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Review

Enhancing Chemical Laboratory Safety with Hazards Risks Mitigation and Strategic Actions

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Abstract: Chemical laboratories, as the cornerstone of scientific innovation, face inherent risks due to the nature of their operations. Hazards such as flammable, explosive, and corrosive chemicals, combined with high-pressure and high-temperature conditions, present significant safety challenges. Accidents not only jeopardize the health and safety of personnel but also risk equipment damage, environmental pollution, and broader societal impacts. Ensuring a safe laboratory environment demands a multifaceted approach involving all stakeholders. Institutional managers must establish and enforce comprehensive safety management systems, covering chemical storage, equipment handling, and waste disposal. Laboratory directors play a pivotal role in overseeing the implementation of these protocols, ensuring all members are well-trained and compliant. Laboratory personnel, as direct operators, must adhere to safety procedures, utilize protective equipment, and responsibly manage experimental waste. By fostering a culture of safety and collaboration, laboratories can effectively mitigate risks, safeguard research environments, and advance scientific progress without compromising well-being.

Keywords: chemical laboratory safety; hazards and risks; laboratory management; security policies and actions

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1. Introduction

Chemistry laboratories in tertiary educational institutions serve as indispensable hubs for foundational research in chemical engineering, materials chemistry, biochemistry, medicinal chemistry, and pesticide sciences [1–3]. While these facilities play a crucial role in fostering innovation and cultivating students' research skills [4], the rapid global expansion of laboratory infrastructure [5–7] and experimental activities has brought significant safety challenges. The increase in chemical laboratory establishments, coupled with advancements in experimental apparatus and technologies, has intensified the complexity of laboratory operations and heightened the risks associated with chemical experiments [3].

Despite the critical role of chemistry laboratories in advancing scientific research and innovation, the safety management systems and awareness among laboratory personnel have not kept pace with the growing complexity and scale of modern experimental practices. This disparity has led to an alarming rise in catastrophic safety incidents, underscoring the persistent risks inherent in laboratory environments. Notable incidents showed the grave consequences of inadequate safety measures in chemical laboratories [8]. In 2008, a research assistant at the University of California, Los Angeles (UCLA) tragically lost their life following a pyrophoric tert-butyllithium accident [9]. Similarly, in 2015, a hydrogen

gas explosion claimed the life of a postdoctoral researcher at Tsinghua University [10], and in 2018, a high-pressure hydrogen cylinder explosion at the Indian Institute of Science in Bengaluru, India, resulted in the death of a young researcher [11]. These tragedies not only cause profound personal loss but also damage the reputations of academic institutions and hinder the progress of scientific endeavors. Such recurring events underscore the critical need for stringent safety protocols, comprehensive risk management systems, and a pervasive culture of safety consciousness within laboratories.

This review emphasizes the urgent need for robust safety strategies and actionable guidelines to address evolving risks in chemical laboratories. By analyzing current and emerging hazards, it identifies key risks and proposes targeted prevention and management strategies. These measures are vital to safeguarding laboratory personnel, protecting valuable resources, and ensuring the integrity of scientific research. By fostering a culture of safety, this review aims to promote sustainable and responsible scientific innovation while minimizing the incidence of laboratory accidents and their broader societal impacts.

2. Current and Emerging Hazards and Potential Risks

For frontline experimental personnel and laboratory administrators, the paramount task is to identify potential hazardous factors and conduct comprehensive risk assessments. This encompasses understanding the properties of various chemicals, the risks associated with the use of experimental equipment, and the unexpected incidents that may arise during experimental procedures [12,13]. Subsequently, based on the assessment outcomes, targeted management measures should be formulated and implemented, such as refining experimental operation processes, upgrading safety equipment, and enhancing safety training [14,15]. This holistic risk management strategy is crucial for mitigating risks, ensuring the safety of laboratories and personnel, and forming the foundation for maintaining the normal functioning of laboratories and the smooth progression of scientific research [16]. According to aspects such as the sources, nature, and destructiveness, the concealed hazards in chemical laboratories can be classified into the following categories (Table 1).

Table 1. The different types of hazards and corresponding risks.

Types of Hazards		Characteristics and Risks
Chemical hazards	Flammable and pyrophoric substances	These reagents can spontaneously ignite when exposed to air or water; improper storage or use may lead to fires.
	Toxic reagents	Exposure to toxic substances can result in acute or chronic health hazards, potentially leading to pain, liver and kidney damage; certain special reagents may even be carcinogenic, teratogenic, have reproductive or cumulative toxicity.
	Corrosive substances	Contact with such substances may cause harm to the skin and mucous membranes, leading to skin corrosion, edema, or congestion.
	Allergens	Such substances may cause allergic reactions in certain individuals, leading to symptoms such as itching, swelling, and subcutaneous bleeding.
	Psychoactive substance	These substances directly act upon the central nervous system, causing either stimulation or inhibition, and their continuous use can lead to dependence.

Table 1. *Cont.*

Types of Hazards		Characteristics and Risks
Physical hazards	High/low temperature	Improper use of equipment providing high or low temperatures can lead to burns or frostbite.
	High pressure or vacuum	High-pressure gas cylinders, gas steel bottles, pressure reactors, and vacuum equipment may lead to explosions.
	Electrocution	In chemistry laboratories, if a large number of instruments and equipment are not maintained in a timely manner, it may lead to electrical shock accidents.
	Laser and radiation harm	Some chemistry laboratories may use laser equipment or radioactive materials, and extreme caution is required when using them.
	Mechanical injury	Improper handle of heavy objects, high-speed rotating equipment, and sharp instruments can cause injury.
Biological hazards	Microbes	Some microorganisms are pathogenic or infectious. Relevant experiments must be carried out in strict accordance with the standard operating procedures (SOP) to avoid the occurrence of biosafety accidents.
	Macromolecular Allergens	Certain biological macromolecules may possess sensitizing effects among specific populations. Therefore, experiment operators are obliged to take proper personal protective measures.

Chemical hazards: Chemical reagents are used and stored in all chemical laboratories. By accounting for the unique properties of different chemicals and their possible reactivity with each other, chemical hazards may be the major source of safety hazards in chemical laboratories [17]. These related hazards include flammable and pyrophoric substances [18–21]; toxic reagents [21–25]; corrosive substances [26–28]; allergens [29,30]; and psychoactive substance [31–33].

Physical hazards: Throughout the entire process of chemical experiment operations, certain specific equipment or instruments may be used, which could lead to some physical hazards. These hazards include high or low temperature [34,35]; high pressure or vacuum [36–38]; electrocution [39]; mechanical injury [40,41]; laser and radiation harm [42–44].

Biological hazards: Both the enduring popularity of traditional disciplines like medicinal chemistry and the surging synthetic biology in recent years have made it necessary to take biological hazards into account in chemical laboratories, such as microbes [45,46] and macromolecular allergens [47–49].

3. Recommended Strategies and Actions for Different Roles

The frequent occurrence of safety accidents in chemical laboratories nowadays is the consequence of multiple factors acting together [50–52], including the employment of hazardous reagents, non-standardized operations, unreasonable procedures, imprudent behaviors of individuals, and the absence of supervision. Achieving the objectives of laboratory safety is not a task that can be accomplished by an individual or through solitary action; it necessitates a mutual effort and communication among various roles, including experimental personnel, laboratory director, and institutional administrators. It is through this multifaceted collaboration that the likelihood of chemical laboratory safety accidents can be significantly reduced, the severity of accidents can be mitigated, and the well-being of the individuals involved and the environment are safeguarded. In the context of experimental activities, these three entities assume divergent roles and

are guided by varied considerations when addressing laboratory safety. As such, they shoulder their respective responsibilities and duties within the overarching objective of safeguarding laboratory security. In the ensuing sections of this comprehensive review, we will delve into an academic dissection of the roles and responsibilities assumed by these three key constituents in the reduction in safety incidents within chemical laboratories. Furthermore, we shall delineate a comprehensive set of protocols and strategic initiatives that are imperative for all stakeholders to implement in their quest to augment the safety standards within laboratory settings (Figure 1).

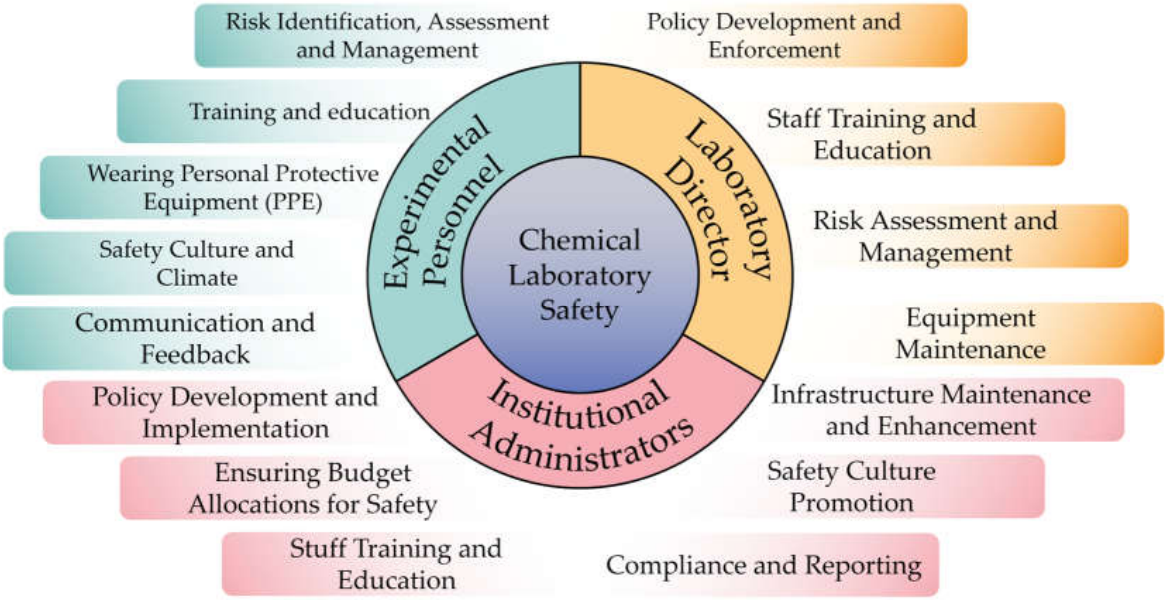


Figure 1. The three roles and their associated tasks in chemical laboratory safety.

3.1. Experimental Personnel

Laboratory personnel are defined as individuals who conduct experimental operations within the space of a chemistry laboratory, including postdoctoral researchers, graduate students, undergraduate students, research assistants, laboratory staff, exchange students, and so on. They utilize chemical reagents and instruments to address scientific queries and facilitate the progression of research projects. The laboratory constitutes their principal site of employment, wherein they typically spend a duration of 10 h or more daily [53]. Extended working hours can lead to a decline in concentration, which in turn increases the likelihood of accidents in hazardous laboratory environments. In the event of an accident, these laboratory personnel are likely to suffer both physical and psychological trauma. Consequently, in light of the potential risks faced by laboratory personnel, several recommendations and specific measures are put forward herein to assist them in reducing the occurrence of laboratory accidents during experimental procedures and safeguarding themselves and others.

3.1.1. Risk Identification, Assessment, and Management

Before commencing experimental procedures, it is essential for laboratory personnel to acquire a detailed understanding of the reagents which might be utilized during the whole experimental cycle, encompassing their physical and chemical properties as well as toxicity. Such information can be retrieved either from the reagent packaging or the accompanying Material Safety Data Sheets (MSDS). Moreover, laboratory personnel are obliged to familiarize themselves with the operating procedures and safety precautions of the machinery and equipment involved in the experiments, along with a clear comprehension of the potential

risks therein. Furthermore, comprehensive risk assessment and management constitute the primary strategies for ensuring the safety of chemical laboratories [54]. By implementing these measures, laboratory personnel can take proactive steps to address potential risks and effectively curtail the occurrence of accidents, thereby enhancing the overall safety and efficiency of the laboratory environment.

3.1.2. Training and Education

Training and education are fundamental to ensuring chemical laboratory safety, with a particular focus on enabling novices to promptly acquire essential safety knowledge and skills [55,56]. Participating in comprehensive safety-related training and education is of great significance. It is not only an effective way for rapid learning but also cultivates a deep sense of safety awareness among laboratory staff. Laboratory personnel should actively engage in various training programs organized either within the laboratory or by the institutional administrators [57]. These programs substantially boost operational confidence, allowing personnel to conduct experiments with a higher level of safety, thus reducing the probability of accidents. Additionally, by continuously emphasizing the importance of safety during training and in the laboratory environment, these initiatives enable individuals to perform their duties more assuredly and precisely, fostering a safety culture that pervades all aspects of laboratory operations.

3.1.3. Wearing Personal Protective Equipment (PPE)

Personal Protective Equipment (PPE) refers to the range of specialized clothing and equipment designed to minimize exposure to severe workplace injuries and health hazards [15,58,59]. PPE encompasses a variety of items such as safety glasses, face shields, hard hats, respirators, gloves, safety harnesses, earplugs, and high-visibility clothing. In the event of a safety incident, PPE serves as the primary protective shield to prevent laboratory personnel from incurring injuries or to mitigate the severity of injuries [60]. Laboratory personnel should possess self-preservation awareness and actively and correctly wear the relevant PPE during experimental procedures. They should also carry out supervision on colleagues involved in experimental operations and remind them to wear PPE properly if they have not. It is important to note that the proper use of PPE is crucial for its effectiveness; improper use may not only fail to provide protection but also introduce new risks. For example, the incorrect use of a gas mask might lead to asphyxiation.

3.1.4. Safety Culture and Climate

Chemical laboratory staff play a crucial role in fostering a robust safety culture and climate, as they ensure that safety is regarded as a shared value and an essential part of lab operations. They must abide by established safety procedures and actively implement relevant safety measures. By actively reporting incidents (both actual and near-misses), they contribute to the improvement of safety procedures. Staff should feel empowered to voice safety concerns without apprehension, creating an environment where safety discussions are promoted and all opinions are valued. Fostering a sense of collective responsibility and pride is essential for cultivating a positive safety climate, in which each team member is responsible for both their own and others' safety. This can be accomplished by conducting team-building activities centered around safety-related issues, led by students and frontline laboratory personnel. For example, these activities might involve extracurricular student organizations focused on safety, laboratory safety teams, and incident learning reports [61–63].

3.1.5. Communication and Feedback

Effective communication is a cornerstone of laboratory safety. It involves the timely and accurate exchange of information about potential hazards, safety procedures, and incident reporting. Frontline laboratory personnel, being at the forefront of laboratory work, have the most direct understanding of the effectiveness of safety measures. For any observed hazards, frontline laboratory personnel should proactively report the discrepancies between management practices and safety protocols under actual conditions [64], which can be carried out via email, telephone, or written correspondence. To ensure the effectiveness of this feedback mechanism, it is necessary to establish a clear communication channel and response system, where the reported issues are promptly addressed and the relevant personnel are informed of the actions taken. This feedback can aid in the improvement and optimization of these measures.

3.2. Laboratory Director

The Laboratory Director assumes the role of principal investigator, tasked not only with the responsibility of steering group members towards the conduct of scientific research and the resolution of scientific quandaries but also with the overarching management of the laboratory, encompassing both day-to-day operations and the safeguarding of laboratory safety protocols. As the custodian of the laboratory's operations, the director is tasked with the responsibility of establishing and preserving a safety regimen and culture that encompasses all facets of the laboratory's activities. This involves a multifaceted approach that includes policy development, staff training, and risk assessment.

3.2.1. Policy Development and Enforcement

Laboratory directors, who are responsible for the overall operation of the laboratory, must possess a profound understanding of the safety regulations and management methods established by the institutional administrators. On this basis, they should formulate corresponding safety management strategies that are customized to the particular conditions within their laboratories. Furthermore, policies, if not implemented with due diligence, are as futile as blank parchment and cannot ensure the laboratory's security. The director has the obligation to demand strict adherence to safety protocols from laboratory personnel and might consider imposing sanctions such as warnings, fines, or suspension of laboratory privileges for violations [15].

3.2.2. Staff Training and Education

One of the director's key responsibilities is ensuring that all staff, including new and experienced members, receive comprehensive training in laboratory safety [65]. This goes beyond initial instruction and involves ongoing refresher courses and updates on new safety protocols. Individuals who do not participate in training earnestly or are absent without reason should be subjected to corresponding punishments. The director is responsible for cultivating a laboratory culture that integrates safety as a fundamental part of research activities, rather than seeing it as an obstacle. It is essential for laboratory personnel to understand that a safe environment is the basis for both personal well-being and experimental efficiency. The director can enhance the understanding and appreciation of safety practices and their significance by organizing sharing sessions, symposia, and interactive forums that engage staff in constructive discussions about safety practices and their importance.

3.2.3. Risk Assessment and Management

The Laboratory Director is charged with proactively identifying potential hazards within the entire laboratory environment and assessing the risks inherent in various laboratory operations [66], such as whether the laboratory space is reasonably divided, whether chemical reagents are stored correctly, and whether special equipment is regularly inspected. During this meticulous risk assessment process, it is imperative to collaborate closely with safety officers or other domain experts. Armed with the assessment findings, the director is entrusted with developing and implementing robust risk mitigation strategies and comprehensive emergency response plans, aiming to reduce the probability of accidents and lessen the severity of their potential consequences [67]. Corresponding measures include providing personal protective equipment and deploying appropriate safety apparatus. Furthermore, regular safety incident drills are crucial in validating the effectiveness of emergency preparedness plans and identifying any potential vulnerabilities that may exist [68–70].

3.2.4. Equipment Maintenance

In chemical laboratories, a variety of equipment is ubiquitous. Regular maintenance and inspection of the equipment are effective measures to ensure laboratory safety and experimental efficiency. The malfunction of the equipment can not only affect the reliability of experimental results and the progress of experiments but also pose safety risks, threatening the people and property within the laboratory environment [71,72]. The laboratory director, as the principal officer for laboratory safety, is obliged to systematically arrange for specialized technicians and equipment manufacturers to conduct quarterly inspections, annual evaluations, and routine maintenance of the laboratory's equipment [73,74].

In their comprehensive role, the Laboratory Director plays a critical part in ensuring the safety of the laboratory environment. By taking a proactive and engaged approach to safety, the director not only upholds the legal and ethical standards but also goes beyond these to create a culture where research can thrive without compromising the well-being of the staff or the community's safety. This leadership is essential, as it shapes the laboratory's success and its standing within the scientific community. The director's actions directly influence the implementation of safety protocols, the quality of research output, and the overall reputation of the lab. Their commitment to safety reflects the lab's commitment to excellence, and it is through this dedication that the director ensures a harmonious balance between scientific progress and the protection of human life and environmental integrity.

3.3. Institutional Administrators

Institutional administrators are responsible for the smooth operation of all laboratories within their institution, with critical responsibility being the assurance of laboratory safety. Typically, an institution houses a significant number of laboratories with diverse types, necessitating a thorough identification of hazardous sources and an assessment of safety risk levels to enhance management efficiency in practical administration. In concrete management practices, institutional administrators can initiate measures from various aspects, such as policy development and implementation, ensuring budget allocations for safety, maintaining infrastructure, conducting emergency procedures and drills, promoting a safety culture, and investigating and reporting incidents.

3.3.1. Policy Development and Implementation

The laboratory safety milieu is contingent upon the meticulous formulation and stringent enforcement of comprehensive safety policies by institutional administrators, which encompass regulations from authoritative entities such as the Occupational Safety and

Health Administration (OSHA) and the Environmental Protection Agency (EPA) [75,76]. These policies are tailored to address the specific needs of laboratories, including a tiered management approach based on laboratory types and internal hazard risk levels, with a particular emphasis on high-risk facilities. The policy framework should also include guidelines for the investigation and handling of accidents, as well as measures for dealing with negligent personnel. The policy framework underscores safety considerations within experimental research and mandates administrators to lead by example, fostering a safety-centric culture where adherence to safety policies becomes a shared value among all members of the laboratory community. The efficacy of policy development and implementation is paramount for ensuring a secure laboratory environment that is compliant with regulatory standards, safeguarding the health and well-being of individuals, and maintaining the integrity of the institution's research endeavors [77,78].

3.3.2. Ensuring Budget Allocations for Safety

Budget allocation is pivotal to laboratory safety, directly impacting the efficacy of safety measures and the well-being of all personnel. Sufficient funding is crucial for ensuring that all necessary safety equipment and protocols are in place and functioning optimally. High-quality personal protective equipment (PPE), for instance, is essential for safeguarding employees from potential hazards. Engaging qualified institutions to handle experimental waste, including chemical and infectious waste, is also an essential requirement [38]. It is imperative to recognize that budget allocation for safety is not a one-time expense but, rather, an ongoing investment. As new safety technologies emerge and safety equipment undergoes technological advancements as well as the evolution of laboratory practices, the budget must be flexible to meet corresponding safety demands. Administrators must advocate for the necessary and adequate resources and demonstrate the return on investment provided by a secure laboratory environment, including reduced downtime, enhanced productivity, and the establishment of a positive reputation for the institution. By prioritizing safety in budget planning, significant risk reduction can be achieved, fostering a secure and efficient laboratory setting.

3.3.3. Stuff Training and Education

Personnel training and education are of utmost importance to laboratory safety, necessitating the development of a comprehensive training program by administrators that encompasses a variety of safety topics tailored to cater to the specific characteristics of laboratories and personnel within the institution. The objective of these training and educational efforts is to equip individuals with the knowledge and skills necessary to respond appropriately to diverse emergency scenarios, including but not limited to fires, chemical spills, equipment malfunctions, and seismic events [56,79]. Such scenarios might involve hazard identification, proper use of safety equipment, emergency evacuation procedures, etc. This is crucial for ensuring that all individuals in the laboratory setting are ready to act quickly and effectively in emergencies, thus minimizing potential harm to both individuals and the integrity of research activities [80–82]. Concurrently, the adoption of new technologies and methodologies like online simulation training and virtual reality-based learning modules in training and education can enhance engagement and effectiveness [83–85].

3.3.4. Infrastructure Maintenance and Enhancement

Institutional administrators bear the crucial responsibility of conducting periodic inspections and maintenance of laboratory buildings and facilities. As vigilant overseers, they are tasked with the upkeep of ventilation systems, electrical systems, potable water systems, alarm systems, access control systems, and other essential infrastructure elements [86]. There is potential for the integration of artificial intelligence (AI) technology into infras-

tructure. For instance, AI-assisted surveillance can continuously monitor the laboratory environment, and the image recognition technology can quickly identify potential safety hazards, while the intelligent early warning systems can provide timely alerts to relevant personnel at the initial signs of incidents [83,85]. Concurrently, it is imperative to subject emergency facilities in communal areas, such as fire control cabinets, emergency showers, and fire hydrants, to a routine of regular inspection, maintenance, and periodic renewal. This encompasses not only the functional testing of these devices but also ensuring their readiness for immediate use, thereby providing necessary protection and support for laboratory personnel in the event of an emergency. These comprehensive measures serve to enhance the safety of the laboratory environment, thus fostering a more reliable and secure work setting for scientific researchers.

3.3.5. Safety Culture Promotion

Cultivating a deeply ingrained and highly safety-conscious cultural environment within an institution is of paramount and enduring significance. In this regard, administrators assume a pivotal and leadership role [87–89]. Firstly, they are duty-bound to actively initiate public discussions on a variety of safety issues, establish seamless communication channels, and encourage every frontline laboratory worker to express their concerns, perspectives, and suggestions for improvement regarding potential safety hazards without apprehension. In response to specific issues raised, administrators must act swiftly and effectively to prevent safety incidents from escalating. Subsequently, for those who consistently adhere to safety regulations and passionately implement safety practices, administrators have the responsibility to provide clear recognition and appropriate incentives. These incentives may encompass material rewards, such as monetary bonuses and tangible prizes, or intangible accolades, such as honorific titles and public commendations. Lastly, institutional administrators can actively advocate for laboratory safety culture initiatives, such as laboratory safety knowledge contests, and lectures. Only through these means can a steadfast and reliable safeguard be provided for the continuous and stable operation of the laboratory, the smooth progression of scientific research, and the life and property security of all associated personnel.

3.3.6. Compliance and Reporting

Within the laboratory management system, ensuring comprehensive and continuous adherence to all pertinent safety regulations is an extremely critical and non-negotiable core responsibility undertaken by administrators [90]. This responsibility encompasses several significant facets of work. Primarily, regarding safety inspection records, administrators are required to establish a stringent, meticulous, and comprehensive recording mechanism to facilitate subsequent traceability and analysis. In the event of any safety incident in the laboratory, regardless of scale, administrators must promptly organize a thorough investigation and compile a standardized accident report document. Furthermore, in documenting the implementation of corrective measures, every corrective action devised in response to issues identified during safety inspections and deficiencies revealed by accidents must be meticulously recorded, including the specific content of the correction, the person responsible, the deadline for the correction, and the final verification of the correction's effectiveness. Through such a comprehensive closed-loop management of safety hazards, not only can clear and transparent historical data on the laboratory's safety status be provided, but it also aids in the timely identification of weak links in management for continuous optimization. This ensures that the laboratory always operates in a safe and compliant manner and effectively prevents the occurrence and escalation of potential safety risks.

4. Conclusions

Chemical laboratories inherently present numerous hazards, including chemical reagents, experimental equipment, and hazardous waste. Identifying risks and implementing preventive measures is essential for all laboratory personnel, particularly novices, to minimize accidents. This process requires continuous vigilance and practice, as even experienced operators cannot guarantee absolute safety. Laboratory safety management is a shared responsibility, with institutional administrators and laboratory directors tasked with establishing and enforcing effective safety protocols. Moreover, fostering a safety-conscious culture encourages all stakeholders to prioritize safety in their experimental planning. Laboratory safety is a persistent and collective goal. By recognizing and fulfilling their responsibilities, all parties can contribute to achieving the shared vision of "zero accidents". Safety serves as the foundation of sustainable scientific advancement, and its prioritization is essential to fostering a secure and reliable laboratory environment for all.

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Abbreviations

The following abbreviations are used in this manuscript:

UCLA	University of California, Los Angeles
SOP	standard operating procedures
MSDS	Material Safety Data Sheets
PPE	Personal Protective Equipment
OSHA	Occupational Safety and Health Administration
EPA	Environmental Protection Agency
AI	Artificial intelligence

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