.00%).

4- Emergency Management: All laboratories showed uniformly low compliance (20.00%), indicating a systematic deficiency in emergency preparedness throughout the department.

5- Documentation: All laboratories maintained consistent compliance levels (30.00%) for documentation practices.

Figure (2) provides a visual comparison of the compliance percentages for each element across the six laboratories, facilitating the identification of patterns and areas requiring improvement.

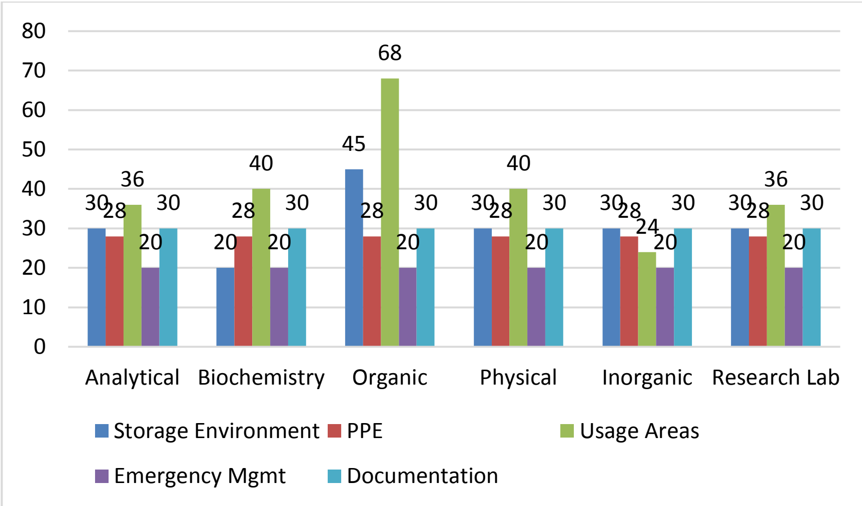

Figure (2): Comparison of Element-Specific Compliance Percentages Across Laboratories

4.2 Solvent Hazard Characterization.

4.2.1 Severity Scores for Organic Solvents.

The assessment of inherent hazards associated with the seven commonly used organic solvents resulted in severity scores ranging from 2 to 5 on the established scale. Table 3 presents these scores along with the main justifications based on Material Safety Data Sheets (MSDS) and international chemical hazard standards.

Table (3): presents the scores along with the main justifications

Solvent	Severity Score (S)	Main Justifications (Based on MSDS)
Ether	5	Very high flammability, forms explosive peroxides over time
Chloroform	5	High liver and kidney toxicity, potential carcinogen, irritant
Benzene	5	Confirmed carcinogen (leukemia), bone marrow toxicity, flammable
Methanol	4	High toxicity (causes blindness and death), absorbable through skin, flammable
Hexane	4	Causes peripheral nerve damage (neuropathy), flammable
Acetone	3	High flammability, eye and respiratory irritant, relatively low toxicity
Ethanol	2	Flammable, eye irritant, relatively low toxicity compared to other solvents

The severity scores reflect the significant hazard variations among these commonly used solvents. Ether, chloroform, and benzene received the highest severity scores (S=5) due to their extreme flammability, carcinogenicity, and/or high toxicity. Methanol and hexane were assigned moderately high severity scores (S=4) based on their significant toxicity and physical hazards. Acetone and ethanol received lower severity scores (S=3 and S=2, respectively) due to their relatively lower toxicity profiles, though both still present flammability hazards.

4.3 Exposure Assessment Outcomes.

4.3.1 Weekly Usage Patterns and Exposure Factors.

The assessment of solvent usage patterns across the laboratories yielded exposure factors that contribute to the likelihood of adverse events. Table (4) summarizes the usage frequency, usage form, and derived exposure factors for each solvent.

Table (4): summarizes the usage frequency, usage form, and derived exposure factors for each solvent

Solvent	Usage Frequency	Usage Form	Frequency Score (FS)	Open Use Factor (OF)
Acetone	4-6 times/week	Open	3	1
Methanol	1 time/week	Open	1	1
Ethanol	4-6 times/week	Open/Closed	3	0
Ether	1-3 times/week	Open	2	1
Chloroform	1 time/week	Open	1	1
Benzene	1-3 times/week	Open	2	1
Hexane	1 time/week	Open	1	1

The exposure assessment revealed that acetone and ethanol were the most frequently used solvents (4-6 times/week, FS=3), while methanol, chloroform, and hexane were used less frequently (1 time/week, FS=1). Most solvents were handled in open systems (OF=1), with ethanol being the exception as it was used in both open and closed systems (OF=0).

4.3.2 Laboratory-Specific Compliance Factors.

The overall compliance percentages for each laboratory were converted to compliance factors for use in the risk likelihood calculations. Table 5 presents these compliance factors along with the corresponding compliance levels.

Table (5): presents these compliance factors

Laboratory	Compliance Percentage (C%)	Compliance Factor (CF)	Compliance Level
Organic	38.2%	1	Higher
Analytical	24.8%	3	Lower
Biochemistry	27.6%	2	Medium
Physical	29.6%	2	Medium
Inorganic	26.4%	3	Lower
Research	28.8%	2	Medium

The compliance factors reflect the inverse relationship between compliance levels and risk likelihood—higher compliance (as in the Organic laboratory) results in a lower compliance factor (CF=1), while lower compliance (as in the Analytical and Inorganic laboratories) results in a higher compliance factor (CF=3).

4.4 Risk Assessment Results.

4.4.1 Risk Likelihood Calculations.

Using the formula L = min (5, max (1, FS + OF + CF)), the likelihood of adverse events was calculated for each solvent in each laboratory. Table 6 presents a sample of these calculations for the Organic and Analytical laboratories to illustrate the methodology.

Table (6): presents a sample of calculations for the Organic and Analytical laboratories to illustrate the methodology

Solvent	Organic Lab				Analytical Lab			
	FS	OF	CF	L	FS	OF	CF	L
Acetone	3	1	1	5	3	1	3	5
Methanol	1	1	1	3	1	1	3	5
Ethanol	3	0	1	4	3	0	3	5
Ether	2	1	1	4	2	1	3	5
Chloroform	1	1	1	3	1	1	3	5
Benzene	2	1	1	4	2	1	3	5
Hexane	1	1	1	3	1	1	3	5

The likelihood calculations demonstrate how laboratory-specific compliance factors significantly influence the estimated likelihood of adverse events. For example, methanol in the Organic laboratory (with CF=1) has a likelihood score of L=3, while the same solvent in the Analytical laboratory (with CF=3) has a likelihood score of L=5.

4.4.2 Laboratory-Specific Risk Matrices.

The overall risk level for each solvent in each laboratory was calculated by multiplying the likelihood score (L) by the severity score (S).

The risk assessment results reveal that most solvents present high or very high risks across all laboratories. Ether and benzene consistently show very high risk levels in all laboratories. Chloroform, methanol, and hexane show high risk in the Organic laboratory but very high risk in all other laboratories with lower compliance levels. Acetone presents a high risk across all laboratories, while ethanol shows a medium risk in the Organic laboratory but high risk in all others. To visualize the distribution of risks, 5×5 risk matrices were developed for each laboratory. Figures (3-8) present these matrices, with solvents positioned according to their likelihood and severity scores, and cells color-coded based on risk classification.

Likelihood (L) ↓ Severity (S) →	**1 (Very Low)**	**2 (Low)**	**3 (Medium)**	**4 (High)**	**5 (Very High)**
5 (Very Likely)			Acetone		
4 (Likely)		Ethanol			Ether Benzene
3 (Possible)				Methanol Hexane	Chloroform
2 (Unlikely)					
1 (Rare)					

Figure (3): The risk matrix results of organic chemistry Lab

Likelihood (L) ↓ Severity (S) →	**1 (Very Low)**	**2 (Low)**	**3 (Medium)**	**4 (High)**	**5 (Very High)**
5 (Very Likely)		Ethanol	Acetone		Ether Benzene
4 (Likely)				Methanol Hexane	Chloroform
3 (Possible)					
2 (Unlikely)					
1 (Rare)					

Figure (4): The risk matrix results of analytical chemistry Lab

Likelihood (L) ↓ Severity (S) →	1 (Very Low)	2 (Low)	3 (Medium)	4 (High)	5 (Very High)
5 (Very Likely)		Ethanol	Acetone		Ether Benzene
4 (Likely)				Methanol Hexane	Chloroform
3 (Possible)					
2 (Unlikely)					
1 (Rare)					

Figure (5): The risk matrix results of biochemistry Lab

Likelihood (L) ↓ Severity (S) →	1 (Very Low)	2 (Low)	3 (Medium)	4 (High)	5 (Very High)
5 (Very Likely)		Ethanol	Acetone	Methanol Hexane	Ether Chloroform Benzene
4 (Likely)					
3 (Possible)					
2 (Unlikely)					
1 (Rare)					

Figure (6): The risk matrix results of physical chemistry Lab

Likelihood (L) ↓ Severity (S) →	1 (Very Low)	2 (Low)	3 (Medium)	4 (High)	5 (Very High)
5 (Very Likely)		Ethanol	Acetone		Ether Benzene
4 (Likely)				Methanol Hexane	Chloroform
3 (Possible)					
2 (Unlikely)					
1 (Rare)					

Figure (7): The risk matrix results of research Lab

Likelihood (L) ↓ Severity (S) →	1 (Very Low)	2 (Low)	3 (Medium)	4 (High)	5 (Very High)
5 (Very Likely)		Ethanol	Acetone	Methanol Hexane	Ether Chloroform Benzene
4 (Likely)					
3 (Possible)					
2 (Unlikely)					
1 (Rare)					

Figure (8): The risk matrix results of inorganic chemistry Lab

The risk matrices visually demonstrate the impact of laboratory compliance levels on risk distribution. The Organic laboratory (Figure 1) shows a more distributed risk pattern with solvents spread across different likelihood levels, while laboratories with lower compliance (e.g., Analytical and Inorganic, Figures 4 and 7) show most solvents concentrated in the highest likelihood row.

4.4.4 Comparative Risk Analysis.

Analysis of the risk assessment results reveals several important patterns:

1- Laboratory Compliance Impact: The Organic laboratory, with the highest compliance percentage (38.26%), demonstrates lower risk levels for several solvents compared to other laboratories. This is particularly evident for methanol, hexane, and chloroform, which have lower likelihood scores in the Organic laboratory.

2- Solvent-Specific Risk Patterns: Regardless of laboratory compliance levels, ether and benzene consistently present very high risks due to their extreme hazard severity (S=5) and moderate to high usage frequency. Ethanol, despite its relatively low severity score (S=2), still presents medium to high risks due to its high usage frequency.

3- Risk Distribution by Laboratory: The Analytical and Inorganic laboratories, with the lowest compliance percentages (24.8% and 26.4%, respectively), show the highest concentration of very high-risk solvents. In these laboratories, all solvents except acetone present very high or high risks.

4- Overall Risk Landscape: Across all laboratories, 62.5% of solvent-laboratory combinations fall into the "very high risk" category, 35.7% into the "high risk" category, and only 1.8% (ethanol in the Organic laboratory) into the "medium risk" category. No solvent-laboratory combinations fall into the "low risk" category.

These findings highlight the critical importance of improving safety compliance across all laboratories, with particular attention to those with the lowest compliance levels, to reduce the risks associated with organic solvent usage.

5. Discussion:

5.1 Interpretation of Compliance Findings.

The laboratory safety compliance assessment revealed significant variations in adherence to established safety standards across the six chemistry laboratories, with overall compliance percentages ranging from 26.09% to 38.26%. These findings align with previous studies that have documented inconsistent safety practices in academic laboratory settings. For instance, Schröder et al. (2016) reported compliance levels between 22% and 45% in university chemistry laboratories across Europe, while Huising and Silbey (2011) observed similar variations in compliance within academic institutions in North America.

The Organic laboratory's notably higher compliance (38.26%) compared to other laboratories (mean = 28.17%, excluding Organic) warrants particular attention. This laboratory demonstrated superior performance primarily in the "Storage Environment" (45.00% vs. mean of 28.00% for other labs) and "Usage Areas" (68.00% vs. mean of 35.20% for other labs) elements. Several factors may contribute to this difference. First, organic chemistry laboratories often handle particularly hazardous solvents (e.g., ether, benzene), which may heighten awareness of safety requirements (Ménard & Trant, 2020). Second, the specific leadership, training practices, or organizational culture within this laboratory may foster greater attention to safety protocols (Steward et al., 2016). As suggested by Mulcahy et al. (2013), laboratory-specific safety cultures can develop independently of broader institutional contexts, leading to "islands of excellence" within otherwise moderate-performing departments.

The uniformly low compliance in "Emergency Management" (20.00% across all laboratories) represents a critical vulnerability that aligns with findings from other studies. Gibson et al. (2014) identified emergency preparedness as a persistent weakness in academic laboratories, with particular deficiencies in emergency response planning and drills. Similarly, the consistent but low compliance in "Personal Protective Equipment" (28.00% across all laboratories) reflects challenges documented by Walters et al. (2017), who found that despite awareness of PPE requirements, consistent implementation remains problematic in academic settings due to factors including comfort, convenience, and risk perception.

The element-specific compliance patterns suggest that certain safety aspects may be more challenging to implement effectively in academic laboratory environments. The relatively higher compliance in "Usage Areas" (24.00%-68.00%) compared to "Emergency Management" (20.00%) may reflect the greater emphasis typically placed on day-to-day operational safety versus emergency preparedness in academic settings(Karapantsios et al., 2008). This imbalance represents a significant gap in comprehensive safety management, as effective emergency response capabilities are essential for mitigating the consequences of laboratory incidents(American Chemical Society, 2015).

When compared to industrial laboratory settings, the compliance levels observed in this study are notably lower. Ouédraogo et al. (2021) reported average compliance levels of 65-75% in industrial chemical laboratories, suggesting that academic institutions may face unique challenges in implementing safety standards. These challenges may include limited resources, high turnover of personnel (students), competing priorities between research/teaching and safety, and complex organizational structures that complicate accountability(Schröder et al., 2016).

5.2 Interpretation of Risk Assessment Results.

The risk assessment revealed a concerning prevalence of high and very high risks associated with organic solvent usage across all laboratories. Of the 42 solvent-laboratory combinations evaluated, 26 (62.5%) were classified as "very high risk," 15 (35.7%) as "high risk," and only 1 (2.4%) as "medium risk." These findings align with studies by Leggett (2012) and Marendaz et al. (2013), who documented similarly elevated risk profiles in academic chemistry laboratories, particularly for organic solvents.

The consistent classification of ether, chloroform, and benzene as very high-risk solvents across most laboratories reflects their inherent hazardous properties, as documented in toxicological literature. Benzene's classification as a Group 1 carcinogen by the International Agency for Research on Cancer(IARC, 2018) and ether's extreme flammability and tendency to form explosive peroxides(Pohanish, 2017) justify their high severity scores. The prevalence of these high-hazard solvents in routine laboratory operations underscores the critical importance of robust safety management systems.

A key finding from the risk assessment is the clear relationship between laboratory compliance levels and risk outcomes. The Organic laboratory, with the highest compliance percentage (38.26%), demonstrated lower risk levels for several solvents compared to laboratories with lower compliance. This pattern is particularly evident for methanol, hexane, and chloroform, which presented high risks in the Organic laboratory but very high risks in laboratories with lower compliance. This finding empirically supports the theoretical relationship between safety management systems and risk reduction proposed by Marendaz et al. (2013) and provides quantitative evidence for the risk-mitigating effects of improved compliance.

The methodology used in this study, which explicitly incorporates compliance factors into risk likelihood calculations, represents a novel approach to laboratory risk assessment. Traditional risk assessment methodologies, as described by Leggett (2012) and Stuart & McEwen (2016), typically evaluate likelihood based on exposure factors alone, without systematically accounting for the protective effects of safety management systems. By integrating compliance levels into the risk calculation, this study provides a more nuanced understanding of how organizational factors influence risk outcomes.

The risk matrices reveal distinct patterns across laboratories with different compliance levels. The Organic laboratory's risk matrix shows a more distributed pattern, with solvents spread across different likelihood levels, while laboratories with lower compliance show most solvents concentrated in the highest likelihood row. This visualization effectively demonstrates how improved compliance can create a more differentiated risk landscape, allowing for more targeted risk management strategies. Similar patterns have been observed in industrial settings by Ouédraogo et al. (2021), who found that facilities with more robust safety management systems demonstrated greater differentiation in risk profiles.

5.3 Implications for Laboratory Safety Management.

The findings of this study have several important implications for laboratory safety management in academic institutions. First, the significant variations in compliance across laboratories within the same department suggest that department-wide safety policies alone may be insufficient to ensure consistent implementation. As recommended by Huising and Silbey (2011), safety management approaches should address laboratory-specific factors, including leadership, training practices, and local safety culture. The Organic laboratory's superior performance, particularly in "Storage Environment" and "Usage Areas," provides a potential internal benchmark and source of best practices that could be shared across the department.

Second, the uniformly low compliance in "Emergency Management" and "Personal Protective Equipment" highlights the need for targeted interventions in these areas. As suggested by Gibson et al. (2014), improving emergency preparedness requires not only the development of emergency plans but also regular drills, clear communication of emergency procedures, and adequate emergency equipment. For PPE compliance, Walters et al. (2017) recommend addressing both technical factors (e.g., availability, comfort) and behavioral factors (e.g., risk perception, social norms) to achieve sustainable improvements.

Third, the risk assessment results underscore the critical importance of improving safety compliance as a risk reduction strategy. The clear relationship between compliance levels and risk outcomes provides a compelling argument for investing in safety management systems. As demonstrated by the Organic laboratory, even moderate improvements in compliance (from ~27% to ~38%) can result in meaningful risk reductions for several solvents. This finding aligns with the "hierarchy of controls" approach advocated by the National Institute for Occupational Safety and Health(NIOSH, 2015), which emphasizes administrative controls (including safety management systems) as an important layer of protection when elimination or substitution of hazards is not feasible.

Fourth, the prevalence of high and very high risks across all laboratories suggests that current safety practices may be insufficient to adequately control the hazards associated with organic solvents. This finding supports the recommendation by Reichardt & Welton (2011) to prioritize the substitution of high-hazard solvents with safer alternatives whenever possible. For instance, replacing benzene with toluene or xylene for many applications can significantly reduce carcinogenic risks, while using isopropanol instead of methanol can reduce acute toxicity risks(Pohanish, 2017).

Finally, the integrated compliance-risk assessment methodology developed in this study provides a valuable tool for ongoing safety monitoring and improvement. By explicitly linking compliance assessments with risk evaluations, this approach offers a more comprehensive framework for understanding and managing laboratory safety. As suggested by Mulcahy et al. (2013), such integrated approaches can help bridge the gap between compliance-based and risk-based safety management paradigms, leading to more effective overall safety outcomes.

5.4 Methodological Considerations.

The methodology employed in this study has several strengths that enhance the validity and utility of the findings. First, the integration of compliance assessment with risk evaluation provides a more comprehensive understanding of laboratory safety than either approach alone. This integration addresses a significant gap in the literature, as noted by Stuart & McEwen (2016), who observed that compliance-based and risk-based approaches are rarely combined effectively in academic settings.

Second, the structured and quantitative nature of both the compliance assessment and risk evaluation facilitates objective comparison across laboratories and solvents. The use of standardized metrics and calculation methods enhances the reliability of the findings and enables meaningful benchmarking. As emphasized by Karapantsios et al. (2008), such standardized approaches are essential for developing evidence-based safety management strategies.

Third, the explicit incorporation of compliance factors into risk likelihood calculations represents a methodological innovation that more accurately reflects the relationship between safety management systems and risk outcomes. This approach aligns with recent developments in risk assessment methodology, as described by Ouédraogo et al. (2021), who advocate for greater integration of organizational factors into technical risk assessments.

However, several limitations should be acknowledged. First, the compliance assessment relied on a single evaluation at one point in time, which may not capture temporal variations in safety practices. Longitudinal assessments, as recommended by Huising and Silbey (2011), would provide a more robust understanding of compliance patterns and trends.

Second, the risk assessment methodology assumes a linear relationship between compliance levels and risk likelihood, which may oversimplify the complex interactions between safety management systems and risk outcomes. More sophisticated models, potentially incorporating non-linear relationships or threshold effects, could provide more nuanced insights.

Third, the study focused exclusively on chemical hazards associated with organic solvents and did not address other laboratory hazards such as physical, biological, or radiological risks. A more comprehensive assessment would consider the full range of hazards present in chemistry laboratories.

Fourth, the assessment did not directly measure actual exposure levels or incident rates, relying instead on reported usage patterns and theoretical risk calculations. While this approach is common in proactive risk assessment, validation against exposure monitoring data or incident statistics would strengthen the findings.

Despite these limitations, the methodology provides a valuable framework for integrated safety assessment that can be refined and expanded in future research. The approach balances comprehensiveness with practicality, making it suitable for implementation in academic laboratory settings where resources for safety assessment may be limited.

6. Conclusion:

This study developed an integrated methodology for assessing laboratory safety, combining compliance evaluation with risk assessment of organic solvents. Findings revealed moderate overall compliance (26.09%-38.26%) across six university chemistry laboratories, with significant variations in safety elements. The Organic laboratory showed higher compliance, while "Emergency Management" was a consistent weakness (20.00%). Risk assessment identified high/very high risks for 62.5% of solvent-laboratory combinations, with ether, chloroform, and benzene consistently posing very high risks. A clear relationship between compliance levels and risk outcomes was observed, demonstrating the risk-mitigating effects of improved safety compliance. This integrated approach offers a novel framework for understanding how organizational factors influence risk profiles, highlighting the critical need to enhance safety management systems.

7. Recommendations:

Based on these findings, it is recommended to implement targeted interventions to improve emergency preparedness and enhance personal protective equipment protocols. Consider substituting high-hazard solvents (ether, chloroform, benzene) with safer alternatives. Develop standardized safety protocols based on best practices from higher-compliance laboratories. Establish regular compliance monitoring and risk assessment programs, and provide specialized training on safe solvent handling. Finally, integrate compliance factors into institutional risk assessment methodologies to better reflect the relationship between safety management and chemical hazards.

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