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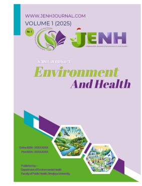

Research Paper

Chemical Health Risk Assessment in Fire and Explosion Incidents in Laboratories (2020-2024): A Literature Review

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Abstract
Working in chemical laboratories poses significant fire and explosion risks, often due to inadequate safety management, such as improper chemical handling and lack of hazard awareness. Chemical Health Risk Assessment (CHRA) is an important method for identifying, evaluating, and managing these risks. This literature review examines the application of CHRA in the context of fire and explosion incidents in laboratories from 2020 to 2024. The objective is to identify key risk factors, evaluate risk assessment methods, and propose recommendations for hazard mitigation. A systematic review of articles from electronic databases was conducted, focusing on risk assessment methods like HAZOP, HFACS-BN, and CHRA in the context of fire and explosion incidents in academic and industrial laboratories. The review found highlight key risk factors include human error, poor chemical management, inadequate storage, and insufficient safety infrastructure. Key mitigation strategies included the implementation of ventilation systems, fire extinguishers, and safety training, were shown to reduce incidents by up to 70%. CHRA was found to be particularly effective in assessing hazardous chemical risks through probability and impact-based approaches. Additionally, combining top-down and bottom-up strategies proved essential for optimizing laboratory safety management. The study concludes that CHRA is a critical tool for identifying and managing fire and explosion risks in laboratories. Strengthening safety infrastructure, enhancing occupational health and safety (OHS) training, and adopting risk-based protocols can significantly improve laboratory safety and reduce potential hazards.

Keywords
chemical health risk assessment, explosion, fire, hazards, laboratory, occupational safety

1. INTRODUCTION

Laboratories play a vital role in research and education, particularly in academic and industrial settings. They serve as spaces for testing theories, developing practical skills, and fostering innovation, making them essential for scientific advancement. Practical activities in laboratories also support hands-on learning, enabling students to deeply understand scientific concepts (Wahab et al., 2021). However, despite their importance, laboratories pose various risks to users, including chemical, biological, physical, ergonomic, and fire or explosion hazards (Zhang et al., 2020b). Laboratory environments are particularly prone to workplace accidents, including fires and explosions, often caused by the use of hazardous chemicals, procedural errors, and inadequate safety management (Bai et al., 2022).

Fire and explosion incidents in laboratories are frequently caused by a combination of factors, such as human error, operational mistakes, improper chemical storage, insufficient risk control measures, and a lack of safety training for laboratory users. Other contributing factors include poor chemical management and inadequate safety infrastructure (Julianto et al., 2024). Major accidents, such as the 2008 fire at the University of California caused by a tert-butyllithium reaction and the 2018 laboratory explosion in Beijing that resulted in three fatalities, highlight the serious risks in laboratory environments when risk management is neglected (Zhang et al., 2020b) (Taheri et al., 2020). Reports indicate that accident rates in academic laboratories are up to 50 times higher than in industrial laboratories (Liu et al., 2023). For example, a study in a Chinese engineering laboratory found that human error was the dominant cause of accidents, while inadequate ventilation and gas leak detectors exacerbated fire risks (Bai et al., 2022). Other studies emphasize the importance of safety training and education to improve operators' awareness of chemical handling (Dehdashti et al., 2024).

Fire and explosion hazards in chemical laboratories are closely linked to the use of flammable and reactive chemicals. Chemicals such as cyclohexane, hydrogen chloride, and Wijs solution require special attention due to their flammable or hazardous properties. These substances are commonly used in laboratory experiments, necessitating strict controls, such as storage in fireproof cabinets and local ventilation systems (Ekinci, 2023). Additionally, the use of personal protective equipment (PPE) and early detection systems is critical to preventing serious incidents, such as explosions caused by chemical vapor accumulation (Ma et al., 2022). Other contributing factors include inadequate ventilation, procedural violations, and improper chemical storage (Dehdashti et al., 2024) (Liu et al., 2023). A lack of safety training and users' unfamiliarity with chemical properties further increase the likelihood of accidents (Nasrallah et al., 2023). The high potential for these risks demands a systematic approach to identifying, evaluating, and managing laboratory hazards.

Several studies have shown that risk assessment methods, such as Chemical Health Risk Assessment (CHRA), Failure Mode and Effect Analysis (FMEA), and Bayesian Network (BN), can help systematically identify hazards and evaluate risks. These methods not only identify hazardous chemicals but also enable more effective risk mitigation measures, such as ventilation management, fire extinguisher installation, and safety training for laboratory users (Taheri et al., 2020) (Zhang et al., 2020a) (Fatemi et al., 2022). Chemical Health Risk Assessment (CHRA), in particular, is a relevant method for managing chemical risks in laboratories. It allows for probability and impact-based risk assessments, covering potential chemical hazards, storage conditions, and work procedures (Ma et al., 2022). In some cases, this method has proven effective in preventing incidents, especially those involving reactive and flammable chemicals (Chen et al., 2020). Furthermore, combining CHRA with other methods, such as HAZOP and HFACS-BN, provides more comprehensive risk analysis (Ekinci, 2023).

Implementing risk-based safety systems like CHRA requires an integrated approach that combines top-down and bottom-up strategies. This approach involves not only management policies but also active participation from laboratory users and technicians in ensuring compliance with safety procedures (Bai et al., 2022). Research shows that combining these approaches can reduce potential incidents by up to 70%, especially when supported by transparent incident reporting systems and ongoing safety training (Chen et al., 2020) (Julianto et al., 2024). However, the implementation of risk assessments in academic laboratories is often limited. Many laboratories lack adequate risk management measures to prevent fires and explosions due to insufficient resources, training, and support systems (Fauziah et al., 2020).

Therefore, it is essential to review the implementation of Chemical Health Risk Assessment (CHRA) as an approach to reducing fire and explosion risks in academic laboratories, particularly from 2020 to 2024. Given the high risks associated with fires and explosions in laboratories, implementing CHRA is a critical step toward creating a safe working environment. Strengthening safety infrastructure, enhancing Occupational Health Safety (OHS) training, and adopting risk-based protocols should be prioritized for institutions with laboratory facilities. This study aims to review risk assessment methods applied in academic laboratories; evaluate the implementation of CHRA concerning fire and explosion incidents; identify common hazards causing these incidents; assess key risk factors; conduct thorough risk assessments; and develop effective mitigation recommendations based on recent literature.

2. METHOD

This study is a literature review aimed at analyzing the implementation of Chemical Health Risk Assessment (CHRA) in managing fire and explosion risks in laboratories. The approach is systematic and structured, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The research is descriptive and qualitative, focusing on the analysis and synthesis of relevant scientific literature. The review is designed to identify key risk factors, evaluate risk assessment methods, and formulate mitigation recommendations.

The literature search was conducted systematically using three major electronic databases: Google Scholar, Science Direct, Elsevier, Scopus, and Semantic Scholar. The search was limited to articles published between 2020 and 2024 to ensure the use of the most recent findings. Keywords used in the search included "Chemical Health Risk Assessment," "Fire and Explosion Risk in Laboratory," "Laboratory Safety Management," "Risk Assessment in Laboratory," "HAZOP," "HFACS-BN," and combinations of these terms.

Inclusion criteria for article selection included: (1) Articles published between 2020 and 2024, (2) Full-text research articles in English or Indonesian, (3) Studies focusing on the implementation of CHRA, HAZOP, HFACS-BN, or related methods in managing fire and explosion risks, and (4) Studies using quantitative, qualitative, or mixed methods. Exclusion criteria included: (1) Systematic reviews, meta-analyses, or expert opinions, (2) Articles addressing risks outside the laboratory context, and (3) Studies with incomplete or irrelevant data.

Article selection was conducted in four stages: initial identification based on keywords, title and abstract screening, full-text evaluation, and data extraction using a prepared review matrix. The review matrix was designed to collect important information from each article, including author names, publication year, article title, research objectives, methods, key findings, and research implications. A total of 23 articles met all criteria and were included in the review.

The selected literature was analyzed using the following steps: (1) Each article was analyzed to identify key risk factors contributing to fire and explosion incidents in laboratories, (2) Articles were evaluated to determine the risk assessment methods used, such as CHRA for hazardous chemicals, HAZOP for operational deviations, and HFACS-BN for human factor analysis. The analysis results were categorized into three main themes: Key risk factors in laboratories, Effectiveness of risk assessment methods, and Recommended mitigation strategies.

3. RESULTS

Based on the analysis of 23 articles that met the inclusion criteria, several key findings can be identified as the application of Chemical Health Risk Assessment (CHRA) in managing fire and explosion risks in the laboratory. The analysis revealed that the level of application of laboratory safety management varies among institutions in terms of preventing fire and explosion risks in the laboratory. The application of CHRA in laboratory risk management showed variations in effectiveness. The percentage of institutions that implemented CHRA showed a higher safety risk of 55-70% compared to institutions that emphasized less on safety training (30-45%).

Factors influencing the effectiveness of CHRA implementation as well as management commitment really need support from top management was a key driver of successful implementation, resource availability required for access to adequate funding and personnel improved risk management efficiency, and the quality of safety infrastructure in the Laboratory such as good ventilation and early detection systems are very important to deal with the risk of fire.

Further analysis identified the major risk factors contributing to fire and explosion incidents in laboratories were human error due to lack of training and non-compliance with standard operating procedures (SOPs), improper storage of reactive or flammable chemicals, which poses significant risks, and the absence of safety equipment such as lack of fire alarms and ventilation systems further increasing the risk of fire and explosion incidents.

Some components of laboratory safety management still need improvement such as fire detection and alarm systems where the average compliance level for this is only around 40-50% in most of the laboratories studied; evacuation procedures and emergency exits at the implementation level only reach 50% which requires more routine updates and training; standard safety documentation which is only around 45% shows the unpreparedness of the institution for standard safety.

Mitigation efforts for handling laboratory accidents, especially fires and explosions, can be done through safety training and K3 awareness based on simulations, which are considered capable of increasing preparedness for incidents by 38%; while strengthening safety infrastructure such as installing local ventilation systems, fire alarms and APARs must be a priority in laboratory management; and conducting periodic safety audits is something that is very important for institutions to do.

4. DISCUSSION

Chemical Health Risk Assessment (CHRA) is a systematic, science-based method designed to identify, evaluate, and manage risks associated with chemical use in laboratories. Based on the literature, CHRA implementation has proven effective in improving laboratory safety, particularly in preventing fire and explosion incidents. However, its effectiveness depends on the quality of implementation and institutional commitment. Institutions with integrated safety management and a strong commitment to safety training showed higher CHRA implementation rates, with up to 70% success in reducing incident risks.

Research by (Ma et al., 2022) demonstrated that CHRA implementation is highly effective in identifying and reducing fire and explosion risks in laboratories. CHRA uses a probability-based approach to assess hazardous chemicals and provides strategic recommendations for immediate implementation. Conversely, laboratories without strong commitment often face challenges in implementing mitigation measures, increasing potential hazards (Ma et al., 2022).

Studies by (Ekinci, 2023) revealed that industrial laboratories had higher safety implementation rates compared to educational laboratories. Compliance with safety standards in industrial laboratories ranged from 70-85%, while educational laboratories achieved only 40-60%. (Shu et al., 2020) noted that CHRA implementation was often uneven in small-scale or educational laboratories due to budget constraints and a lack of competent personnel. Studie by [8] found that many laboratories did not fully utilize CHRA due to a lack of expertise and infrastructure. (Bai et al., 2022) also found that laboratories with limited resources faced higher risks due to poor chemical management and inadequate fire detection systems.

Key factors contributing to high fire and explosion risks in laboratories include a) Human Error: Mistakes in chemical handling, SOP violations, and a lack of hazard awareness. Studies show that 60% of incidents are caused by human error (Bai et al., 2022); b) Inadequate Safety Training: Many laboratories lack regular OHS training for staff and students. (Zhou et al., 2020) reported that only 40% of laboratories conducted regular OHS training; c) Lack of Safety Audits: Institutions that did not conduct regular safety audits had lower preparedness levels (Bai et al., 2022); d) Poor Documentation: Approximately 45% of laboratories lacked standardized safety procedures (Chen et al., 2020); e) Inadequate Safety Infrastructure: Many laboratories lacked proper ventilation, fire alarms, and fire extinguishers (Shu et al., 2021); f) Improper Chemical Storage: Improper storage of reactive or flammable chemicals was a major cause of incidents (Ma et al., 2022).

The discussion highlights the importance of CHRA implementation in reducing fire and explosion risks in laboratories. However, challenges such as human error, limited infrastructure, and insufficient training and documentation must be addressed. Institutions should enhance safety training, strengthen infrastructure, and adopt modern technologies to support better risk management.

5. CONCLUSION

Based on the literature review, fire and explosion incidents in laboratories pose serious threats that require greater attention to safety management. The implementation of Chemical Health Risk Assessment (CHRA) has proven effective in identifying, evaluating, and managing chemical risks in laboratories. Key risk factors include procedural non-compliance, insufficient safety training, poor chemical management, and inadequate safety infrastructure such as detection and ventilation systems.

The analysis shows varying levels of compliance with safety standards, with some institutions demonstrating good preparedness while others face significant shortcomings. This study emphasizes the importance of top management commitment, regular safety audits, and ongoing training in improving laboratory safety. Modern technologies, such as IoT-based fire detection systems and digital documentation, can enhance risk mitigation efforts.

To support the implementation of safety measures and create a safe and productive work environment, the following recommendations are (1) implement CHRA in all laboratories to identify potential hazards and develop risk-based mitigation plans, (2) conduct regular safety training to improve staff awareness and preparedness for potential incidents, (3) perform safety audits at least twice a year to ensure compliance with safety protocols and identify weaknesses, (4) ensure adequate safety infrastructure, including proper ventilation, early fire detection systems, and personal protective equipment (PPE), (5) demonstrate strong commitment from top management by providing sufficient financial and human resources to support safety programs, and (6) enforce stricter regulations by government and regulatory bodies, including penalties for non-compliance with safety standards.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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