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Implementing sustainable undergraduate laboratories using the IUPAC Guiding Principles of Responsible Chemistry

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The 2025 IUPAC Guiding Principles of Responsible Chemistry provide an emerging framework for advancing sustainability and responsibility in chemical practice. However, their application within undergraduate teaching laboratories remains limited. This case study reports a curriculum-wide sustainability audit of 25 undergraduate chemistry laboratory modules delivered across Stages 1–3 (undergraduate program years 1–3) at the University College Dublin, School of Chemistry. The assessment integrates the IUPAC Guiding Principles of Responsible Chemistry with the established 12 Principles of Green Chemistry to evaluate laboratory practices, prioritise interventions, and support systematic improvement at the programme scale. Sustainability-relevant features, including solvent selection, hazardous reagents, energy-intensive operations, and waste streams, were mapped using document analysis and stakeholder input from technical officers and teaching staff. A qualitative scoring framework was developed to assess sustainability benefit alongside implementation difficulty, supported by visualisation tools such as heatmaps, interaction networks, and prioritisation matrices. Fifteen targeted interventions were implemented, including protocol optimisation, equipment upgrades, and chemical substitution, resulting in reduced water consumption, waste generation, and reliance on hazardous substances while maintaining experimental integrity.

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Sustainability spotlight

Traditional chemistry labs often conflict with sustainability goals. This study addresses this by embedding responsible practices into University College Dublin's undergraduate curriculum. We audited 25 modules using the 2025 IUPAC Guiding Principles of Responsible Chemistry to create a framework for systematic improvement. By replacing hazardous reagents and eliminating water-intensive equipment, we reduced the environmental impact while modelling ethical, systems-aware professional behaviour. This research provides a visualized roadmap for curriculum transformation that preserves essential learning outcomes. Directly advancing SDGs 4, 7, 12, and 16, this initiative transforms laboratories into models of efficiency and active learning. Ultimately, it equips future scientists with the values and practical skills required for responsible innovation and a global culture of scientific trust.

1. Introduction

1.1 Implementing sustainability in undergraduate chemistry laboratories

In the late 20th century, the concept of sustainable development emerged through international policy debates, most notably formalized by the 1987 Brundtland Commission.[1] It was later consolidated into the widely used three-pillar model, which links the environment, economy, and society.[2,3] In 2015, all United Nations Member States established a global partnership to adopt the 2030 Agenda for Sustainable Development, which aimed to benefit people and the planet, now and in the future.[4] Its heart is the 17 Sustainable Development Goals (SDGs), which outline interconnected targets spanning poverty, health, education, gender equality, climate, and responsible consumption and production, among others, providing a global agenda for sustainability (United Nations Sustainable Development Goals https://sdgs.un.org/goals).[4] As a signatory of the Beyond Benign Green Chemistry Commitment,[5] UCD Chemistry is committed to implementing the four core Student Learning Objectives:[6] theory (12 Principles of Green Chemistry), toxicology, laboratory skills for greener design,

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and professional application. This stakeholder-driven framework directly supports these objectives while aligning with UN SDGs 4, 12, and 13.

The 2030 Agenda for Sustainable Development frames sustainability as a shared responsibility across society, and a recent scholarship highlights the need for developing sustainability competencies among all citizens.[7–10] Education has widely been identified as a primary mechanism of advancing public understanding of sustainability, with sustainability education increasingly integrated into curricula across educational levels.[8,10–13] Higher education plays a particularly influential role, as university students represent future scientists, engineers, educators, and policymakers, whose professional decisions will affect sustainable development.[11,12,14] Studies in chemistry and science education further show that engagement with sustainability-focused learning experiences during the undergraduate stage can positively influence students' values, decision-making, and long-term professional intentions.[13,15–17]

Within this broader context, chemistry holds a unique position because it integrates theoretical understanding with experimental practice,[18,19] offering meaningful opportunities to embed sustainability principles through both conceptual learning and hands-on activities. Laboratory teaching forms a substantial component of undergraduate chemistry[20,21] and is a major site of material use, energy consumption, and waste generation.[22–24] These characteristics position teaching laboratories as critical environments for implementing sustainability practices and modelling responsible professional behavior.[11,22,25] Embedding sustainable laboratory practices in undergraduate laboratory teaching modules therefore has the dual potential to reduce the environmental footprint of chemistry education and to provide students with experiential exposure to sustainability-oriented approaches relevant to their future academic or professional work.[14,15,22,26]

This work was inspired by the UN SDGs, and here we present a case study which investigates how sustainability can be systematically embedded into undergraduate chemistry laboratory teaching in a leading university in Ireland.

1.2 Gaps in sustainable chemistry laboratory practice

A wide range of chemistry education research, including both curricula and laboratory teaching, has sought to integrate sustainability in response to the UN SDGs. Some case studies focus on how targeted interventions can enhance the environmental performance of teaching laboratories. For instance, Baum *et al.* reported that replacing water-cooled condensers with waterless devices in undergraduate laboratories significantly reduced water consumption while maintaining experimental integrity.[25] Research by Freese and colleagues documented substantial reductions in energy use and greenhouse gas emissions following the coordinated implementation of sustainable laboratory practices across university settings.[22] At the pedagogical level, Zuin *et al.* made international efforts to embed green and sustainable chemistry principles into teaching laboratories,[11] while Widyantoro *et al.* designed an experimential learning workshop to train preuniversity teachers in integrating green chemistry through case-based learning.[15] Curriculum level initiatives, such as Clapson *et al.*'s integration of sustainability themes into existing chemistry courses[27] and the UK "Green Shoot" project, further illustrate the diversity of approaches taken across institutions. Besides individual courses, several frameworks and audit tools have been introduced to support laboratory sustainability, including institutional programmes that outline recommended practices for energy use, waste management, and procurement. Cannon *et al.* additionally proposed an actionable definition and a set of evaluative criteria for green chemistry laboratories, offering a structured basis for assessing specific practices.[24]

Despite this growing body of work, existing approaches remain fragmented.[28–32] Current frameworks do not yet provide a unified, globally applicable mechanism that enables educators and researchers to systematically evaluate the sustainability of laboratory teaching practices and keep improving the implementations. This highlights the need for a more comprehensive and universal assessment framework to support the continuous enhancement of sustainability in chemistry teaching laboratories.

1.3 Aims of this IUPAC-guided tutorial case study

The primary aim of this case study was to enhance the sustainability of undergraduate chemistry laboratory teaching while preserving essential learning outcomes and the development of core practical skills. Building on existing efforts towards green laboratory practices within the School of Chemistry, this work introduces the 2025 IUPAC Guiding Principles of Responsible Chemistry as a novel framework for evaluating and improving sustainability across undergraduate laboratory modules, moving beyond the traditional focus on the 12 Principles of Green Chemistry (1998) by integrating the recent International Union of Pure and Applied Chemistry (*IUPAC*) *Guiding Principles of Responsible Chemistry* into the evaluation framework (see Section 2.2). By applying this emerging international framework to a real institutional context, this study seeks to provide a practical, evidence-informed model that can support school-wide and programme-level sustainability efforts in chemistry education.

2. Context and methods

2.1 Institutional and curricular context

This case study was conducted across the undergraduate chemistry laboratory curriculum at the University College Dublin (UCD), School of Chemistry, encompassing 25 modules delivered in Stages 1–3 and spanning introductory, physical, and synthetic laboratory classes. Many experiments used in these modules are long-established legacy protocols widely adopted internationally and were originally designed before sustainability considerations became central to chemistry education. As highlighted in the School's sustainability review, recurring challenges such as excessive use of disposable consumables, inefficient waste-handling practices, reliance on water-intensive condensers, and outdated solvent choices signalled the need for a systematic curriculum-wide assessment. This study therefore draws on inputs from Technical Officers (TOs) across all laboratory floors, reviews of all laboratory manuals, and discussions within UCD's "Wet Lab" sustainability group. The latter cross-school and unit groups were recently established to identify and discuss sustainability issues in all fields (not solely chemistry). The "School's sustainability review" refers to our UCD Teaching & Learning SATLE-funded project titled "Education for Sustainable Development – Development of Sustainable Chemistry in Undergraduate Teaching Laboratories" (commenced 2023). This institutional project conducted a preliminary assessment of sustainability challenges across our laboratory teaching portfolio, including hazardous reagent use, waste generation, and infrastructure limitations. The present work builds upon this foundational review by: (1) implementing a structured, curriculum-wide assessment framework (Section 2.2), (2) developing and piloting specific interventions informed by stakeholder collaboration, and (3) creating student-facing educational materials (sustainability inserts) to enhance pedagogical outcomes. Thus, while the initial review identified operational challenges, this study provides the systematic methodology, implementation data, and educational innovations that constitute our research contribution.

2.2 Assessment framework: from 12 Principles of Green Chemistry to the IUPAC Guiding Principles of Responsible Chemistry

For initial experiment-level analysis, this study used the 12 Principles of Green Chemistry, a longstanding framework for evaluating hazards, waste, solvent choice, and energy use in laboratory protocols.[11,33] While these principles remain foundational, their 1998 formulation provides limited guidance on broader ethical, cultural, and communication dimensions, increasingly recognised as essential to sustainable chemical practice.[34–36]

To provide a broader framework for curriculum-level evaluation, the assessment also incorporated the 2025 IUPAC Guiding Principles of Responsible Chemistry, an IUPAC initiative that explicitly extends sustainability discussions beyond process greenness to include responsibility, ethics, equity, communication, data integrity, and interdisciplinary collaboration in chemical practice and education. The framework is organised into eight guiding principles: Responsible Innovation (P1); Safety, Security, and Sustainability (P2); Community Engagement and Education–Honest Reporting (P3); Inclusivity, Equity, & Belonging (P4); Communication and Collaboration (P5); Equitable Access (P6); Integrity and Accuracy (P7); Convergence Across Disciplines (P8) (https://iupac.org/responsible-chemistry/). In this study, these eight principles were not treated as a replacement for the 12 Principles of Green Chemistry but as a complementary layer for evaluating how proposed laboratory changes support responsible chemistry at the programme scale (*e.g.*, transparency, inclusivity, stakeholder engagement, and systems-aware decision-making), in addition to improving protocol-level sustainability performance. The 12 principles, IUPAC frameworks, and UN SDGs will be discussed in more detail in Section 4.3.

To address these limitations, the assessment implemented the 2025 IUPAC Guiding Principles of Responsible Chemistry, which articulate the shift from what chemistry can do to what chemists should do and emphasise responsibility, transparency, equity, collaboration, and systems thinking in contemporary chemical education and practice.[37,38] These principles were built on emerging work in systems thinking and responsible innovation as central components of sustainability-oriented chemistry education.[14,34,39–41] Each potential intervention was therefore evaluated through a hybrid rubric: traditional sustainability indicators derived from the 12 Principles were combined with an IUPAC-based assessment of its contribution to responsible practice.

To improve transferability and reproducibility, the framework was implemented as a stepwise scoring procedure that can be applied in other teaching-laboratory contexts. First, candidate interventions were identified through review of laboratory manuals and stakeholder consultation (including technical officers and teaching personnel). Second, each intervention was scored against all eight IUPAC Guiding Principles of Responsible Chemistry on a 1–5 scale (1 = minimal contribution; 5 = strong contribution), and the mean of these eight scores was calculated as the IUPAC-based responsibility score; this score was used for principle-level profiling and visual comparison (*e.g.*, radar-chart visualisation). Third, the same underlying 1–5 scores were used for prioritisation and implementation planning; for the prioritisation matrix visualisation only, these 1–5 values were linearly rescaled to a 1–10 axis to improve graphical resolution and readability. Importantly, this rescaling is a presentation step and does not change the relative ranking or interpretation of interventions. Finally, score interpretation was calibrated through discussion with technical officers and graduate demonstrators to improve contextual consistency and practical relevance in the undergraduate laboratory setting.

Because neither framework is inherently quantitative, a structured scoring scheme was developed and calibrated through discussions with TOs, graduate demonstrators, and postgraduate (PG) researchers to ensure consistency and relevance within the undergraduate laboratory context.[42,43] This combined framework enabled both a process-level evaluation of experimental sustainability and a system-level appraisal of how laboratory practices align with modern expectations for responsible chemistry.[44]

2.3 Sustainability audit and data collection

Sustainability-related information for this case study was gathered from four complementary sources: structured discussions with the TOs responsible for undergraduate laboratory sessions, meetings of UCD's cross-school and unit "Wet Lab" sustainability group, sustainability-focused proposals submitted within the School of Chemistry Graduate Teaching Assistant (GTA) module, and a systematic review of all undergraduate laboratory manuals. TO discussions provided operational insights into daily practices, including excessive use of gloves and acetone, waste-handling behaviours, choice of solvents and indicators, and the impact of older equipment on water and energy consumption. The "Wet Lab" group contributed an institution-wide perspective on ongoing and planned sustainability initiatives. The Chemistry GTA module is mandatory for all PhD students. One of the assessments in this module consists of proposing a new or revised version of an undergraduate (UG) experiment from one of the modules taught in the school. The School's postgraduate GTA assignments highlighted the potential modifications or alternative experiments that could be implemented without compromising learning outcomes. Laboratory manuals were reviewed session-by-session to document the chemicals, solvents, energy-intensive steps, waste streams, and existing sustainability notes associated with each experiment, originally mapped against the 12 Principles of Green Chemistry and subsequently reinterpreted through the IUPAC Guiding Principles of Responsible Chemistry.

2.4 Scoring and quantification of IUPAC-aligned sustainability benefits

A qualitative scoring rubric was developed to evaluate how each proposed intervention aligned with the IUPAC Guiding Principles of Responsible Chemistry.[11,37] These eight principles served as the analytical framework for rating all interventions. Two members of the project team independently scored each intervention on a five-level scale (1 = very low alignment; 5 = very high), drawing on written descriptions of each intervention, discussions with TOs, and contextual knowledge of undergraduate laboratory practice. Discrepancies greater than one scale point were resolved through consensus. Full scoring guidelines and all eight principles' ratings are provided in the Supplementary Information. The metric used in the improvement priority matrix, a composite "IUPAC Responsible Chemistry Benefit" score, was calculated from four core principles most directly related to sustainability in this context: Responsible Innovation; Safety, Security & Sustainability; Ethical Behaviour; Equitable Access.[42,43] The mean 1–5 scale score was rescaled to a 1–10 scale for use on the *y*-axis of the priority matrix.

Implementation difficulty was rated separately on a 1–10 scale based on qualitative judgement of four factors: (i) resource requirements, (ii) additional time or workload, (iii) behavioural or procedural change needed, and (iv) level of institutional approval involved. These factors were obtained through conversion into a single score for each intervention. Plotting benefit against difficulty enabled comparison between low-effort, high-impact interventions and more resource-intensive changes.

2.5 Visualisation

To support interpretation of the sustainability audit across the full undergraduate laboratory curriculum, all coded data were converted into structured datasets and visualised using Python

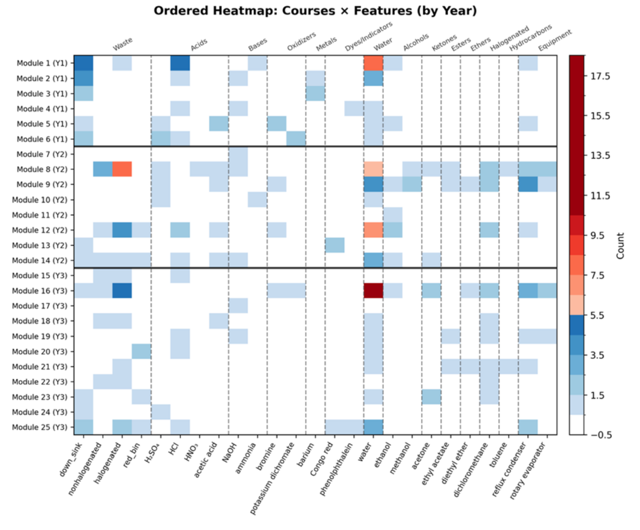

Fig. 1 Curriculum sustainability landscape (modules × features heatmap).

3.10.8. Multiple complementary visualisation approaches were employed to capture different dimensions of the analysis. An ordered heatmap of modules × sustainability features was generated to provide a curriculum-wide baseline landscape (Fig. 1), highlighting recurring patterns in solvent use, waste streams, water-intensive operations, and hazardous reagents. Circular interaction networks were constructed to illustrate the complexity and frequency of chemical usage relationships across modules. For each proposed intervention, process-mechanism diagrams were created to illustrate the operational changes and their expected reductions in water, waste, or hazardous chemicals. Summary bar charts were used to quantify the number and type of implemented improvements across laboratory streams. A priority matrix plotting implementation difficulty against the IUPAC Responsible Chemistry Benefit score was developed to support evidence-based ranking of interventions, while radar charts were produced to map each intervention against all 8 IUPAC principles and to generate an overall alignment profile. Collectively, these visual tools enabled clear comparison across modules, supported prioritisation decisions, and facilitated communication with TOs, instructors, and institutional stakeholders.[26,45]

3. Results

3.1 Baseline curriculum-wide sustainability landscape

Each experiment was coded for a set of features related to solvent choice, hazardous reagents, energy-intensive operations, and waste streams. The resulting course-feature matrix is shown as an ordered heatmap in Fig. 1, using numbers to represent the names of different modules. Counts of individual features per module ranged from 0 to 18. Halogenated solvents, bromine, potassium dichromate, and toxic pH indicators (*e.g.*, Congo red and phenolphthalein) were concentrated in a subset of Stage 2 and Stage 3 modules, forming identifiable hotspots

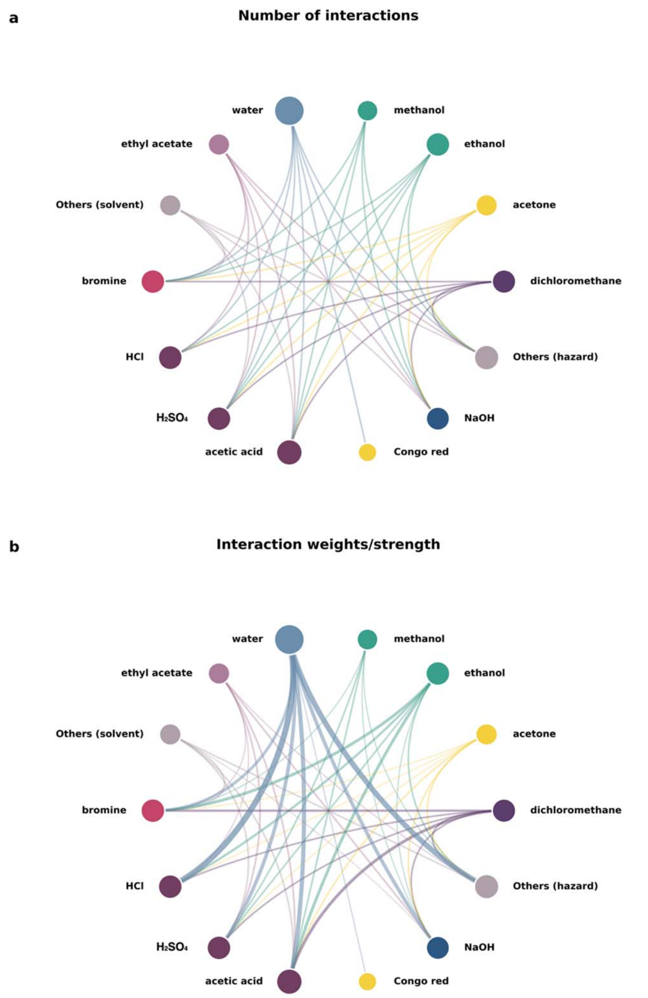

Fig. 2 Chemical usage interaction networks. (a) Number of interactions between chemical nodes. (b) Interaction weight/strength.

within the curriculum. In contrast, several Stage 1 modules contained primarily water and down-sink chemicals.

An interaction network of commonly used reagents and waste categories across all modules was constructed (Fig. 2). The nodes represented chemicals or grouped categories (*e.g.*, other solvents and other hazardous waste), while the edges represented co-occurrence within the same experiment. Fig. 2a presents the qualitative relationships, depicting the number of interactions and highlighting strong mineral acids (HCl and H_2SO_4), sodium hydroxide, acetic acid, and dichloromethane as high-degree hubs that connect multiple modules. Fig. 2b presents the interaction weight, where water and common acids/bases accounted for the largest usage interactions, while particular species, such as Congo red, contributed fewer, but distinct interactions.

3.2 Stakeholders and implemented improvements

This improvement case study involved different stakeholders. The stakeholder collaboration network in Fig. 3 summarises the roles and connections with this ecosystem. Faculty, undergraduate students, and TOs formed the core triad of primary

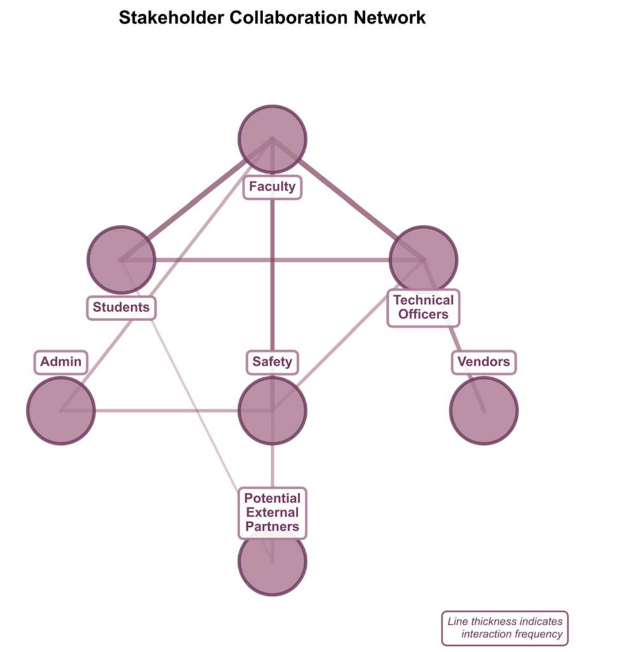

Fig. 3 Stakeholder collaboration network.

stakeholders, supported by internal collaborators (*e.g.*, administrative staff), safety services, and external partners such as vendors or potential collaborators from other institutions. Line thickness reflected the interaction frequency, with thicker connections observed between faculty and technical officers and between these groups and safety services.

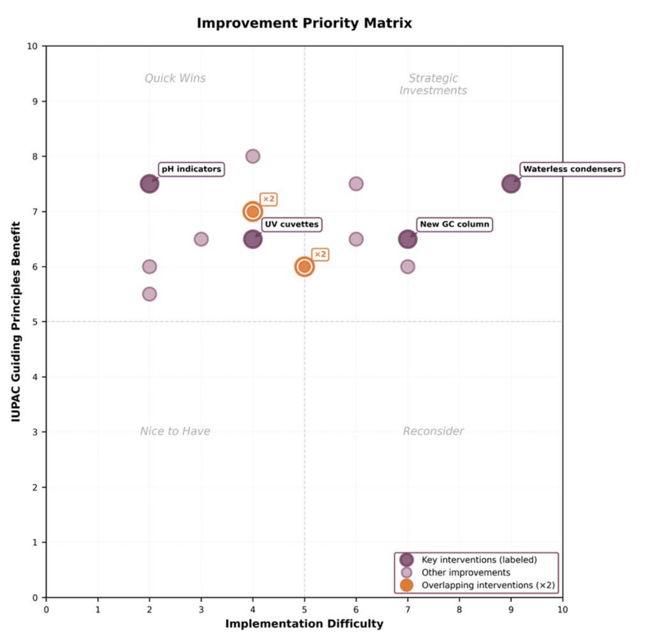

Fig. 4 Improvement priority matrix (Note: two interventions share identical (benefit, difficulty) scores and therefore overlap at the same coordinates; the full mapping and identifiers are provided in the SI (Fig. 4 dataset).).

Each potential intervention was then scored for the IUPAC Guiding Principles of Responsible Chemistry benefits and implementation difficulty. These scores were plotted on a two-dimensional prioritisation matrix (Fig. 4). Points in the upper-left quadrant (Quick Wins) represented actions with high IUPAC benefits and relatively low difficulty, such as substituting pH indicators and using reusable UV-vis cuvettes. Points in the upper-right quadrant (Strategic Investments) represented high-benefit but higher-difficulty actions, including the adoption of waterless condensers and the replacement of a gas chromatography column. Options with lower benefits or higher difficulty occupied the remaining quadrants.

Implementation outcomes across the three laboratory types and intervention categories are shown in Fig. 5a and b. In total, 15 distinct improvements were implemented: six in physical chemistry laboratories, five in introductory laboratories, and four in synthetic laboratories (Fig. 5a). When grouped by type (Fig. 5b), protocol optimisation measures were most frequent (eight interventions), followed by equipment upgrades (five interventions) and targeted chemical substitutions (two interventions).

3.3 Implemented interventions and IUPAC principles alignment

As an example, a representative intervention is illustrated in Fig. 6, showing reflux experiments where traditional water-

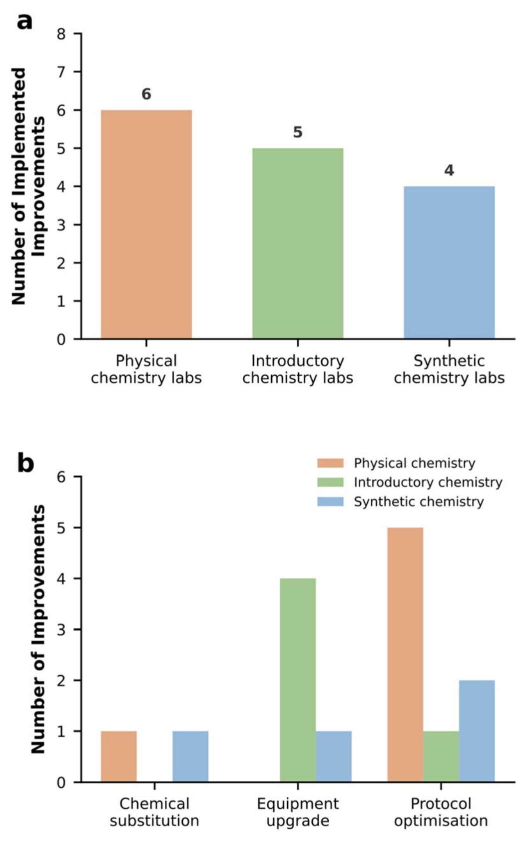

Fig. 5 Curriculum-wide implementation of sustainability improvements. (a) Total number of implemented improvements by laboratory type. (b) Breakdown of improvements by intervention category across each laboratory type.

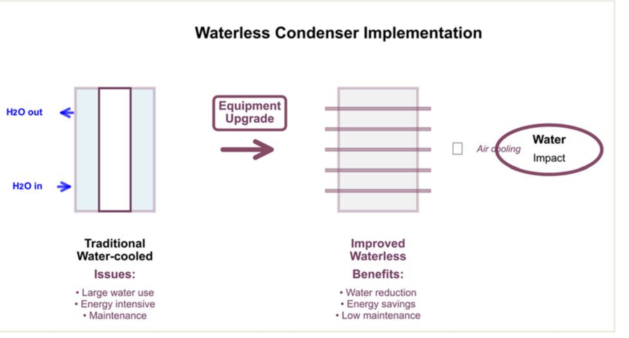

Fig. 6 Waterless condenser implementation.

cooled condensers were replaced with air-cooled waterless condensers. The schematic illustrates the main issues associated with the original setup (large water consumption, energy-intensive operation, and maintenance requirements) and shows the corresponding reductions in water and energy use achieved through the waterless design.

4. Discussion

This study provides a curriculum-wide analysis of sustainability practices in undergraduate chemistry at the School of Chemistry, UCD, integrating module-level features, stakeholder-informed prioritisation, and alignment with contemporary IUPAC frameworks. The results collectively reveal where hazardous or resource-intensive practices are concentrated, why different laboratory types adopt distinct improvement strategies, and how distributed interventions can advance responsible chemistry across an entire school. This section interprets these findings and discusses their educational, institutional, and international implications.

4.1 Interpreting the baseline patterns and stakeholders' priorities

The baseline landscape shows that first year modules predominantly used safer and less complex chemicals compared to higher and more specialized modules, consistent with established practices in introductory laboratory education where risk and procedural complexity are intentionally minimised to support novice learners.[30,46] What this study newly contributes is a programme-level perspective revealing that hazardous reagents, such as dichloromethane, bromine, and potassium dichromate, were concentrated in a small number of later-stage synthetic modules. This pattern is aligned with broader analyses of sustainable laboratory practice, which highlight how a relatively small subset of procedures or solvents can dominate environmental and safety impacts.[22,47] The co-occurrence patterns visualised in the heatmaps instead indicate recurring co-use of reagents and solvents across modules (*i.e.*, correlation rather than causation): for example, bromine frequently appears in modules that also use ethanol and dichloromethane. This highlights potential opportunities for co-optimisation within those modules, but any resulting change in associated

Fig. 7 Alignment of implemented improvements with the 8 IUPAC Guiding Principles of Responsible Chemistry (P1–P8).

solvent use would depend on the redesigned experimental conditions and require validation.[47]

Differences among laboratory types also illustrate how sustainability choices are shaped by pedagogical context. Physical chemistry laboratories prioritised protocol optimisation to support operational clarity and consistency under high-throughput first year teaching conditions. Introductory laboratories prioritised equipment upgrades due to the need for accurate data collection, whereas synthetic laboratories, characterised by mechanism-heavy experiments, focused on procedural refinements that benefit multiple related experiments. Similar patterns, where pedagogical aims and experimental complexity constrain sustainability options, have been noted in broader discussions of green chemistry teaching and laboratory practice.[22,26,46,48] This integrated explanation addresses a notable research gap: previous sustainability analyses typically examined individual experiments in isolation, without explaining why different laboratory types adopt distinct optimisation strategies at the curriculum scale.[22,48]

4.2 Educational and institutional implications

Several interventions identified in this study have implications beyond environmental performance. The adoption of waterless condensers, for instance, provides substantial reductions in water use, energy consumption, and maintenance demands, illustrating a scalable intervention that can be replicated across laboratories that still rely on traditional water-cooled condensers.[22,25] In parallel, waste reductions across plastic, glass, and sharps (Fig. 7) point to opportunities for shifting laboratory culture toward resource-aware practice, which aligns with calls to embed sustainability literacy, systems thinking, and responsible resource use into chemistry education.[22,26,46,49,50]

The long timelines involved in validating safe and reliable replacement indicators or reagents reveal a practical constraint: sustainability ambitions must be balanced with the need for pedagogical stability and reliable student learning experiences. This highlights the importance of institutional support mechanisms, including shared reagent-testing protocols, centralised procurement decisions, and routine sustainability audits: elements that echo recent proposals for systemic reform of laboratory practice.[22,51,52] Interactive tools to visualise sustainability trade-offs and impacts have also been recommended as a way to support both staff decision-making and student learning, and the visual approaches used in this study resonate with that direction.[37,51,53]

These insights address another gap in the existing literature. While previous green chemistry and sustainable laboratory studies have documented specific interventions and provided conceptual frameworks,[22,46–48] few have examined how instructor expertise, laboratory culture, and student readiness influence the implementation and scalability of sustainability improvements across an entire curriculum.[22,26,52] These factors were not directly assessed in the present study (*e.g.*, *via* staff/student surveys, interviews, or structured observations); accordingly, we do not attribute the prioritisation patterns reported here to these constructs. Future work will incorporate targeted implementation-focused data collection alongside sustainability metrics to better explain adoption pathways and scalability across diverse laboratory contexts. The curriculum-wide, stakeholder-informed model presented here demonstrates how distributed interventions can be realistically adopted while respecting diverse teaching constraints in physical, introductory, and synthetic laboratories.

4.3 Positioning the findings within the 12 principles, IUPAC frameworks, and UN SDGs

Mapping the implemented interventions to international sustainability frameworks shows that the portfolio of changes contributed to multiple dimensions of responsible chemistry. The classical 12 Principles of Green Chemistry emphasise safer solvents, waste minimisation, energy efficiency, and design for degradation,[33,47,48] and several of the implemented chemical substitutions and protocol refinements directly reflect these principles. However, the newer IUPAC Guiding Principles of Responsible Chemistry extend beyond chemical design to encompass governance, culture, inclusion, and education—dimensions particularly relevant to undergraduate laboratory settings.[37,52,54]

The quantitative profiles generated in this study demonstrate strong contributions to safety, sustainability, and systems thinking, with moderate but meaningful improvements across other dimensions of responsible chemistry. This helps to fill an important research gap: although the IUPAC framework has recently gained visibility as a global reference point, few empirical studies have operationalised these principles within real laboratory environments, especially at the curriculum scale.[26,30,37,51,55] The research findings therefore provide one of the first practical demonstrations of how the guiding principles can be used as a diagnostic and evaluative tool in chemistry education, complementing earlier work on integrating the molecular basis of sustainability and circularity into curricula.[26,52]

Finally, by reducing hazardous waste, water consumption, and dependence on toxic indicators, the implemented changes in this study directly support SDG 12 (Responsible Consumption and Production). Meanwhile, the integration of sustainability literacy, systems thinking, and visual tools for understanding sustainability into routine student laboratory practice advances SDG 4.7 (Education for Sustainable Development).[26,30,54] Together, these contributions position this case study as a replicable model for how chemistry departments can operationalise global sustainability goals and contemporary IUPAC guidance through targeted laboratory interventions.

5. Conclusions

This case study demonstrates how sustainability can be systematically embedded into undergraduate chemistry laboratory teaching through a curriculum-wide audit and an IUPAC-aligned evaluation framework. Mapping 25 laboratory modules revealed clear patterns in solvent use, hazardous reagents, and resource-intensive practices, allowing targeted identification of experiments with the greatest potential for improvement. Using a hybrid framework that combined the 12 Principles of Green Chemistry with the 2025 IUPAC Guiding Principles of Responsible Chemistry, interventions were prioritised based on their sustainability benefit and feasibility.

The implementation of 15 improvements, such as waterless condensers, reusable equipment, greener indicators, and protocol optimisation, showed that meaningful reductions in water use, waste generation, and hazardous chemical reliance can be achieved without compromising learning outcomes. The visual tools developed in this study further enabled transparent decision-making and communication across stakeholders.

This work offers a practical, transferable model for chemistry departments seeking to operationalise responsible and sustainable laboratory teaching. By linking institutional practice to contemporary IUPAC guidance, the study contributes a replicable approach for advancing sustainability across undergraduate laboratory curricula.

Author contributions

Quancheng Hu: validation, formal analysis, investigation, visualisation, software, writing – original draft, writing – review and editing; Raphaël Abolivier: investigation, writing – original draft, writing – review and editing, formal analysis; Hans-Georg Eckhardt: supervision, validation, formal analysis, writing – review and editing; Demetra Achilleos: validation, formal analysis; James Sullivan: supervision, conceptualisation, methodology, validation, formal analysis, resources, project administration, writing – review and editing, visualization; Leila Negahdar: conceptualisation, methodology, validation, formal analysis, resources, writing – review and editing, supervision, project administration, funding acquisition; Fun Man Fung: supervision, methodology, conceptualisation, resources, visualisation, writing – review and editing.

Conflicts of interest

The authors declare no conflict of interest.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5su00966a.

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