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From Compliance to Competency: A Simulation-Led Approach to Embedding Real-World Health and Safety Skills in Biomedical Education

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Abstract

Background

Traditional higher education approaches to laboratory health and safety often rely on passive instruction, failing to build real-world competency. Consequently, undergraduate students frequently view safety compliance as a bureaucratic hurdle, resulting in poor engagement.

Methods

We implemented an active learning pre-laboratory experience using a simulated, ICT-assessed "Smart Worksheet" developed with LearnSci for a cohort of Year 1 biomedical science undergraduates (n = 46). Access to physical laboratory sessions was gated by completion of the online activity. Students were required to extract critical regulatory data from non-standardised, multi-supplier Safety Data Sheets (SDSs) to complete digital Control of Substances Hazardous to Health (COSHH) forms and execute a *de novo* Risk Assessment.

Results

Digital tracking revealed rapid procedural skill development through task repetition. Mean scores improved significantly from 58.3% during the first task to a peak of 70.1% by the third ($P < 0.0001$). However, performance dropped to 64.6% ($P = 0.0016$) when students transitioned to constructing a holistic buffer synthesis risk assessment.

Conclusions

The digital simulation achieved 100% student engagement, successfully turning compliance into an active professional competency. While repetitive scaffolding establishes procedural fluency, subsequent performance decline reveals a critical cognitive bottleneck when transitioning to autonomous risk mitigation that requires targeted pedagogical support.

Background

There is a concern that hands-on laboratory work is declining in Biomedical Sciences degrees (1, 2). This is in spite of the QAA Subject Area Benchmarks stating that laboratory work forms an essential part of Biomedical Science and Biomedical Sciences Courses (3). The reduction in hours is due, in large part, to the advances brought about by the COVID-19 Pandemic, and the precipitation of online, hands-off instruction (4), and a shrinking academic workforce (5). Indeed, the use of Virtual Laboratory tools to facilitate a “hands-off” approach has spanned the discipline from molecular biology to ecology (6). This creates somewhat of a conflict of interests insofar as like most STEM graduate roles in the UK, there exists an inherent expectation that a graduate will have an acute awareness of commercial obligations, leadership, digital literacy and project, especially in the fundamental role of Health and Safety awareness that fits into their future roles (7, 8). Acknowledging this fact comes with a need to move beyond teaching Health and Safety as a body of knowledge and instead equip students with the skills required to navigate professional safety frameworks and workplace documentation. This includes identifying where relevant information can be obtained, verifying that it is current and reliable and applying it appropriately to support safe profession practice. Within HE, particularly within the literature, there is a fundamental lack of conversation on how best to scaffold this essential learning journey, especially because it is outside of “scientific knowledge” gathering in the traditional sense. Nonetheless it addresses a fundamental employability skill.

A primary pedagogical barrier persists in the field of Health and Safety: the profound (and sometimes understandable) indifference of the student body toward the subject matter. The literature suggests that learning this subject matter has traditionally deployed methods that are not interactive, engaging, or relevant to the learners' specific contexts, which can lead to poor uptake and retention (9), and that taking an active learning approach to this subject matter could well be advantageous (10). We therefore decided to make this an engaging and essential learnt skill to our graduates, starting with a Year 1 Biomedical Science-specific module. We wanted to present a unique challenge and opportunity to the students to learn Health and Safety in a familiar laboratory setting, supported and encouraged by a low-stakes assessment that makes the task although “bland”, accessible, understandable to its essential role to protect oneself and others in a work environment, and start to develop that need to explore beyond computer programme-provided boundaries.

Methodology

Rationale and Curriculum Alignment

Current literature revealed a notable absence of formalised, skill-based Health and Safety (H&S) training tailored specifically for undergraduate biomedical scientists. While traditional instruction often relies on the passive identification of hazard symbols (11), such methods frequently fail to translate into real-world application or professional competency (12). Indeed, although the Quality Assurance Agency (QAA) benchmarks assume safety literacy under the broad mandate that students must "work safely and within practice," the specific mechanisms for achieving this are rarely articulated.

To maximise engagement with this critical employability skill, and in line with work previously published from our group (13, 14) we made the decision to transition from abstract theory to an active learning model. In this framework, students completed prerequisite safety theory (pre-learning) which was then immediately validated through supervised practical application.

Ethical Approval

The study was ethically approved by the University of South Wales, Faculty of Computing, Engineering and Sciences Ethics Committee (FALL-FCES-LT-2226). It was conducted in accordance with GDPR and the recommendations for physicians involved in research on human subjects adopted by the 18th World Medical Assembly, Helsinki 1964 and later revisions.

Design and Implementation

In collaboration with LearnSci (Learning Science Ltd, Bristol, UK), we utilised expertise in simulated ICT-assessed worksheets to co-design a low-risk/high-reward learning activity. The primary objective was to embed Control of Substances Hazardous to Health (COSHH) and Risk Assessment (RA) competencies by tying their completion to the "reward" of a physical laboratory experiment.

The digital interface required students to navigate the complexities of Safety Data Sheets (SDS) to extract relevant data. A significant pedagogical challenge addressed during development was the lack of standardisation across different chemical suppliers; students were required to reconcile these industrial discrepancies to complete their documentation accurately.

The assessment workflow was structured as follows:

Data Acquisition: Students identified and captured necessary safety parameters from various SDS formats.

Documentation: For a selection of up to three reagents, students completed a formal COSHH form.

Quantification of Risk: Students were required to perform a comprehensive Risk Assessment for the final synthesised product.

Smart worksheet User Experience

The Smart Worksheet was designed to provide an interactive and user-friendly learning experience, embedded into Blackboard (Figure 1A), our virtual learning environment (VLE). Students were presented with a series of structured tasks requiring them to extract and interpret information from SDSs, including hazard pictograms, signal words, risk classifications, and appropriate control measures. As students entered their responses, the system provided immediate automated feedback, allowing them to confirm whether their answers were correct before progressing. Where an incorrect response was submitted, students were given clear prompts Figure 1B indicating that their answer should be reviewed and were encouraged to revisit the SDS documentation. The activity allowed multiple attempts, enabling students to learn through trial, reflection, and correction rather than being penalised for mistakes. This formative approach promoted active engagement with the hazard information, reinforced correct interpretation of laboratory safety documentation, and supported the development of confidence in risk assessment and COSHH-related decision-making.

Gating

Laboratory access was linked to completion of the Smart Worksheet through a low-risk/high-reward gating framework. Students were required to complete all sections of the digital activity before attending the associated practical session, which was physically making a buffer for Tris borate EDTA (TBE), using all the chemicals presented to them in the Smart Worksheets. The Smart Worksheet was delivered through the LearnSci platform and consisted of a sequential series of tasks requiring students to extract information from authentic SDSs, complete COSHH documentation, and perform risk assessment activities.

Progress through the worksheet was monitored electronically, allowing module staff to verify completion prior to the laboratory session. Students were unable to bypass individual tasks, ensuring engagement with each stage of the activity. The worksheet therefore functioned as a prerequisite learning activity, providing students with prior exposure to laboratory hazards, chemical classifications, and risk management procedures before entering the physical laboratory environment.

This approach was designed to align with standard laboratory practice, where safety documentation must be completed before experimental work can commence. By embedding COSHH and risk assessment activities within a simulated environment prior to the practical class, students were able to develop familiarity with safety documentation in a low-risk setting before applying these principles during laboratory-based activities.

Addressing SDS Divergence

A deliberate feature of the activity was the use of SDSs sourced from different commercial suppliers. Although SDSs broadly follow the Globally Harmonized System (GHS) framework, the presentation and location of key information varied considerably between manufacturers. For example, hazard information for chemicals such as Tris Base, Boric Acid, and EDTA was often located in different sections and presented using varying layouts, terminology, or levels of detail depending on the supplier. Hazard classifications, precautionary statements, exposure control recommendations, and personal protective equipment requirements were therefore not always immediately identifiable in the same location across documents. Students were required to navigate multiple document formats and reconcile equivalent safety information from different sources rather than simply transferring data from a standardised template. This design element was intentionally incorporated to replicate the variability encountered in research and industrial laboratory environments and to encourage active interrogation and interpretation of safety documentation.

Statistical Analysis

Data were analysed using R 4.2.2. Following a confirmation of lack of normal distribution using Shapiro-Wilk W Tests ($P < 0.05$), a Friedman non-parametric test with Dunn's multiple comparisons was conducted. Significance was established at $P < 0.05$.

Results

The efficacy of the integrated Health and Safety (H&S) simulation was evaluated across a cohort of undergraduate biomedical scientists (n=46). Performance metrics were segmented into four distinct pedagogical phases to track the transition from theoretical data acquisition to applied risk management as follows:

Section 1: COSHH Risk Assessment for Tris Base

Section 2: COSHH Risk Assessment for Boric Acid

Section 3: COSHH Risk Assessment for EDTA

Section 4: Creating a Risk Assessment for Making a Buffer

Data are summarised in table 1, but briefly, the data indicate clear and rapid learning during the chemical-specific documentation phases of sections 1-3 of the Smart Worksheet. In Section 1 (Tris Base), students achieved a mean score of 58.3%, however, through iterative practice, scores improved to 69.2% (P = 0.013 vs Tris Base) in Section 2 (Boric Acid) and reached a peak of 70.1% (P = <0.0001 vs Tris Base) in Section 3 (EDTA). This suggests that while H&S documentation is frequently characterised by students as a bureaucratic hurdle, technical proficiency in this area is a skill that responds rapidly to repetitive, low-stakes simulation.

Table 1: Results of student performance on the Smart Worksheet

Section Number	Task Name	# Questions	# Points	% Questions attempted	Not completed	Not attempted
1	COSHH & Risk Assessment for Tris Base	5	10	100	0	0
2	COSHH & Risk Assessment for Boric Acid	13	17	100	0	0
3	COSHH & Risk Assessment for EDTA	5	9	100	0	0
4	Risk Assessment for Making a Buffer	6	12	100	0	0

COSHH – Control of Substances Hazardous to Health. Data are raw values. * denotes a statistically significant difference from Section 1 (P < 0.05), COSHH & Risk Assessment for Tris Base

Section 4 (Buffer Synthesis RA) returned a mean score of 64.6% (P = 0.0016 vs the Peak of EDTA). Here, students transitioned from individual component analysis to the holistic assessment of a practical experiment.

Broadly, the task repetition involved in sections 1-3 (data acquisition and documentation) showed an increase in student attainment (Figure 1) with a decrease in attainment when the activity changed to creating a risk assessment.

Discussion

This is, to our knowledge the first study that has specifically used Smart Worksheets to teach laboratory health and safety to biomedical science students. Our data suggest several important findings as follows: First, when the students first attempted to evaluate COSHH and Risk Assessments for chemicals, they only returned a mean score of 58%. This initial underperformance highlights the primary "roadblock" identified in the study: the significant cognitive load associated with reconciling non-standardised Safety Data Sheets (SDS). By the third iteration, the proverbial hazard of navigating industrial documentation had been largely mitigated through familiarity (15) in much the same way as a (traditionally thought of) “Digital Native” is familiar with e.g., a computer operating system compared with a “Digital Immigrant”. Here the students returned a mean score of 70%, which is a First-Class grade. The point where students transitioned from individual component analysis to the holistic assessment of a practical experiment saw a significant decrease in performance which is interesting and suggests despite the barrier of data acquisition being cleared, the quantitative mitigation of risk may have required a higher level of professional judgment that the Year 1 undergraduate students have yet to develop. Finally, our data collectively suggest that while symbol recognition and data entry are easily mastered through repetition, the transition from a passive risk observer to an active risk engineer remains the most demanding aspect of safety pedagogy.

The lack of standardisation in safety data sheets despite the United Nations (UN) Globally Harmonized System (GHS) can mean that learning to work with these documents is more like detective work than science. The UN-GHS mandates a specific 16-section format, but it is not a legally binding international treaty; rather a voluntary system that only carries legal weight once it is incorporated into regional or national legislation (16), resulting in very different looking documents depending on chemical or supplier. Our data suggest that it is entirely possible that when introduced to the task of dissecting SDS, students find the task cognitively overloading, resulting in the phenomenon of Over-Challenge Boredom (17). The fact that generations of students have found learning Health and Safety “boring” could well be because they have been deploying boredom as an avoidance-orientated coping strategy (18) and a defence mechanism against the cognitive friction of data extraction, leading to a temporary disengagement from the task until procedural fluency is established. This establishment of fluency was evidenced in our data as the mean student score increased from Section 1 to Section 3 (Figure 2). Based on the above, initial performance could well have been suppressed by high extraneous cognitive load (19) as students were required to navigate unfamiliar digital interfaces and non-standardised industrial documentation simultaneously. By the time the students reached Section 4 – The Risk Assessment for Making a Buffer, the students had refined their data-extraction skills through deliberate practice (20) were yet to be able to apply their findings to a holistic risk assessment with accuracy.

Reasons for this drop in performance in Section 4 are interesting and varied but broadly break down into four main domains as follows: a steep vertical step in Bloom's Taxonomy, a shift from external to internal cognitive load, unpractised risk perception, and a quirk of digital scaffolding. Regarding the transition in Bloom's, it has long been known that students can become proficient in executing step-by-step processes while possessing very little conceptual understanding of what those steps mean and indeed, why they must do them (21). The world of chemical engineering pedagogy provides further support for this and indeed our data, by suggesting that procedural, algorithmic fluency and conceptual synthesis are two entirely independent cognitive dimensions (22). Our data adds to the body of evidence that mastering the step-by-step mechanics of a topic does *not* automatically transfer into conceptual understanding. Regarding cognitive shift, our data can be explained by an exponential increase in element interactivity (23) in Section 4. In this section student transitioned to managing the competing distractors (elements) of e.g., chemical properties, volume, reaction environment, and the human interaction with those elements. I.e., cognitive load increased (24) and performance simultaneously declined. With regards to unpractised risk perception, it is important to reiterate that these students were Level 4 (Year 1) undergraduates and are therefore novices to the professional laboratory environment. They do not, therefore possess the experience needed to filter out irrelevant information from relevant information. Therefore, when generating a *de novo* risk assessment, students are forced to look at a complex operational environment and make qualitative value judgments. Because they lack an expert schema, it is possible that they treat all variables with equal weight, resulting in immediate working memory breakdown (25). Finally, our data follow a previously reported problem in scaffolding digital learning; that there is a distinct difference between well-structured digital tasks (Sections 1-3) and ill-structured digital tasks (Section 4). This occurs because the digital skills built in the first three sections (scanning, matching, and data entry) do not seamlessly aggregate into the skill (holistic evaluation) required for the final section (26,27).

Our data suggest that our students through repetitive practice, displayed proficiency in identifying risk, which constitutes Remember and Understand in the revised Bloom's Taxonomy (28). Section 4, however, which involves quantifying a risk and developing methods of mitigating that risk requires a higher level of professional judgment and indicates a remaining pedagogical gap between those lower levels and the Analyse and Apply levels that Section 4 demanded. It would appear that our activity trained our students to "beat the boredom" of SDS, but the transition from passive identifier to active risk manager still requires further support. We succeeded, however, in positioning active learning in H&S as an online key to unlocking a physical laboratory session and achieved 100% engagement with that task and transitioned this subject from an academic requirement that existed on the peripheries to a professional competency that the students not only engaged with but improved on with practice.

The concept of pre-laboratory quizzes in order to access a physical session is not new (29,30). A key driver for our Smart Worksheet transition was to increase engagement. However, in its implementation, we allowed our Year 1 module to directly fulfil a Competency Sign-Off equivalency for e.g., the Health Care Professions Council Standards of Proficiency for Biomedical Scientists Standards 1 (Practise safely and effectively within their scope of practice) and 14 (Establish and maintain a safe practice environment) and the QAA Benchmark (2023) "Independently produce and apply risk assessments for completing practical work in a safe and reliable manner". Our data support the previous literature that states that pre-laboratory gating significantly increases student engagement and readiness to practice (31–33).

Limitations and Future Directions

While the integration of the digital simulation yielded 100% engagement and demonstrated rapid procedural skill acquisition, several experimental limitations within the study design must be considered.

A primary limitation is the single-cohort, single-institution design of the study. The data were evaluated across a relatively small sample size (n=46) of Level 4 undergraduate biomedical science students within a single module. Consequently, the findings regarding cognitive load, task boredom, and procedural learning rates may be influenced by specific institutional entry requirements, demographic traits, or prior educational backgrounds. To increase the generalisability of our findings, future work should expand to multi-cohort, multi-institution studies to evaluate whether these performance steps remain consistent across broader student populations.

Although the Smart Worksheet successfully developed students' ability to locate and interpret information within SDSs, the present study did not formally assess whether these skills translated into improved behaviour within the laboratory environment itself. Future iterations of the project will therefore incorporate structured in-laboratory observations to evaluate whether students who successfully complete the simulation demonstrate improved safety awareness, hazard identification, and risk-management behaviours during practical sessions.

The study was also limited by the absence of student perception data. While completion rates and performance metrics indicate strong engagement, no formal evaluation of student confidence, attitudes towards Health and Safety, or perceptions of the activity was undertaken. Future deliveries will incorporate student feedback and reflective evaluation to explore whether the intervention influences confidence, motivation, and perceptions of professional responsibility.

Finally, the present study focused on immediate performance outcomes and did not evaluate longer-term retention of knowledge or skills. Future research should investigate whether the improvements observed during the activity are maintained throughout the academic year and whether repeated exposure to authentic safety documentation contributes to the development of sustained safety literacy and professional competency.

Collectively, these limitations highlight the need for further research examining the transferability, retention, and broader educational impact of simulation-based Health and Safety training within undergraduate biomedical science education.

Abbreviations

COSHH

Control of Substances Hazardous to Health
CTE
Career and Technical Education
EDTA
Ethylenediaminetetraacetic Acid
GHS
Globally Harmonized System (of Classification and Labelling of Chemicals)
H&S
Health and Safety
HCPC
Health and Care Professions Council
HE
Higher Education
ICT
Information and Communication Technology
ITA
Institutional Transformative Agreement
JUNE
Journal of Undergraduate Neuroscience Education
QAA
Quality Assurance Agency (for Higher Education)
RA
Risk Assessment
SDS
Safety Data Sheet
SDSs
Safety Data Sheets
STEM
Science, Technology, Engineering, and Mathematics
TA
Transformative Agreement
TBE
Tris Borate EDTA
UK
United Kingdom
UN
United Nations
UN
GHS–United Nations Globally Harmonized System
USW
University of South Wales
VLE
Virtual Learning Environment

Declarations

Ethics approval and consent to participate

The study was approved through the Faculty of Computing, Engineering and Science Ethics Committee at the University of South Wales, UK. All students signed informed consent for Data Sharing when they started the Smart Worksheet.

Consent for publication

Not applicable.

Availability of data and materials

Data sharing is available on request from the corresponding author.

Competing interests

The authors report there are no competing interests to declare.

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Authors' contributions

SO and LF conceived and designed the study. LF, SO, AB, and AW drafted the manuscript. LF analysed and interpreted the data. AW and AB were responsible for data collection. All authors read and approved the final manuscript.

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Declaration of generative AI use

Generative AI was not used in the preparation of this manuscript.

References

1. Heng ZSL, Koh DWS, Yeo JY, Ooi CP, Gan SKE. Effects of different delivery modes on teaching biomedical science practical skills in higher education during the 2021 pandemic measures. Biochem Mol Biol Educ. 2022;50(4):403–13. 10.1002/bmb.21637 . PubMed PMID: 35621717; PubMed Central PMCID: PMC9347998.
2. Scott S, Millar BC, McClean S, Editorial. Education and Training in Biomedical Science. Br J Biomed Sci. 2024;81. 10.3389/bjbs.2024.13598.
3. Quality Assurance Agency for Higher Education. Subject Benchmark Statement: Biomedical Science and Biomedical Sciences. 2023.
4. Daniel SJ. Education and the COVID-19 pandemic. Prospects. 2020;49(1–2):91–6. 10.1007/s11125-020-09464-3.
5. Mass redundancies will trash the reputation of UK HE [Internet]. 2025 [cited 2025 Jul 15]. Available from: https://www.timeshighereducation.com/opinion/mass-redundancies-will-trash-reputation-uk-universities
6. Lewis DI. The pedagogical benefits and pitfalls of virtual tools for teaching and learning laboratory practices in the biological sciences. High Educ Academy: STEM. 2014;1–30.
7. Threeton MD, Kwon K, Fleck JA, Ketchem RB, Farzam L. An investigation of instructional practices which promote occupational safety and health. Int J Occup Saf Ergon. 2021;27(3):902–10.
8. Love TS, Roy KR, West SS. A Call to Prioritize Safety in STEM and CTE: Addressing Overcrowded Classes and Other Critical Safety Issues. Laboratories. 2024;1(1):52–8. 10.3390/laboratories1010003.
9. Gao Y, Gonzalez VA, Yiu TW. The effectiveness of traditional tools and computer-aided technologies for health and safety training in the construction sector: A systematic review. Comput Educ. 2019;138:101–15. 10.1016/j.compedu.2019.05.003.
10. Minnick W, Cekada T, Marin L, Zreiqat M, Seal B, Mulroy J. The impact of active learning strategies on retention and outcomes in safety training. Creative Educ. 2022;13(2):526–36.
11. Lesch MF. Warning symbols as reminders of hazards: Impact of training. Accid Anal Prev. 2008;40(3):1005–12. 10.1016/j.aap.2007.11.009.
12. Hill RH, Finster DC. Laboratory Safety for Chemistry Students [Internet]. Wiley; 2011. Available from: https://books.google.co.uk/books?id=2qwFs9_IoJsC
13. Fall L, Surendran S. Playful Learning for Anatomy: Using Play-Doh to Visualise the Heart. J Foundation Year Netw. 2023;6:51–64.
14. Surendran S, Fall L. Teaching Principles of an Action Potential Using Candy. J Undergrad Neurosci Educ. 2025;23(2):A44–9. doi:10.59390/KCYI1299 PubMed PMID: 40655179; PubMed Central PMCID: PMC12243887.
15. Turner P. Being-with: A study of familiarity. Interact Comput. 2008;20(4–5):447–54. 10.1016/j.intcom.2008.04.002.
16. Ta GC, GHS Implementation to Strengthen Global Chemical Hazard Communication. Will We Ever Get There? ACS Chem Health Saf. 2021;28(3):153–8. 10.1021/acs.chas.0c00114.
17. Acee TW, Kim H, Kim HJ, Kim JI, Chu HNR, Kim M, et al. Academic boredom in under- and over-challenging situations. Contemp Educ Psychol. 2010;35(1):17–27. 10.1016/j.cedpsych.2009.08.002.
18. Nett UE, Goetz T, Hall NC. Coping with boredom in school: An experience sampling perspective. Contemp Educ Psychol. 2011;36(1):49–59. 10.1016/j.cedpsych.2010.10.003.
19. Skulmowski A, Xu KM. Understanding Cognitive Load in Digital and Online Learning: a New Perspective on Extraneous Cognitive Load. Educ Psychol Rev. 2022;34(1):171–96. 10.1007/s10648-021-09624-7.
20. Ericsson KA, Krampe RT, Tesch-Römer C. The role of deliberate practice in the acquisition of expert performance. Psychol Rev. 1993;100(3):363–406. 10.1037/0033-295X.100.3.363.
21. Nakhleh MB. Are Our Students Conceptual Thinkers or Algorithmic Problem Solvers? Identifying Conceptual Students in General Chemistry. J Chem Educ. 1993;70(1):52. 10.1021/ed070p52.
22. Cracolice MS, Deming JC, Ehlert B. Concept Learning versus Problem Solving: A Cognitive Difference. J Chem Educ. 2008;85(6):873. 10.1021/ed085p873.

23. Chen O, Kalyuga S, Sweller J. The worked example effect, the generation effect, and element interactivity. J Educ Psychol. 2015;107(3):689–704. 10.1037/edu0000018.
24. Sweller J. Cognitive Load During Problem Solving: Effects on Learning. Cogn Sci. 1988;12(2):257–85. 10.1207/s15516709cog1202_4.
25. Johnstone AH. Why is science difficult to learn? Things are seldom what they seem. Comput Assist Learn. 1991;7(2):75–83. 10.1111/j.1365-2729.1991.tb00230.x.
26. Jonassen DH. Instructional design models for well-structured and III-structured problem-solving learning outcomes. Education Tech Research Dev. 1997;45(1):65–94.
27. Kim JY, Lim KY. Promoting learning in online, ill-structured problem solving: The effects of scaffolding type and metacognition level. Comput Educ. 2019;138:116–29. 10.1016/j.compedu.2019.05.001.
28. Anderson LW, editor. A taxonomy for learning, teaching, and assessing: a revision of Bloom's taxonomy of educational objectives. Complete ed., [Nachdr]. New York: Longman; 2009. p. 352.
29. Coleman SK, Smith CL. Evaluating the benefits of virtual training for bioscience students. High Educ Pedagogies. 2019;4(1):287–99. 10.1080/23752696.2019.1599689.
30. Huseeb I, Ramos-Harrison I, Kenny A, Klymenko T, Ludwig F, Clark J, et al. Integrating Smart Worksheets into mandatory pre-laboratory exercises increased exercise completion rates and laboratory test grades. Emerg Top Life Sci. 2025;9(5):ETLS20253023. 10.1042/ETLS20253023.
31. Rollnick M, Zwane S, Staskun M, Lotz S, Green G. Improving pre-laboratory preparation of first year university chemistry students. Int J Sci Educ. 2001;23(10):1053–71. 10.1080/09500690110038576.
32. Seery MK. Flipped learning in higher education chemistry: emerging trends and potential directions. Chem Educ Res Pract. 2015;16(4):758–68. 10.1039/C5RP00136F.
33. Agustian HY, Seery MK. Reasserting the role of pre-laboratory activities in chemistry education: a proposed framework for their design. Chem Educ Res Pract. 2017;18(4):518–32. 10.1039/C7RP00140A.

Figures

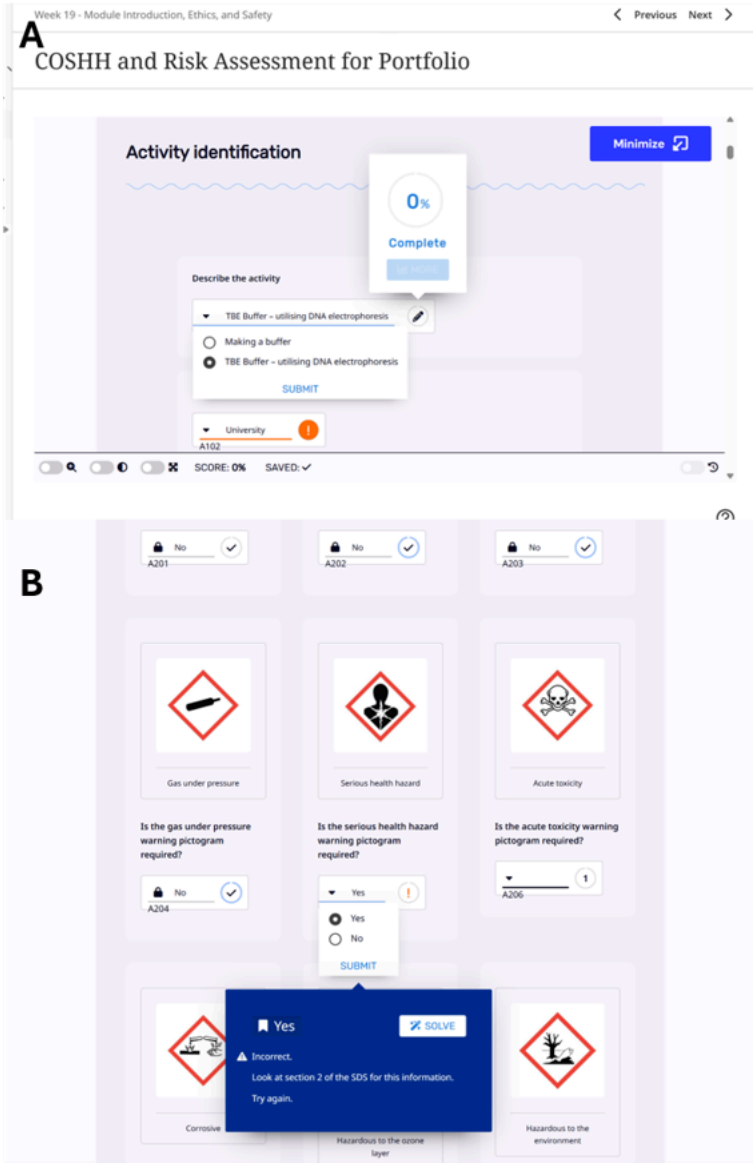

Figure 1

The Smart Worksheet User Interface. A – Landing page, and B – Example of correct and incorrect responses with the formative explanations and prompts for incorrect answers

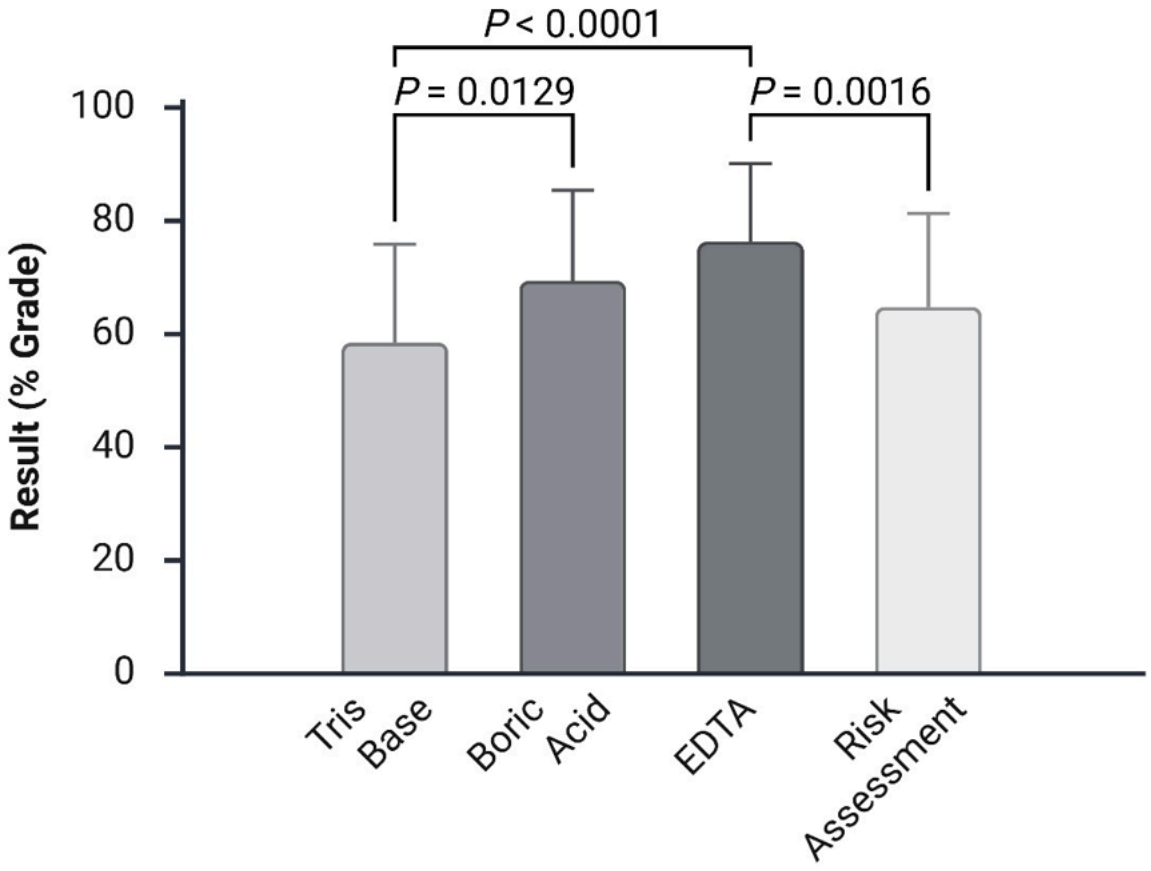

Figure 2

Results of mean student grade for each activity. Tris Base, Boric Acid, and EDTA were the data acquisition and documentation tasks, with Risk Assessment being the task of creating a risk assessment for making a buffer. P Values are the result of Friedman non-parametric test with Dunn's multiple comparisons.