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TEACHING LABORATORY SAFETY AS A FOUNDATIONAL SCIENTIFIC COMPETENCY: BRIDGING THE GAP FROM HIGHER SECONDARY EDUCATION TO UNDERGRADUATE EDUCATION

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Abstract

Laboratory work is vital to science education, yet safety is often transferred to students as a short list of exclusions closely before an experimentation rather than taught as a designed body of knowledge and practice. This proposed paper examines the instructive significances of the limited, disjointed and often non-assessed treatment of laboratory safety at the higher secondary and undergraduate levels. It draws upon the author's book, Safety Measures in Academic Chemistry Labs, and a focused review of recognised laboratory-safety frameworks and recent chemistry-education research. The analysis identifies a development gap: students may accomplish given experiments without methodically learning hazard recognition, risk assessment, the grading of controls, Safety Data Sheet clarification, chemical exclusion, waste management, emergency response, near-miss reporting or the moral responsibilities of laboratory work. This gap exposes students, teachers, laboratory staff, infrastructure and the environment to avoidable risk. It also deterrents to graduates entering postgraduate study and research, where they are expected to exercise independent judgement. The paper proposes a spiral, competency-based safety curriculum beginning at the higher level. Safety should be obviously taught, practised, evaluated and documented before students undertake independent research. Such integration can *transform safety from rule acquiescence into scientific competence, professional accountability and a maintainable laboratory culture.*

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Keywords: Laboratory safety education, safety culture, risk assessment, undergraduate chemistry, research preparedness

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Introduction

Chemistry is an experimental science. Through laboratory work, students link theory with thought, acquire practical laboratory skills, learn accurate dimension and develop habits of scientific perceptive. The same environment, however, contains chemical, physical, electrical, thermal, biological hazards. Acids, alkalis, volatile solvents, toxic substances, broken glassware, pressurised apparatus, open flames, hot surfaces and electrical equipment can cause injury when hazards are not recognised and risks are not controlled. Laboratory safety is therefore not an voluntary supplement to practical chemistry; it is part of learning how science is sensibly conducted.

In many academic settings, particularly at the higher secondary and undergraduate levels, students receive instructions such as 'wear a laboratory coat', 'do not taste chemicals' and 'handle acids carefully'. These instructions are necessary, but they do not establish safety education. Students may follow a prearranged process under close administration without understanding why mismatched chemicals must be separated, how exposure can occur, how a Safety Data Sheet (SDS) should be understood, why a particular control is selected, or what action is required when an incident or near miss occurs. Because safety is commonly embedded informally within individual practical sessions and is seldom assessed as a distinct competence, its coverage depends heavily on the teacher, the institution and the time available.

The significance is a headway gap. A student can complete years of practical work and still enter a postgraduate laboratory without a systematic framework for recognizing hazards, assessing risk and preparing for emergencies. At the research level, procedures are less prescriptive, unfamiliar substances may be used, experiments may be scaled or modified, and

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researchers are expected to make independent decisions. Deficits that were concealed by close supervision at school or college therefore become serious disadvantages in research. The National Research Council highlights that safety in academic chemical research must be embedded in official values, everyday planning and individual behaviour, while the American Chemical Society (ACS) recognizes safety knowledge and skills as explicit undergraduate learning outcomes (National Research Council; American Chemical Society, Guidelines). These prospects cannot be met through a one-time warning or a signature in a laboratory register.

This paper argues that laboratory safety must be introduced as a structured and measurable learning province at the higher secondary level and developed increasingly throughout undergraduate education. It uses the educational architecture developed in the author's Safety Measures in Academic Chemistry Laboratories—basic rules, hazard communication, risk assessment, personal protective equipment (PPE), safe chemical and equipment handling, emergency response, waste management, good laboratory practices (GLP) and safety culture—to propose a practical curriculum pathway. The central objective is to prepare students not only to avoid accidents in teaching laboratories but also to become competent, responsible and research-ready scientists.

Literature Review

International safety guidance has increasingly moved from rule-based compliance towards risk-based education. The ACS organises chemical safety around RAMP: Recognise hazards, Assess risks, Minimise risks and Prepare for emergencies. Its guidelines for academic institutions state that students should acquire defined safety knowledge and skills by the completion of undergraduate education and apply them throughout their education and professional lives (American Chemical Society, Guidelines). Parallel guidelines for secondary schools recommend progressively developing students' understanding of hazards, risks, appropriate equipment, procedures and emergency response (American Chemical Society, Guidelines for Secondary Schools). This continuity is significant: safety competence should begin before university rather than being postponed until students encounter advanced or research laboratories.

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The National Research Council differentiates a safety culture from mere acquiescence. In a strong culture, safety is a core value, responsibility is shared, incidents and near failures are deliberated, risks are well-thought-out before work begins, and institutional leaders provide the necessary capitals and answerability (National Research Council). Prudent Practices in the Laboratory similarly treats planning, hazard evaluation, control measures, emergency groundwork and responsible chemical management as essential to laboratory work (National Research Council, Prudent Practices). These outlines demonstrate that safety is a mode of scientific thinking: the chemist forestalls penalties, evaluates uncertainty and designs controls before deploying matter.

Recent research specifies that exposure to laboratories do not robotically produce satisfactory safety capability. A 2023 study of university students reported that a considerable quantity did not validate excellent consciousness of laboratory safety, strengthening the distinction between attendance in practical classes and mastery of safety principles (Wu, Yang, and Xu). Other work examining undergraduate discernments, cognizance and attitudes has found incongruities among self-assurance, knowledge and actual safe practice. A person may observe a laboratory as safe or believe that they behave safely while lacking the procedural knowledge needed in an unfamiliar situation (Ayi and Hon). Assessment of safety training in undergraduate education likewise shows uneven inclusion of safety principles and cultural expectations, suggesting that systematic curriculum mapping remains necessary (Zhao et al.).

The literature also supports active and repeated approaches. Safety learning improves when students participate in pre-laboratory risk assessment, hazard communication, peer discussion, inspection, incident analysis and reflective reporting rather than passively receiving rules. Student laboratory-safety-officer models, for example, give learners responsibility and leadership in maintaining a safe culture (Donaghy et al.). Such approaches align with competency-based education because they require students to demonstrate judgement and behaviour, not merely recall definitions.

Within the Indian educational context, laboratory safety is present in varying degrees in institutional instructions and practical manuals, but it is not always visible as a unceasing, credit-bearing and assessed learning progression from higher secondary school through the undergraduate degree. The problem is therefore not that no teacher ever gives safety guidance. The problem is fragmentation: coverage may be brief, repetitive at a basic level, disconnected from later experiments and omitted from prescribed assessment. When the syllabus does not overtly define conclusions, allocate time and assess performance, safety can be treated as common sense. Yet concepts such as exposure routes, GHS pictograms, chemical compatibility, control ladders and hazardous-waste segregation are learned competencies, not common sense.

The author's Safety Measures in Academic Chemistry Labs addresses this educational gap through a student-friendly headway from foundational principles to professional practice. It mixes hazard recognition and communication; risk assessment; PPE; chemical storage, handling and disposal; emergencies, first aid and fire safety; waste management and environmental responsibility; GLP; and safe use of equipment and glassware. Its fundamental intention is that habits formed in academic laboratories continue into research, industry, healthcare and education. The present paper encompasses that scheme into a curricular model connecting school, college and research preparation.

Methodology

This study adopts a conceptual, narrative-review and curriculum-design methodology. It does not report an experimental involvement or claim survey findings. First, the principal concepts and learning sequence in Safety Measures in Academic Chemistry Laboratories were mapped: safety responsibility, hazard identification, risk assessment, hierarchy of controls, PPE, chemical management, emergency preparedness, waste management, GLP, equipment safety, documentation and safety culture. Second, these concepts were compared with recognised frameworks published by the ACS and the National Research Council and with recent empirical studies of laboratory-safety knowledge, perceptions and training in chemistry education. Third, the analysis was organised around the educational changeover from supervised higher secondary practical work to undergraduate laboratory work and, finally, to independent postgraduate or research activity.

The resulting curriculum proposal follows four design principles: development, explicitness, active practice and assessment. Development means that concepts increase in depth as student self-sufficiency increases. Explicitness requires named learning consequences and assigned teaching time. Active practice requires learners to apply safety reasoning during reliable laboratory tasks. Assessment requires indication that students can recognise hazards, justify controls and respond fittingly, rather than merely sign that instructions were read. The proposal is intended as an adaptable framework for institutions; local regulations, facilities, experiments and emergency procedures must also be incorporated.

Results and Discussion

The analysis identifies five interrelated findings. First, the major educational weakness is not simply a lack of rules, but a lack of conceptual continuity. Students repeatedly hear elementary prohibitions while advanced competencies remain unstructured. A coherent sequence should connect a label on a reagent bottle to hazard classification, exposure pathway, risk level, control selection, waste route and emergency response. Without these connections, safety information remains isolated and is easily forgotten.

Second, delayed safety education leaves students inadequately prepared for research. In a teaching practical, quantities and steps are predetermined and the instructor is nearby. Research changes these conditions. The researcher may select a solvent, change concentration or temperature, operate equipment outside a familiar routine, work after normal hours, or manage an unexpected reaction. Each decision requires the researcher to anticipate hazards and evaluate risk before acting. A graduate who has learned only to obey instructions may be technically capable but unable to plan safe independent work. This limitation affects research confidence, efficiency and integrity as well as physical safety.

Third, the absence of systematic knowledge creates risk at several levels. At the individual level, it increases the possibility of exposure, burns, cuts, inhalation and inappropriate emergency action. At the group level, unsafe storage, poor housekeeping and unreported near misses expose classmates, teachers and laboratory staff. At the institutional level, incidents can damage equipment, interrupt teaching and create legal and reputational consequences. At the environmental level, careless disposal transfers laboratory risk to drains, soil, water and waste

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handlers. Safety education is thus simultaneously a health, educational, ethical and sustainability requirement.

Fourth, an approach centred mainly on PPE is inadequate. PPE is visible and straightforward to teach, but it is among the later options in the hierarchy of controls. Students must learn to ask whether a hazard can be eliminated, a safer substance or microscale method substituted, an engineering control such as a fume hood used, or the procedure administratively restricted before relying on gloves or goggles. Teaching this hierarchy also improves experimental design and supports green chemistry by encouraging smaller quantities, safer alternatives and reduced waste.

Fifth, safety culture is learned through repeated institutional behaviour. If teachers bypass precautions to save time, if broken equipment is normalised, or if near misses are ignored, students learn that productivity is valued above safety. Conversely, when every practical begins with purposeful risk discussion, when staff model correct practice, and when students can stop work and ask questions without embarrassment, safety becomes part of scientific identity. The hidden curriculum—the behaviour that students observe in everyday laboratory practice—must reinforce the formal curriculum.

Table 1: Proposed progression of laboratory-safety competencies

Stage	Core competence	Learning activity	Evidence of learning
Higher secondary	Recognise common hazards and GHS pictograms; follow labels and instructions; use basic PPE; practise safe behaviour, housekeeping and simple emergency actions.	Safety induction; pictogram and label exercises; teacher demonstration; short pre-lab checklist; evacuation and spill-response drills.	Observation checklist, short quiz and demonstration of correct procedure.
UG—foundation	Interpret SDS information; identify exposure routes; distinguish hazard from risk; segregate chemicals and waste; inspect glassware and basic equipment.	Pre-lab hazard worksheet; SDS search; compatibility exercise; waste-sorting activity; incident case discussion.	Practical safety station, risk worksheet and laboratory-record component.

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UG—advanced	Apply RAMP and the hierarchy of controls; prepare a risk assessment; select controls; manage scale-up, heating, pressure, electrical and instrument hazards; report near misses.	Student-led risk briefing; peer safety review; equipment inspection; emergency scenario; microscale or safer-substitution redesign.	Assessed risk assessment, oral defence and observed emergency response.
Research entry	Plan non-routine work; evaluate unfamiliar substances and procedures; document changes; define stopping criteria; communicate risk; participate in safety leadership.	Project-specific induction; supervisor review; safety minute; near-miss analysis; periodic audit and refresher training.	Authorised competency record before independent work and periodic revalidation.

The proposed progression avoids treating safety as a single introductory lecture. At the higher secondary level, the emphasis is recognition, disciplined behaviour and response under close supervision. At the undergraduate foundation level, students interpret information and connect hazards with controls. Advanced undergraduates independently apply risk-management principles and defend their choices. Before research, students demonstrate competence for non-routine work and accept responsibility for communication, documentation and continuous improvement.

Implementation need not displace large portions of disciplinary content. A short foundation module can introduce terminology and emergency procedures; thereafter safety can be embedded in each practical. A five-minute pre-laboratory risk discussion, a one-page hazard analysis, correct waste segregation and a short post-laboratory reflection can make safety visible throughout the course. Departments can designate safety learning outcomes in practical syllabi, provide standard templates, train instructors and technical staff, and include safety performance in practical examinations. Students who fail a critical safety competency should receive remediation before proceeding to higher-risk work.

Assessment is essential because learning outcomes that are not assessed are easily marginalised. A balanced system should include knowledge questions, observation of behaviour and application to unfamiliar scenarios. For example, students may be asked to interpret an SDS extract, identify incompatibilities in a storage plan, choose controls for a volatile solvent, demonstrate eyewash use, or analyse the causes of a near miss. Assessment should reward

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reporting and learning rather than concealment. A near miss reported promptly is valuable evidence for prevention and should not automatically be treated as misconduct.

Institutions with limited resources can still strengthen education. Risk assessment, label reading, SDS interpretation, waste planning, housekeeping and incident analysis depend more on sound organisation than on expensive equipment. Resource limitations, however, must never be used to justify experiments for which essential controls and emergency facilities are absent. The correct educational lesson is that an experiment should be modified, miniaturised, substituted or postponed when risk cannot be adequately controlled.

The proposed model also supports broader educational goals. It develops critical thinking because students must justify decisions; communication because they must explain hazards and controls; ethics because their actions affect others; and environmental responsibility because chemical choice and disposal have consequences beyond the laboratory. In this sense, safety is not a competing addition to chemistry education. It is a practical context in which scientific knowledge, judgement and responsibility are integrated.

Conclusion

Laboratory safety cannot remain an informal collection of warnings delivered at the point of use. When systematic teaching is absent or fragmented at higher secondary and undergraduate levels, students may complete prescribed practical work without acquiring the knowledge and judgement required for unfamiliar situations. This creates avoidable risk in academic laboratories and places graduates at a disadvantage when they enter postgraduate study, research or scientific employment.

A continuous, competency-based curriculum should therefore begin with hazard recognition and safe behaviour at the higher secondary level, develop SDS use, risk assessment, chemical management and emergency response during undergraduate study, and culminate in independent planning, documentation and safety leadership before research work. The content must be explicitly taught, repeatedly practised and formally assessed. Teachers, technical staff, supervisors and institutional leaders must model the same expectations.

The essential educational shift is from simple obedience to informed responsibility. Students should not merely know that a rule exists; they should understand the hazard, evaluate the risk, select and justify controls, prepare for failure and consider the effects of their work on other people and the environment. Embedding these competencies early will reduce accidents, strengthen scientific integrity and give future researchers the confidence to work independently without treating safety as separate from science. Laboratory safety is, ultimately, a foundational scientific competency and a defining element of professional practice.

References

1. Ayi, Helene-Rosina, and Chun-Yip Hon. "Safety Culture and Safety Compliance in Academic Laboratories: A Canadian Perspective." Journal of Chemical Health & Safety, vol. 25, no. 6, 2018, pp. 6–12. https://doi.org/10.1016/j.jchas.2018.05.002.
2. American Chemical Society. Creating a Safety Culture. ACS Committee on Professional Training, https://www.acs.org/education/policies/acs-approval-program/guidelines/safety-culture.html. Accessed 13 Aug. 2026.
3. American Chemical Society. Guidelines for Chemical Laboratory Safety in Academic Institutions. ACS Committee on Chemical Safety, 2016, https://www.acs.org/content/dam/acsorg/about/governance/committees/chemicalsafety/publications/acs-safety-guidelines-academic.pdf.
4. American Chemical Society. Guidelines for Chemical Laboratory Safety in Secondary Schools. ACS Committee on Chemical Safety, https://institute.acs.org/acs-center/lab-safety/education-training/high-school-labs.html. Accessed 13 Aug. 2026.
5. Donaghy, Connor M., et al. "Empowering Student Laboratory Safety Officer Programs to Strengthen Academic Safety Culture." ACS Chemical Health & Safety, 2024. https://doi.org/10.1021/acs.chas.3c00103.
6. George, Sajimol. Safety Measures in Academic Chemistry Labs (Ensuring a Safe Learning Environment). Current Publications, 2026.

7. Wu, Guixiang, Yanfei Yang, and Chenglin Xu. "Determination of University Students' Laboratory Safety Awareness: A Cross-Sectional Study." Journal of Chemical Education, vol. 100, no. 9, 2023, pp. 3402–3409. https://doi.org/10.1021/acs.jchemed.3c00305.

8. Zhao, Aaron Y., et al. "An Assessment of Laboratory Safety Training in Undergraduate Education." Journal of Chemical Education, vol. 101, no. 4, 2024, pp. 1626–1634. https://doi.org/10.1021/acs.jchemed.3c01299.

9. National Research Council. Prudent Practices in the Laboratory: Handling and Management of Chemical Hazards. Updated ed., National Academies Press, 2011, https://doi.org/10.17226/12654.

10. National Research Council. Safe Science: Promoting a Culture of Safety in Academic Chemical Research. National Academies Press, 2014, https://doi.org/10.17226/18706.