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Review Article

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Chemical Laboratory and Process Safety in Research and Industrial Settings: A Critical Review of Hazard Identification, Risk Assessment, and Safety Culture Development

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Abstract: Chemical laboratories and industrial process environments pose a high risk of accidents due to the continuous handling of hazardous materials, the use of complex equipment, and fluctuations in operational conditions. Despite existing safety regulations, standard operating procedures, and engineering controls, chemical accidents still occur in academic research laboratories and industrial settings. This critical review scrutinizes chemical laboratory and process safety through three interrelated perspectives: hazard identification, risk assessment, and the development of a safety culture. It draws on established literature and structured safety management frameworks, such as Hazard Identification, Risk Assessment, and Risk Control (HIRARC). The review evaluates commonly used hazard identification approaches, such as task-based analyses, inspections, checklists, and chemical hazard reviews, emphasizing their effectiveness and limitations in capturing non-routine, dynamic, and cumulative risks. Qualitative, semi-quantitative, and quantitative risk assessment techniques are examined with respect to their practicality, subjectivity, and reliability in both research and industrial contexts. The discussion highlights safety culture as an important factor in determining the long-term effectiveness of safety systems. Leadership commitment, training, communication, and worker engagement have been critically evaluated and identified as significant factors influencing safe behaviour and risk perception. By comparing academic and industrial environments, the review highlights persistent gaps. It concludes that, for sustainable chemical safety, integrating systematic risk management frameworks with a strong, context-sensitive safety culture grounded in continuous learning and shared responsibility is essential.

Keywords: Chemical laboratory safety, Process safety management, Hazard identification, Risk assessment, Safety culture, HIRARC framework.

INTRODUCTION

Chemical laboratories and industrial process facilities are important to technological development, scientific advancement, and economic growth, yet they operate in environments with inherent, often unavoidable hazards (Wang *et al*., 2025). The day-to-day use of hazardous chemicals (poisonous, flammable, corrosive, and reactive), along with pressurized systems, high-temperature reactions, electrical equipment, and specialized analytical instruments, exposes laboratory technicians and plant operators to various risks (Fatemi *et al*., 2022). Historical examinations of chemical accidents have consistently shown that, despite advances in chemical knowledge and safety technology, these working conditions remain prone to incidents such as fires, explosions, acute toxic exposures, and long-term occupational health effects (Palacios *et al*., 2024). In industrial settings, chemical safety has significantly improved as a result of major accident investigations and regulatory responses. This has led to the development of structured process safety management systems (Behie *et al*., 2020). These systems highlight proactive hazard identification, comprehensive risk assessment, and the implementation of multiple safety measures at all stages of chemical process development, from initial design through to full operational capacity (Ahmad *et al*., 2019; Soltanzadeh *et al*., 2024). Despite all this, there are incidents in the industrial sector that are linked to organizational problems, poor change management, and a decline in safety culture, rather than to technical deficiencies (Gonyora and Ventura-Medina, 2024). This reveals chemical safety as a socio-technical challenge that is more complex than an engineering problem.

Academic and research laboratories present a distinct yet equally important safety context. Laboratory safety is often perceived as less hazardous than in industrial processes. However, evidence shows that accident rates in academic laboratories can be appreciably higher (Kong *et al*., 2021; Nasrallah *et al*., 2022). Research laboratories are characterized by modification to experimental procedures and the development of novel reactions, and by teams that consist primarily of students and junior scientists with limited experience in identifying potential hazards and managing risks (Mugivhisa *et al*., 2021; Nasrallah *et al*., 2023). The academic focus on productivity, publication, and innovation can deliberately deprioritize safety, thereby

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normalizing unsafe practices and relying on subjective risk assessment. To address these challenges, the adoption of structured risk management frameworks such as Hazard Identification, Risk Assessment, and Risk Control (HIRARC) has become more prevalent in both academic and industrial settings (Wahab *et al*., 2021). The main goal of these frameworks is to provide a systematic way to identify hazards related to activities, materials, and equipment, assess the likelihood and severity of potential harm, and select appropriate control measures through risk prioritization. Although HIRARC and similar methods yield practical benefits through their direct approach and versatility, their effectiveness depends highly on the rigor of application and the skills of individuals performing the assessments (Adikwu *et al*., 2025). Typically, risk assessments are treated as fixed documentation processes rather than dynamic tools that guide daily decisions and influence experimental planning.

The limitations of hazard identification and risk assessment tools have highlighted the essential role of organizational and cultural factors in chemical safety (Dasgupta and Islam, 2024). Safety culture, characterized by shared values, beliefs, attitudes, and behaviours concerning safety, has been recognized as a significant factor influencing the operation of risk management systems (Danso *et al*., 2022). A strong safety culture fosters open communication, increases near-miss reporting, and supports a continuous learning process, whereas a weak safety culture may violate rules and discourage proactive hazard reporting. In academic laboratories, high personnel turnover and hierarchical power structures can make it more challenging to develop a safety culture. In the industry, production pressures and complacency can undermine the established safety system (Sussman *et al*., 2023). Therefore, a thorough evaluation of the chemical laboratory and process safety is necessary. This review aims to synthesize and critically assess the existing literature on these interrelated issues, compare practices in laboratories and industries, identify ongoing gaps, and emphasize emerging green approaches to chemical safety.

HAZARD IDENTIFICATION IN CHEMICAL LABORATORIES AND INDUSTRIAL PROCESSES

Hazard identification is the basis upon which every safety management system is built. In laboratories, the main hazards include highly toxic, flammable, or reactive chemicals; high-pressure systems; electrical equipment; and ergonomic risks (Abedsoltan and Shiflett, 2024). Research has shown that the individual and experience-dependent nature of laboratory hazard identification contributes to inconsistencies and to the failure to recognize non-obvious hazards (Liu *et al*., 2023). On the other hand, industrial process environments rely on various hazard identification methods, including checklists, job safety analysis, and systematic reviews, during process design and operation. The HIRARC framework offers an active approach to identifying hazards associated with tasks, materials, and equipment before incidents occur. However, literature indicates that industrial hazard identification can become routine, so emergent risks may not be captured during non-routine operations such as maintenance or process modification (Zhang *et al*., 2024; Arthur and Annankra, 2025). One of the identified gaps in both situations is the lack of attention to combined and cumulative hazards. Experimental studies show that scientists study hazards in isolation, whereas industrial studies may divide risks by processing unit (Wang *et al*., 2020). Such fragmentation can hinder the interactions among chemical, physical, and human factors that lead to major accidents.

RISK ASSESSMENT APPROACHES

Risk assessment techniques (Figure 1) translate perceived hazards into prioritized actions. In academic laboratories, qualitative risk assessment techniques are prevalent and typically rely on risk matrices that combine likelihood and impact (Vaezi *et al*., 2023). Although these methods are user-friendly and easy to apply, academic papers criticize their subjectivity and reliance on users' evaluations, especially among novice students and junior researchers. In industrial environments, semi-quantitative risk assessment methods that follow HIRARC principles are more widely used. These approaches assign numerical ratings to likelihood, severity, and exposure, allowing those ratings to be grouped by tasks and processes. Industrial case studies have shown that such methods lead to greater consistency and documentation (Rupiwardani *et al*., 2022; Yunita *et al*., 2024). Critics maintain that assigning numerical scores can foster overconfidence in the results and may not accurately reflect improbable but severe events (Schwarz *et al*., 2019). In both domains, risk assessments are often treated as static documents rather than living processes.

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Reviewed studies highlight that risks change with modifications to experimental design, scale-up, personnel, and operating conditions (Furlong *et al*., 2025). Failing to update risk assessments has been associated with repeated incidents involving hazards that were already deemed controlled. Recent applications of artificial intelligence and machine learning in mining operations demonstrate enhanced hazard prediction and accident prevention, highlighting that data-driven tools can improve traditional risk assessment methods in chemical safety management (Arthur *et al*., 2025).

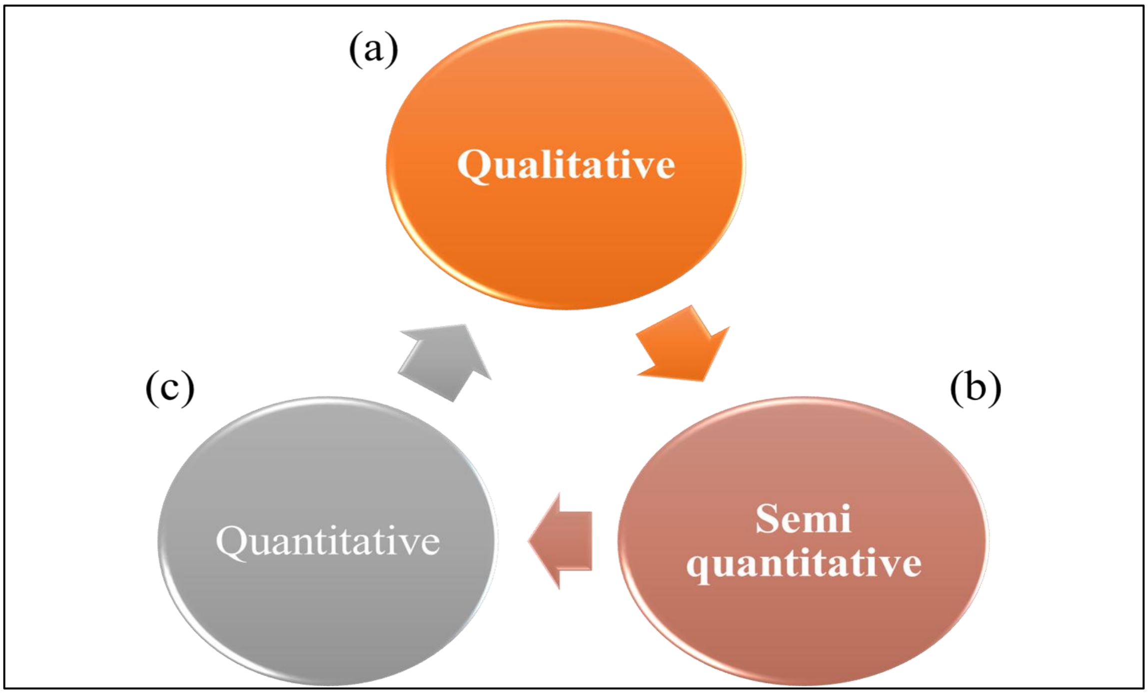

Figure 1: Schematic diagram of risk assessment approaches

RISK CONTROL AND HIERARCHY OF CONTROLS

The hierarchy of controls (Figure 2), comprising elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE), is considered standard practice in the laboratory and industrial safety literature (Omari Shekaftik *et al*., 2023). Elimination and engineering controls are used more in industrial environments because of the dual forces of regulations and positively driven economic factors. In research laboratories, reliance on administrative controls and PPE remains common (Pillai *et al*., 2025). Literature criticizes this practice, arguing that training and PPE are inconsistent in effectiveness and prone to human error (Scott and Unsworth, 2020). Although engineering controls, such as fume hoods and ventilation systems, are in place, their effectiveness is often compromised by poor maintenance or improper use. Studies based on HIRARC indicate that the selection of control measures should align with the results of risk ranking (Henny *et al*., 2025). A consistently observed limitation is the lack of adequate post-implementation evaluation. In both academic laboratory and factory environments, it is often assumed that risks are acceptably managed when controls are in place, and the need for continuous verification and improvement is overlooked (Jogie *et al*., 2025).

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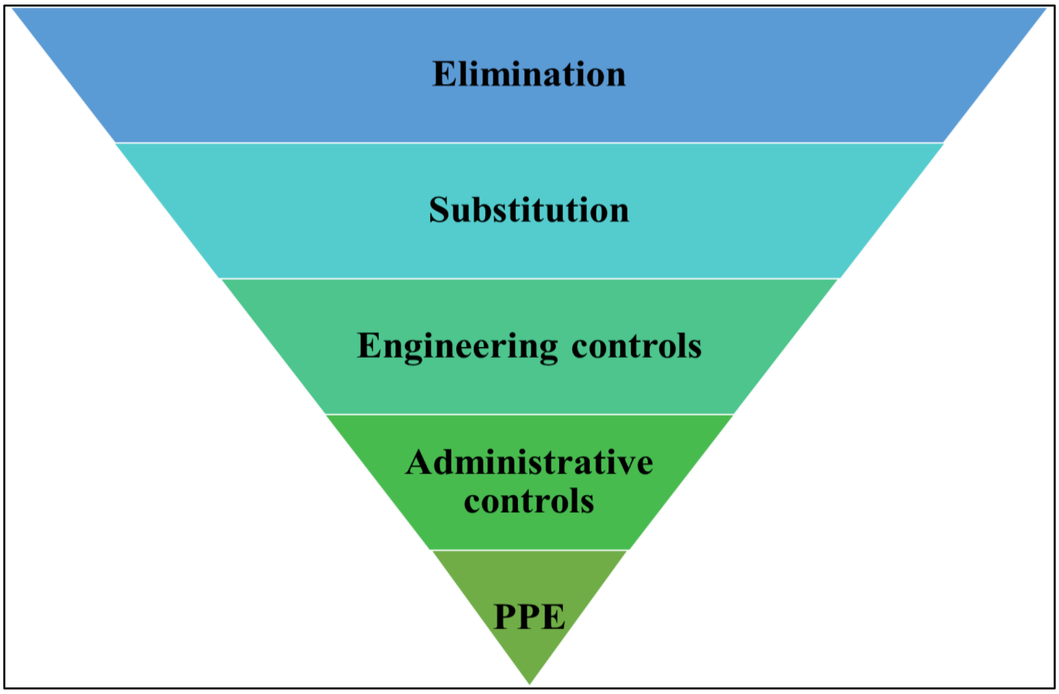

Figure 2: Schematic diagram of hierarchy of controls

SAFETY CULTURE DEVELOPMENT

Safety culture has emerged as one of the most essential factors in determining long-term safety performance. Safety literature consistently distinguishes between compliance-driven and value-driven safety cultures. In academic laboratories, strict hierarchies and continual changes in the student population can adversely affect the safety culture (Lin *et al*., 2024). Safety is often regarded as an obstacle to research output, and as a result, unsafe practices become the norm, according to reports from various studies (Dyreborg *et al*., 2022). Frameworks for industrial safety culture prioritize leaders' commitment, workers' involvement, and open communication. Research based on industrial case studies shows that a strong safety culture positively affects hazard reporting and learning from near misses (Pedrosa *et al*., 2025). However, Literature warns against safety culture initiatives that are superficial and focused on slogans rather than actual change in the system. One key finding from the comparative studies is that the growth of safety culture should be tailored to the specific context (Al-Mekhlafi *et al*., 2025). Directly transferring industrial safety culture models to academic laboratories may fail if educational goals and resource constraints are not considered. However, academics' focus on learning and inquiry makes it possible to integrate safety as a fundamental scientific value rather than an external requirement.

Integration of HIRARC and Safety Culture

Literature consistently highlights the complementary and interdependent relationship between safety culture and technical risk management tools in chemical laboratories and industrial settings (Ezenwa *et al*., 2022). HIRARC provides a formalized safety decision-making process through a systematic, structured framework for hazard identification, risk assessment, and the selection of control measures. However, the effectiveness of the HIRARC methodology is not determined by its inherent characteristics but by users' capabilities and involvement, as well as organizational support. Under such conditions, a lack of a supportive safety culture would most likely reduce HIRARC activities to administrative or compliance-driven exercises with no meaningful impact on daily laboratory practices or operational behaviours (Adrahtas *et al*., 2025).

A positive safety culture requires functional tools that translate shared values and safety consciousness into concrete actions. Without structured tools such as HIRARC, safety culture initiatives may become vague, and the system may rely on informal norms rather than systematic risk-control strategies (Siang *et al*., 2025). Empirical research indicates that incorporating HIRARC into daily laboratory planning, experimental design, and industrial operations promotes proactive risk awareness and collective responsibility and makes communication about hazards easier across

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organizational levels (Harun and Soh). Linking incident reporting and near-miss analysis to formal risk reassessment signifies the integration of continuous learning. However, sustaining this integration over the long term remains difficult, especially in areas where new staff are frequently assigned, research activities are changing, or operational demands are shifting (Al-Mekhlafi *et al*., 2025). Continuous leadership involvement, training, and risk assessment are necessary to keep both the technical framework and the underlying safety culture active, current, and effective, and to meet these challenges (Yazdi, 2025).

CHALLENGES AND RESEARCH GAPS

Literature indicates that specific challenges and gaps remain. The first challenge is that empirical evaluation of lab risk assessment practices remains limited, as most studies rely on self-reported data, checklists, or cross-sectional surveys (Tziakou *et al*., 2023). This limitation prevents determining whether hazard identification and risk assessment tools, including HIRARC, lead to a decrease in accident rates or sustained improvements in safety performance. Few studies have adequately evaluated the long-term effectiveness of the control measures in place, leaving their reliability under changing operational conditions and evolving research activities in question (Ezenwa *et al*., 2022).

Another significant gap is that current industrial risk assessment methodologies cannot scale down to or adapt to small research laboratories (Zhao *et al*., 2023). The industrial framework has been built around stable processes. Academic labs undergo continuous changes across all aspects, including design, materials, and staff, raising questions about the applicability of existing tools without modification or adaptation to the context (Hollá *et al*., 2024). The evaluation of safety culture continues to rely mainly on subjective indicators such as people's opinions and feelings, which are difficult to compare and therefore limit meaningful comparisons not only between institutions but also across sectors.

Future studies should prioritize longitudinal, mixed-methods research to link hazard recognition and risk evaluation to measurable safety outcomes, such as incident counts, near-miss reporting trends, and control effectiveness. It is important to adopt a multidisciplinary approach that integrates chemical safety concepts with human factors engineering, organizational behaviour, and safety management science to develop more durable, flexible, and evidence-based safety frameworks suitable for both laboratory and industrial settings (Yalcin *et al*., 2023).

CONCLUSION

This critical review highlights that chemical laboratories and industrial environments rely on established frameworks for hazard identification and risk assessment. Their effectiveness depends primarily on the quality of implementation and the strength of the surrounding safety culture. Structured tools such as HIRARC provide systematic approaches to identifying hazards, assessing risks, and selecting control measures. However, their impact is diminished when they are treated as administrative requirements rather than active decision-making instruments. Industrial environments benefit from formalized safety management systems but remain vulnerable to procedural complacency and overreliance on documentation. Research laboratories face additional challenges, including high personnel turnover, inconsistent training, evolving experimental activities, and limited supervision. Existing research identifies two main problems that hinder the proper evaluation of risk assessment effectiveness and the development of standardized safety culture assessment methods that would enable organizations to compare their safety performance with that of other organizations. The results show that sustainable chemical safety requires both technical controls and systematic risk management frameworks, which must be implemented through proper safety practices, including active leadership from all employees and ongoing educational programs. Protecting people and the environment requires research and industrial practices to shift from compliance-based safety methods toward active safety systems that rely on continuous assessment of organizational safety procedures.

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