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Sustainable analytical chemistry laboratories: the critical role of education

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Over the past 20 years, interest in sustainability principles within analytical chemistry laboratories has increased rapidly. Advocates for green analytical chemistry have sought opportunities to educate themselves and incorporate sustainable practices into their work. As climate change remains a continual concern for current and future generations, there is growing pressure to address the carbon emissions from scientific work. Furthermore, to achieve the UN Sustainable Development Goals (SDGs) and with many funding bodies now placing a greater emphasis on incorporating sustainability within funding applications, there is an increasing need for all scientists to receive education in this field. A pyramid approach is proposed for sustainable science education through which there is a shift from teacher-based learning to student-based learning. Through exploring the different career stages of a scientist, appropriate pedagogical approaches have been identified. This allows a variety of training opportunities to be created to cement sustainable practices into routine approaches. By establishing a strong foundational knowledge in basic scientific practices at school level, students can develop robust, sustainable experimental design and coding skills, which can be carried forward into their later careers. When looking at the further education level, where training becomes more specialised, more technique-specific education is required. While Green Chemistry is beginning to be incorporated into universities through course designs, we identified that training should be mandatory rather than due to interest. For those undertaking continued professional development (CPD), the introduction of greenness metric frameworks and sustainability accreditation schemes provides useful tools for upskilling individuals. Despite this, many resources are arguably used primarily by those already interested in the subject. This perspective urges everyone, at any level, to include sustainability in experimental design and participate in accreditation schemes.

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Sustainability spotlight

Education is a powerful catalyst for embedding sustainability into analytical chemistry. This article explores how teaching sustainability principles across all levels, from schools to senior professional roles, can transform laboratory practice and align with the UN Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Analytical laboratories face challenges including high energy usage, chemical waste, and costly instrumentation, yet education provides the foundation for change in practices. By integrating sustainability into curricula, training, and leadership development, the community can develop greener methods, encourage resource efficiency, and promote innovation. Empowering learners at every stage ensures that sustainability becomes not an addon, but a core value driving the future of analytical chemistry.

1 Introduction

Analytical chemistry laboratories span a range of scientific disciplines, advancing scientific knowledge and underpinning critical work in areas such as environmental monitoring, healthcare, food safety, and industrial innovation.[1] However, they are also associated with a considerable carbon footprint, with operations often involving significant energy consumption, hazardous waste generation, and reliance on resource-intensive materials and equipment.[2–4] As global awareness of climate change and ecological degradation increases,[5] there is both a growing interest and an urgency to embed sustainability into all areas of analytical chemistry.

Over the past two decades, interest in sustainability within the field of analytical chemistry specifically has increased rapidly.[6] Scientific publications on the topic have surged by an average of 1436% (±708%) across four major research databases (Fig. 1a), reflecting a paradigm shift in how scientists approach laboratory practice. To guide the development of

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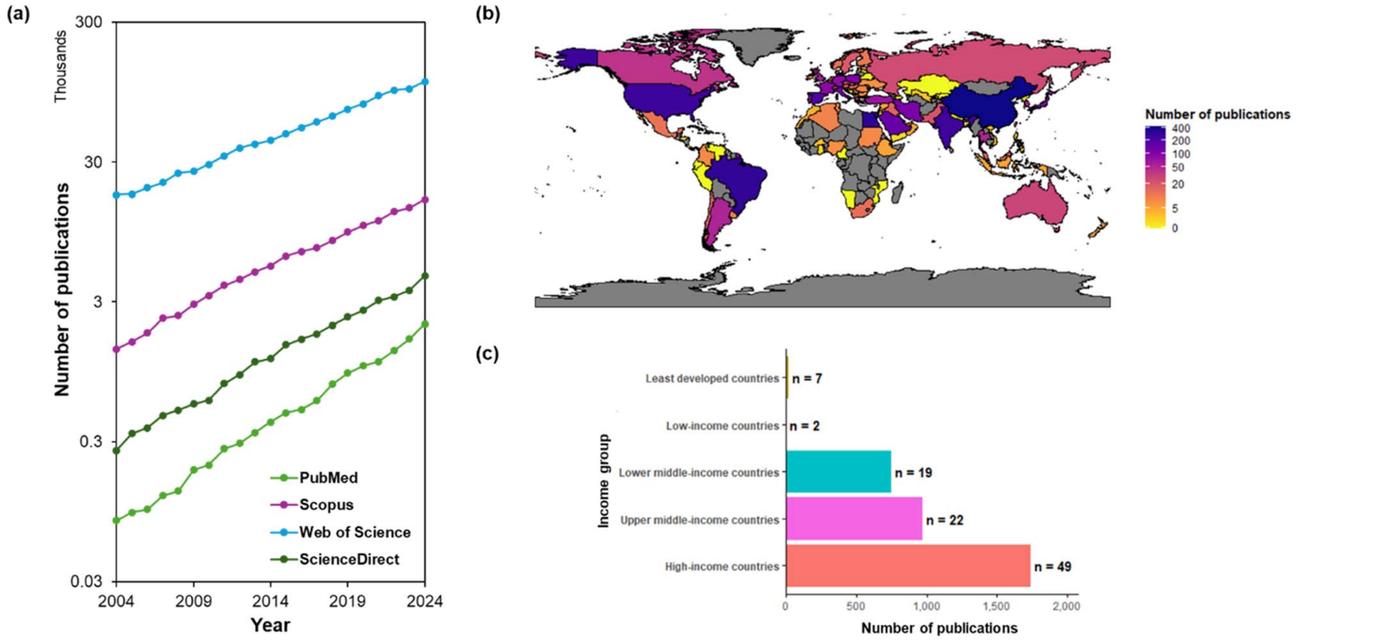

Fig. 1 (a) Temporal trends in publication volume across major research databases (2004–2024) for articles retrieved using the search query: 'analytical chemistry' AND ('sustainability' OR 'green') (logarithmic scale; accessed on 29 August 2025). (b) Global heatmap representing the geographic distribution of publications by country/territory and (c) corresponding bar chart summarising publication counts by World Bank income group, based on the OECD Development Assistance Committee (DAC) list of ODA recipients[138] (n = number of countries per group). Data panels (b) and (c) were obtained from Scopus using the following search: "analytical chemistry" AND ("sustainability" OR "green") with filters PUBYEAR > 2003 AND PUBYEAR < 2025, SUBJAREA, "CHEM", and DOCTYPE, "ar" (accessed on 29 August 2025). Heatmap colour intensity is log 10-scaled and reflects publication volume between 2004 and 2024.

environmentally responsible laboratory methods, the 12 Principles of Green Chemistry introduced in 1998, provide a comprehensive framework for minimising the carbon footprint of chemistry without compromising quality or performance.[7–9] The movement toward greener chemistry began with efforts to reduce solvent use and improve waste management, gradually expanding to encompass broader goals like energy efficiency, circular resource use, and sustainable procurement.[10] In 2013, the foundational 12 principles were adapted to specifically address Green Analytical Chemistry (GAC),[11,12] which were complemented by the introduction of the '10 Principles of Green Sample Preparation' in 2022.[13]

To further support scientists in embedding sustainability into their research, a range of frameworks such as the Laboratory Efficiency Assessment Framework (LEAF), UK Network for Sustainable Research (UKNSR) and My Green Lab (MGL) offer tools and metrics to help researchers evaluate and reduce their environmental impact.[2,4,14] These schemes are becoming more popular among scientists, supporting the transition toward more sustainable practices, while maintaining the integrity of scientific data.[4,15,16] Nevertheless, in some cases, most sustainability efforts in analytical chemistry laboratories remain concentrated in settings with high quality leadership, community participation and system resilience. Whilst many high-resource settings are expected to support the rapid adoption of green practices due to having access to advanced technologies and stable infrastructure, this may not always be the case.[17] One key example is the cost of engagement with schemes such as LEAF and MGL. LEAF participation typically ranges between £1100 and £2600. For MGL, academic laboratories pay approximately $350–$500 per laboratory for up to five laboratories, while commercial organisations pay significantly higher rates, ranging from $2800 to $4000 for 1–50+ laboratories.[4] This risks overlooking the unique challenges faced by laboratories in low and middle-income countries (LMICs), where constraints in funding, fragile supply chains, and underdeveloped regulatory frameworks can significantly hinder progress. Without deliberate inclusion, global sustainability initiatives may inadvertently deepen scientific inequities. Addressing these gaps requires a shift in perspective: sustainability must be reimagined not as a privilege of well-resourced institutions, but as a universal standard, flexible, context-sensitive, and co-developed with communities across the economic spectrum. Only then can the global scientific enterprise move toward a truly sustainable and equitable future.[18]

This aligns closely with the United Nations Sustainable Development Goals (UN SDGs), a global blueprint for peace, prosperity, and planetary health.[19] Several SDGs are directly relevant to analytical chemistry laboratories,[20] including:

- Goal 9: Build resilient infastructure, promote inclusive and sustainable industrialisation and foster innovation;

- Goal 12: Ensure sustainable consumption and production patterns;

- Goal 13: Take urgent action to combat climate change and its impacts.

By aligning laboratory practices with these goals, the scientific community can contribute meaningfully to global sustainability targets while advancing its own research missions.[3] However, sustainability is not a one-dimensional challenge. The "three-legged stool" framework offers a balanced and inclusive model for sustainable laboratory practice. It emphasises three interdependent pillars: environmental responsibility (*e.g.*, minimising waste, emissions, and energy use), economic viability (*e.g.*, ensuring cost-effective and scalable solutions), and social equity (*e.g.*, promoting safe, accessible, and inclusive scientific environments).[18,21,22] This framework recognises that sustainability is not merely a technical challenge but a multidimensional pursuit that must adapt to diverse global contexts.[23] Nevertheless, even this balanced model is incomplete without a fourth, often overlooked element: education. "Goal 4: Quality Education" of the UN SDGs emphasises inclusive and equitable education for all.[19] It could be argued that the "sustainability stool" framework is redundant without the proper principles for emerging researchers. Scientists must be equipped with the right knowledge, training, and critical thinking skills[10,24] before they can meaningfully align their research aims with sustainable practices. In this sense, education becomes the table that the stool sits under. In analytical chemistry, this means integrating sustainability into curricula, training programs, and professional development. It means teaching not only the technical aspects of green and sustainable chemistry, but also the economic and social dimensions of laboratory work. Education transforms sustainability from an abstract ideal into an actionable standard. In this perspective, we examine sustainability in analytical chemistry laboratories through the lens of the three-legged stool (*i.e.*, environmental, economic and social dimensions). We then explore how these elements intersect and how education can serve as a catalyst for a more inclusive, informed, and context-sensitive approach, guiding the global scientific community toward a more sustainable future. We discuss different pedagogical strategies across various career stages, ranging from school and higher education to continued professional development (CPD). Finally, we present recommendations and future directions for implementing and strengthening sustainability-focused education tools.

2 The challenge of sustainability in analytical chemistry laboratories

Analytical chemistry laboratories face complex sustainability challenges that span environmental, economic, and social dimensions. Environmentally, routine procedures often generate hazardous waste and rely heavily on toxic solvents and single-use plastics.[2–5,25] This is a common issue across laboratories in universities, research institutions, hospitals, and educational settings alike. Studies estimate that laboratories consume five to ten times more energy than an equivalent-sized office.[3,26] In universities, they account for ~60.0% of total energy consumption and carbon emissions.[2,27] Specialist instrumentation can be a large energy contributor which cannot be controlled by the scientist, *e.g.*, mass spectrometry (MS).[28,29] Therefore, analytical chemists are now turning to make techniques like sample preparation and chromatography more sustainable.[13] A recent study compared 174 methods used in a wide range of analytical laboratories (*e.g.*, food and pharmaceutical), where 67.0% of them had a poor greenness performance,[30] confirming the widespread need for more sustainable practices.

Traditional extraction methods, such as liquid–liquid extraction (LLE) and solid-phase extraction (SPE), rely heavily on single-use plastic and hazardous solvents.[31] Although alternative approaches like dilute-and-shoot (DaS) require less plastic and solvent, the resulting loss in analytical sensitivity limits their suitability in many applications.[13] Whilst extraction techniques cannot be completely eradicated, miniaturised techniques are now being designed and optimised (*e.g.*, micro-solid phase extraction (μSPE)).[31] Fig. 2a shows the gradual increase in publication numbers exploring the use of μSPE. This technique uses significantly smaller sample and solvent volumes compared with traditional SPE methods, as seen in Fig. 2b. Moreover, during the μSPE method development, scientists are consciously also incorporating less hazardous solvents to improve the sustainability of the extraction process. For example, Opetová *et al.* (2025) identified ethanol as a suitable green alternative to acetonitrile when extracting proteins from biological fluids.[32] Overall, comparing some other example SPE and μSPE methods showed a larger use of 'Recommended' solvents over 'Hazardous' ones[33–36] when ranked according to CHEM21 (ref. 37) (Fig. 2c).

Classic chromatography-based methodologies have a large environmental impact, such as liquid chromatography (LC), which requires large solvent usage.[38] In contrast, solvent-efficient techniques such as ultra-high performance liquid chromatography (UHPLC) and sub- or supercritical fluid chromatography (SFC) significantly enhance sustainability.[39,40] UHPLC methods employ shorter columns with smaller particle sizes operating at higher pressures, while SFC is inherently greener because it employs supercritical CO_2 as the primary mobile phase, greatly reducing the need for organic solvents. Both methods improve efficiency, resolution, and analysis speed, demonstrating that high-quality results can be achieved through greener approaches.[39,41] Another opportunity lies in selecting the most appropriate analytical technique, *e.g.*, detector, for the experiment. LC-MS/MS can consume several thousand kilowatt-hour (kWh) annually, making them substantial contributors to laboratory carbon footprints.[28,29] Whilst these techniques offer exceptional sensitivity and accuracy, they also require more energy, solvents, and maintenance. In contrast, UV-vis spectrophotometry, though less sensitive, is far more energy-efficient, requires fewer consumables, and has a lower environmental footprint.[42] When ultra-trace detection is not required, greener alternatives such as UV-vis, fluorescence, or electrochemical detection (EDC) can reduce waste and emissions whilst maintaining adequate analytical performance.[43,44] Striking the right balance depends on the specific application, and sustainability should be prioritised without compromising data integrity. AstraZeneca recently evaluated

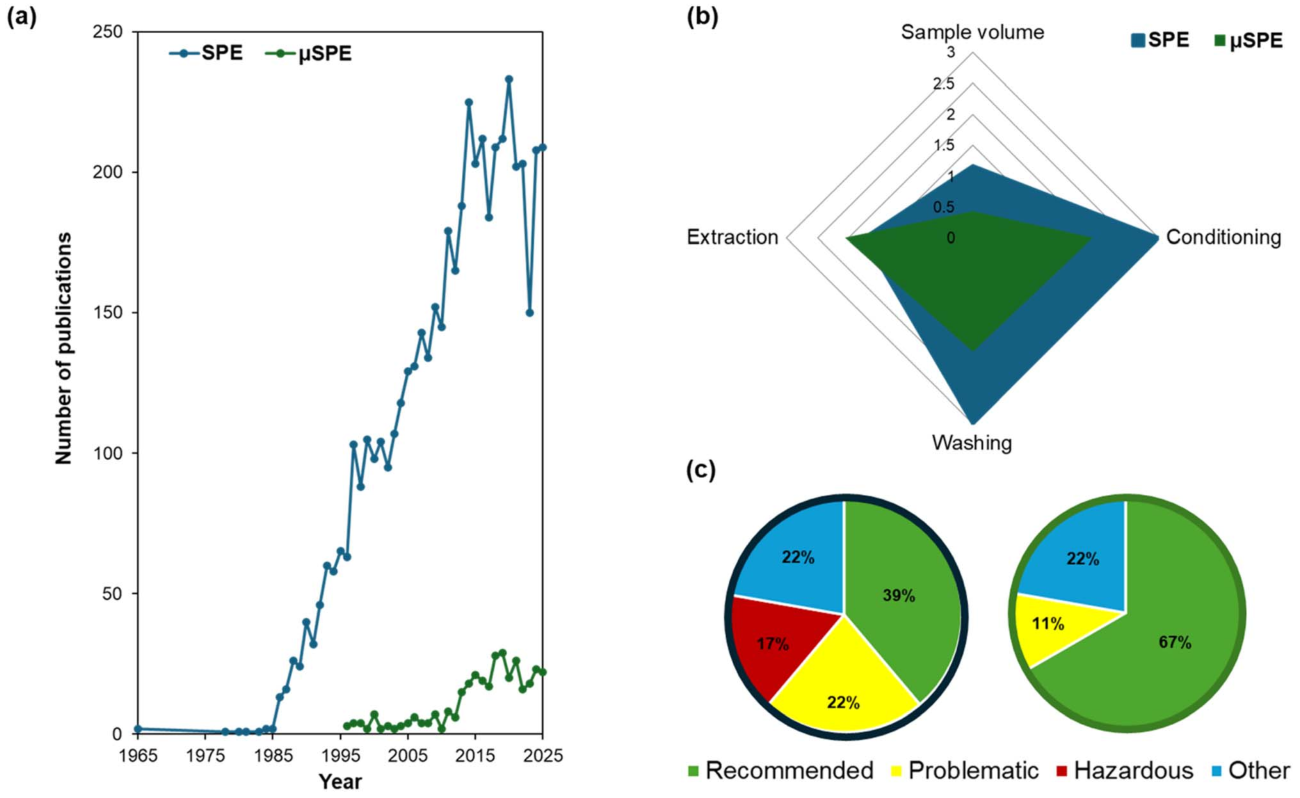

Fig. 2 (a) Trends in publications using solid phase extraction (SPE) and micro solid phase extraction (μSPE) using the following search: 'urine' AND ('solid phase extraction' OR 'SPE') plus 'urine' AND ('micro solid phase extraction' OR 'μSPE') (accessed on 28 November 2025) in Scopus. (b) Radar plot illustrating the average solvent consumption of conventional SPE *versus* μSPE for urine-based drug analysis, based on data from published studies. (c) Pie charts showing the percentage distribution (%) of solvents used in the selected SPE and μSPE articles utilised in the radar plot,[33–36] categorised according to CHEM21 solvent guide.[37]

methods based on the Analytical Method Greenness Score (AMGS) to produce a baseline for greenness for all late-stage development LC and SFC methods. This demonstrates that even industry-related sectors can apply greenness metrics to their method optimisation.[16] It is also worth noting that access to low-carbon instrumentation may be limited or not considered, confirming the need to educate researchers on selecting appropriate techniques for different analytical objectives. Whilst many energy-related metrics are often controlled by instrument manufacturers, overall, research highlights that downsizing instruments, selecting greener solvents, and shortening chromatographic separation times all contribute to lowering the environmental impact.[39,45]

There are many tools to evaluate sustainability metrics, such as the Analytical GREEness metric for sample PREParation (AGREEprep),[46] Analytical GREEnness calculator (AGREE),[47] AMGS,[48] and the Sample Preparation Metric of Sustainability (SMPS);[31,46–49] further metrics can be found in Table S1. These tools help researchers evaluate and optimise laboratory methodologies as guides to aid decisions around solvent use, reagent selection, and throughput efficiency.[31,45] However, despite the availability of many tools, none address the entire analytical process whilst integrating performance, practical considerations and economic factors at the same time.[31] Many metrics are therefore poorly suited to real-world applications, as they focus primarily on environmental impact while neglecting method reliability and practical applicability.[50] It is important that the whole analytical process is considered.[13] Nonetheless, they remain useful for educating scientists on how to reduce the environmental footprint of their methods. To address these limitations, frameworks such as White Analytical Chemistry integrate three complementary dimensions: analytical performance (red), environmental sustainability (green), and practical and economic efficiency (blue).[51] This holistic approach enables transparent and comparable evaluation of analytical methods and is particularly useful for selecting or developing technologies prior to implementation, as demonstrated in applications such as quality control of new medicines.[50]

Alongside the integration of environmental considerations, maintaining high data quality is essential to ensure that laboratory practices align with the broader goals of environmental protection.[16] Integrating greener options into analytical workflows helps minimise hazardous waste and enhance overall sustainability. However, changes such as modifying solvent types or reducing volumes may raise concerns about potential impacts on accuracy, precision, or sensitivity. Method optimisation is therefore critical when trialling these alternatives.[16] Although some may view this as resource-intensive or counter-intuitive to sustainable goals, others argue it represents a worthwhile investment with long-term environmental benefits.[52] Balancing short-term effort with long-term gains is key to advancing greener analytical practices. Achieving these requires a shift in mindset, demonstrating that environmentally conscious analytical methods can maintain rigorous scientific standards while reducing environmental impact.

Economically, many current practices reflect a model of "weak sustainability", where incremental efficiency gains fail to address deeper structural dependencies on non-renewable inputs.[18] For example, solvent recycling may reduce costs but still relies on fossil-derived feedstocks. Transitioning toward "strong sustainability" requires strategic investment in disruptive innovations that decouple analytical chemistry from unsustainable materials and energy sources.[18] Approaches like Design of Experiments (DoE),[53] *in silico* simulations[38] and preventive maintenance can reduce resource use and operational costs. A recent example in a cellular pathology laboratory in Ireland saved €37,000 annually through simple changes which focused on reducing clinical waste and energy consumption.[54] Even simple changes, such as raising freezer temperatures from −80 °C to −70 °C, can cut energy consumption by up to 30.0%;[55,56] though broader adoption depends on validated guidelines and institutional support. Limited published data on the impact of this change on sample quality and stability has led to reduced uptake in some laboratories. Regulatory bodies such as the Human Tissue Authority (HTA) provide little guidance, focusing mainly on consistent temperature monitoring.[57] To encourage adoption, robust validation studies and widely accepted guidelines are needed to confirm that higher temperatures do not compromise sample integrity, highlighting an important area for future research.

Socially, sustainability must centre on people. Creating safe, inclusive, and equitable laboratory environments is essential to ensure that greener practices are accessible to all.[23,58,59] Sustainability literacy, embedded through education, training, and standard operating procedures (SOPs), empowers scientists to make informed decisions. However, these need to be kept instep with the funding of individual facilities to ensure inclusion and promote collaboration.[60,61] This challenge is reflected in the global research landscape: the number of publications mapped under the terms 'analytical chemistry' AND ('sustainability' OR 'green') reveal that countries with lower economies, particularly across Africa (Fig. 1b), contribute substantially fewer outputs on this topic compared to higher-income countries (HIC) or regions (Fig. 1c). A similar trend is also observed in the analysis of funding sources. Least developed and low-income countries show no publications supported by their own national agencies, whereas the majority of funded publications originate from upper middle-income countries, largely driven by China (Fig. S1a). In contrast, although HICs account for the largest number of distinct funding countries ($n = 20$), their total publication output remains lower than that of upper middle-income countries (Fig. S1b). Using the Times Higher Education (THE) Impact Rankings (2025), which assess 2526 universities across 130 countries or territories based on progress towards the UN SDGs,[62,63] we further examined sustainability performance within institutions offering chemistry programs. The analysis was focused on SDGs 9, 12 and 13, which are directly relevant to analytical chemistry laboratories. This revealed that certain countries, such as Australia (*i.e.*, an HIC), achieve the highest sustainable average SDG scores (Fig. S2). Examining the relative contribution of each SDG, least developed and low-income countries lack data for these goals (Fig. S3a), while SDG 13 is predominantly represented among HICs. Most lower middle-income countries also show no SDG 13 data, with the exception of Nigeria and Pakistan (Fig. S3b). Principal component analysis (PCA) of these SDGs, visualised as an HJ-biplot,[64] demonstrates clustering of countries across all income groups, with 82.2% of the total variance explained (Fig. S4). Nevertheless, HICs generally cluster closer to the SDG vectors, reflecting their better access to advanced technologies and instrumentation, including more sustainable ones.[12] This disparity was already highlighted in 2010, when the Pan Africa Chemistry Network held a congress on Green Chemistry.[12,65] During the meeting, participants emphasised the need for a set of green chemistry principles tailored to the challenges faced in Africa. The 12 Principles of Green Chemistry were originally developed in HICs and are often ill-suited to African contexts due to significant differences in economic development and infrastructure. In response, the Greener Africa principles were introduced, underscoring that simplicity and practicality are essential, and that technologies must not only function but also be easily maintained within African settings.[65]

In many LMICs, practices such as recycling, reusing, repairing equipment, and minimising waste are common and, in some cases, more prevalent than in the Global North.[66] These practices reflect sustainable resource use and value creation within a circular economy framework[66] and can therefore represent a positive outcome for sustainability. This stands in contrast to the replacement-oriented culture typically observed in wealthier institutions. However, in many LMICs, these approaches are often the only viable options,[67] which can limit their effectiveness. In forensic science, for example, many regions in the Global South continue to face significant limitations in trained personnel, financial resources and access to advanced technologies. Initiatives like "frugal forensics" aim to develop context-sensitive solutions that meet local needs without compromising analytical quality or scientific integrity.[68]

MS instrumentation is also often inaccessible in developing countries due to its cost and infrastructure requirements. As a result, low-cost alternatives are recommended. In Argentina, for example, researchers have piloted the ARSOlux biosensor as a simple, cost-effective field tool to detect bioavailable arsenic in natural waters, offering an alternative to expensive spectrometric analysis and enabling water quality monitoring in regions with limited analytical infrastructure.[69] Similar resource-driven approaches are evident in clinical applications, where colourimetric-based techniques and rapid diagnostic tests are commonly used.[67] One example is the development of paper-based analytical devices, such as the Chemotherapeutic Paper Analytical Device (ChemoPAD), which provides a low-cost, field-deployable screening tool for detecting substandard and counterfeit chemotherapeutic drugs in settings where access to conventional analytical laboratories is limited.[70] However, some of these methods can frequently fall short in sensitivity and specificity, particularly for disease screening in asymptomatic individuals, and often lack broad applicability.[67] Charitable initiatives are increasingly addressing this gap. One example is the Recycling Organization for Research Opportunities (RORO), which redistributes surplus scientific analytical instrumentation to academic institutions in developing regions and provides training to users who would otherwise be unable to afford new equipment.[71] Where possible, RORO also supplies spare parts and preventative maintenance kits, helping to extend the usable lifespan of donated instruments.[67,71]

3 Education as a catalyst for change

One of the main barriers in integrating sustainable practices is the need for targeted education and training which are aimed at promoting their adoption within the analytical chemistry community.[72,73] Education is a powerful driver for sustainable transformation in analytical chemistry and lays the foundation for long-term change. Scientists, at any career stage, need to be equipped to make environmentally responsible decisions.[18] From school training to professional development, sustainable practices must be embedded into the curricula, laboratory protocols, and institutional culture. This includes the introduction of Green Chemistry principles, resource-efficient techniques and ethical considerations to ensure these practices become integral to their scientific identity and practice. Training in sustainable analytical chemistry is usually limited to short courses, conferences, one-off activities or specific modules within the degree. Additionally, these are often only undertaken by those who already have an interest in this subject area.[73] Addressing this is therefore critical if sustainability literacy is to be established as a core professional competency, essential for the long-term advancement of both chemical education and practice.

There is, however, an argument that educational approaches targeting sustainable science should start as early as possible. Integrating sustainable practices into science classes should encourage behavioural changes later in life.[74] School teachers are therefore in a unique, yet impactful, position to instil sustainable and best practices into their students. Importantly, they are also upskilling the next generation of scientists, allowing them to carry these practices into their future scientific careers, leading to lasting change (Fig. 3).[52]

However, currently basic environmental metrics, such as solvent reduction and waste minimisation,[75] are not taught due to the constraints of long-standing traditions and a rigid curriculum.[76] Embedding a three-pillar perspective within curricula enables students to critically evaluate analytical methods in terms of their environmental impacts, economic feasibility, and social accessibility. This can be operationalised through the inclusion of sustainability appraisal exercises within laboratory reports, in which students systematically assess experimental protocols across all three dimensions.[77] In parallel, structured discussions and collaborative projects may be employed to examine broader issues of equity in analytical chemistry,[78] including disparities in access to instrumentation and the potential of open-source methodologies to enhance global participation. This can cultivate sustainability literacy that extends beyond isolated environmental metrics or technical efficiency. Importantly, sustainability education must be inclusive and accessible, without risking excluding underfunded laboratories, reinforcing global disparities in scientific participation.[23,52]

Equally important is the upskilling of professionals already working within analytical chemistry to bridge existing knowledge gaps and foster broader adoption of sustainable practices. Nonetheless, there may still be hesitation in the uptake of sustainable practices due to a lack of evidence[79] or institutional

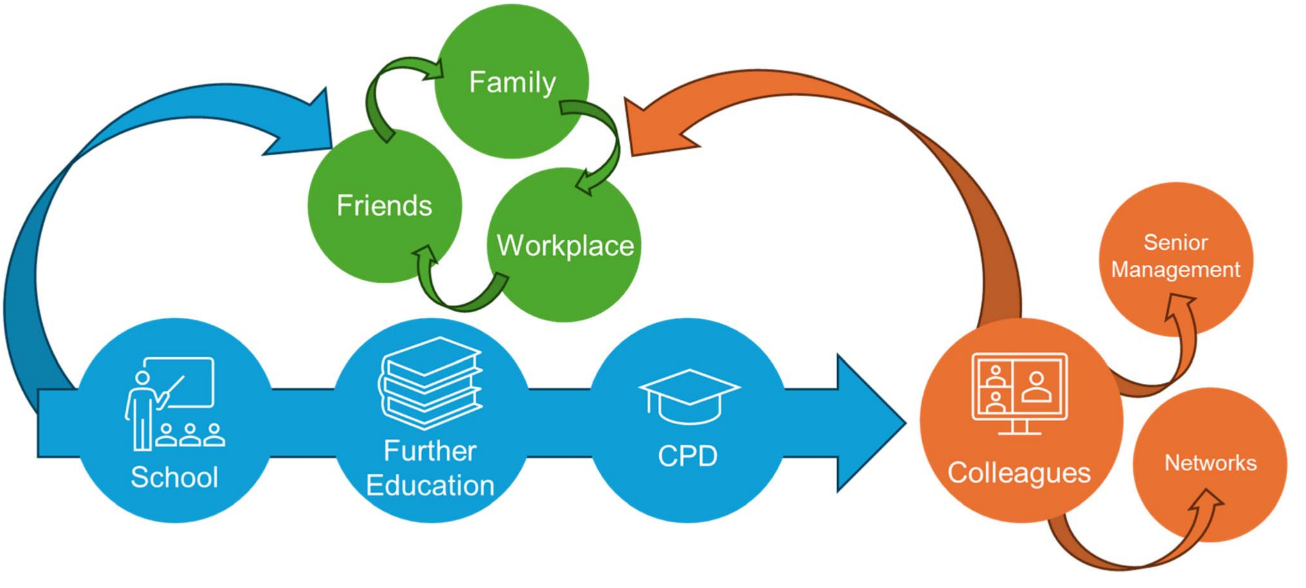

Fig. 3 Educational and professional pathways shaping sustainability engagement. A flow diagram outlining the progression from school to career, highlighting how education influences professional networks, workplace culture, and personal relationships, key touchpoints for embedding sustainability across life stages.

support. This strengthens the collective responsibility of the scientific community to rigorously evaluate these approaches and actively disseminate findings that demonstrate their validity and reliability.

Further evidence supporting the need to educate the scientific community in sustainability is the growing emphasis placed on environmental responsibility by major funding bodies. In response to the escalating climate crisis, organisations such as Science Foundation Ireland (SFI) and Cancer Research UK now incorporate sustainability criteria into the evaluation of research proposals.[80,81] Additionally, the Wellcome Trust coordinated the 'Concordat for the Environmental Sustainability of Research and Innovation Practice', bringing together the UK Research and Innovation (R&I) sector.[82] The concordat aims to encourage research institutions to embed sustainable practices, reduce their carbon footprint, and promote responsible resource management across all areas of scientific research. Without targeted education and training, the implementation of such practices risks being superficial or inconsistent, limiting their potential impact. Therefore, scientists need to be upskilled to allow them to make the most informed sustainable experimental designs.

4 Integrating education into sustainable analytical chemistry laboratories

Education focusing on sustainability prepares future professionals to reduce human impact on the environment.[83] In this discussion, the focus is on different pedagogical approaches and key topics for educating about sustainable practices in analytical laboratories. It is important to emphasise that education, in this context, encompasses all stages of a scientific career and begins from an early age. For any discipline, foundational concepts are introduced during school, expanded at college and university, and further developed throughout professional practice, forming a simple pyramid-like progression (Fig. S5). The same model can be applied to the teaching of sustainable analytical chemistry and laboratory practice with basic, universally applicable principles that should be introduced early and then reinforced throughout one's career.

UNESCO's Education for Sustainable Development (ESD) supports this approach by introducing three interconnected learning dimensions: cognitive, socio-emotional and behavioural,[84] all of which are essential for cultivating a comprehensive understanding of sustainability and empowers learners to take meaningful action in laboratory environments. Importantly, the SDGs call for everyone to have access to these ESDs by 2030.[85] In Scotland, the ESD equivalent is named Sustainable Development Education (SDE) and forms part of the Scottish Government's "Target 2030": to inspire change to allow every place educating children of ages 3–18 to become a 'Sustainable Learning Setting'.[86]

It is important to recognise that different pedagogy must be considered when educating scientists about sustainability within analytical chemistry, as it shapes how information is transferred and absorbed. Teacher-centred educational approaches could be more advantageous at school, where foundational knowledge is being established (Fig. S5). In environments where learning is more self-directed (*e.g.*, university and the workplace), there is a greater emphasis on student-centred teaching.[87] Due to their career stage, students arguably are the most valuable tool in shifting the scientific community towards more sustainable practices, as the foundational knowledge they gain during their education can make their adaptation second nature.[10] This, however, does not disregard the importance of educating those already in the workforce. It simply confirms further that a different pedagogical route needs to be explored. Importantly, at any level, education should inspire, empower and equip the individual.[88]

4.1 Education at school level: building foundational knowledge

Sustainability related education has largely been a focus within higher education as it is linked to 'employability' due to a large focus on fulfilling green job targets.[83,89] However, introducing sustainability concepts in science classes enables young students to begin integrating these practices from the very beginning.[90] When taught from an early age, sustainability thinking is more likely to be carried forward into their future scientific training and careers. Moreover, engaging young children in discussions surrounding sustainability is also a powerful tool in sparking conversations in their households[91] as they share what they have learnt in school with their families. This represents an early example of education creating a ripple effect, where classroom learning prompts wider awareness and further learning beyond the school environment (Fig. 3).[92]

At a school age, learning for sustainability is supported through teacher-facilitated approaches. Educators play a crucial role in presenting information to students.[93] Learning which develops knowledge is not sufficient, as skills are developed further through application and prevents the teacher from being the "fount of all knowledge".[94] Therefore, problem and context-based learning (PBL and CBL, respectively) should be encouraged as students progress through their education.[93] Crucially, this supports the implementation of the ESDs as pedagogical approaches should empower students with not only the knowledge and values but also the ability to address challenges posed by the SDGs. A CBL-style Green Chemistry module was designed which introduced the Principles of Green Chemistry to high school students. Topics such as waste prevention and the use of safer solvents were incorporated leading to an improvement in students' attitudes towards Sustainability and Green Chemistry.[95]

Understanding the most effective pedagogy alone will not ensure adequate teaching on sustainability as it also needs to be supported by the school curriculum.[96] Despite climate change having been long embedded in the curriculum, a recent report from the Royal Society of Chemistry (RSC) highlighted that four in five young people think climate change and sustainability should be a priority within the classroom. This is supported by both primary (nine in ten) and secondary level (two thirds) of

Chemistry teachers.[88] These statistics suggest that more coverage of this topic is not only seen as important but also of great interest to the student population. Understanding these topics is crucial for students to appreciate the relevance of Green Chemistry within the context of climate change. However, there is a lack of evidence regarding the practical application of sustainability within the laboratory being taught, suggesting a substantial knowledge gap.

An equally important consideration is that many teachers will require training themselves. Organisations such as the RSC and STEMLearning provide resources to upskill teachers in this area.[97–99] A workshop entitled "Environmental Sustainability Workshop for A-Level Chemistry Teachers" was held in Singapore, with 18 chemistry teachers participating. This highlights that there is an interest in this subject area.[93] In the Philippines, school teachers were surveyed on their awareness, attitude, knowledge, perception, and views on Green Chemistry education. The study indicated that they had moderate awareness of these topics as well as low awareness of the 12 Principles of Green Chemistry.[100] Teachers in LMICs may have limited training surrounding sustainability. If educators are unaware, incorporating these topics into the curriculum becomes challenging and must be addressed to ensure an equal distribution of a workforce knowledgeable in sustainability practices. It is important to acknowledge that schools in LMICs may lack the funding needed to invest in teacher development, compared to better-resourced institutions, which highlights the social pillar of the sustainability stool.

Attitudes may also differ between countries. A survey carried out at a school in Indonesia showed that despite being aware of Green Chemistry, 47.2% of teachers disagreed with it. This was actively shown in the students' approaches to practical chemistry (*e.g.*, using more reagents than required).[101] These findings are a stark contrast to those in the RSC report, which surveyed educators within the UK and Ireland. The key difference lies in the teacher's location, suggesting that they may have received different levels of training surrounding sustainability and the importance of its incorporation into the chemistry curriculum.[77]

At a school level, foundational knowledge should be built, which can cover fundamental issues relating to climate change and the importance of more sustainable actions. There are key sustainable practices that can be taught at schools that are applicable across several different sciences, including analytical chemistry. One example is the theory of DoE instead of the traditional one-factor-at-a-time (OFAT), which can minimise the number of trials needed for method development and validation, saving both time and materials, and therefore money. DoE successfully allows users to study variables and outputs in a minimal number of experiments, resulting in identification of the ideal parameters.[53] The teaching of practical classes in this manner is a powerful tool for students to learn the possibility of providing high-quality data in a sustainable manner.

Education surrounding the incorporation of new technology is also crucial, encompassing both its benefits and potential drawbacks. Emerging tools such as artificial intelligence (AI), *in silico* simulations and computer-assisted method development offer the promise of faster and greener approaches.[38] However, it is important to recognise the hidden environmental costs. For example, training AI models can generate nearly five times the lifetime emissions of an average American car.[102] As analytical chemistry becomes increasingly reliant on computational methods, it is essential to address these impacts through comprehensive education.[103] Coding and computational literacy have now become part of the school curriculum,[104] which is important for future career prospects, but sustainability considerations must also be integrated to ensure responsible practice is not overlooked. Lannelongue *et al.* (2003) proposed the GREENER principles as a framework for promoting environmentally sustainable computational science.[105] These principles include actions such as the estimation of the environmental impact, as well as governance. As computational approaches become increasingly embedded across scientific careers, this may represent one of the most critical areas in which sustainable education is needed.[105]

Importantly, the demand for green skills (22.4%) has already surpassed the green talent within the workforce (12.3%) between 2022 and 2023. As the demand for chemists specialising in Green Chemistry is expected to grow by 5.0% by 2029,[89] there is a clear need for a more sustainability-focused chemistry curriculum.[88] A skills gap was also identified by the RSC, with 68.0% of practising chemists indicating a lack of knowledge and skills required for current and future green jobs.[106] This need is strengthened further with the UK Government's aim to support two million green jobs by 2030.[88] Whilst the drive for these topics is encouraging, there is still a lack of examples demonstrating how sustainability laboratory approaches are taught within analytical chemistry.[107] The focus is largely on developing sustainable approaches to existing technologies and does not consider daily laboratory practices. However, if taught effectively, students should feel inspired and interested in sustainability, leading to empowerment to apply green analytical methodologies to these types of scenarios as they continue their education.[89]

4.2 Training scientists: further education to continued professional development

In principle, an individual's laboratory practices is fundamentally shaped by their initial training. As scientific education becomes more specialised at further career stages, it is essential to place greater emphasis on developing strong foundations in analytical techniques which builds upon basic scientific knowledge. In the lens of sustainability, this includes the application of rigorous yet greener methodology. Most importantly, this should include discussions surrounding the advantages and disadvantages of different techniques, which equip individuals to choose the most appropriate technique. Educating individuals to critically assess whether the most sensitive technique is required, or if simpler techniques can adequately address the research question is one vital aspect. Achieving this shift will require changes in behaviour and mindset among scientists. Arguably, laboratories may not have the necessary instrumentation or equipment in place to do so, but this raises the importance of sharing resources, which addresses the social pillar of the sustainability stool.

4.2.1 Further education. The pedagogical approach at the university level shifts away from a teacher-led model to more active and participatory methods. Whilst lectures are effective for knowledge dissemination, they should act as a springboard for students to engage critically with the taught topics. Methods such as BPL and CBL activities, group work and reflective projects allow students to facilitate their own learning and decision making by allowing students to apply their knowledge in relevant scenarios within the real world.[108] Through the contextualisation of knowledge into relevant case studies or problems, students can implement theory in a meaningful way.[93] PBL allow students to become active problem-solvers by engaging with critical issues. Furthermore, they encourage learners to participate actively with research, discussion and solution development. This student-centred teaching approach fosters a sustainability mindset in scientists, while allowing them to become more critical and shaping them into independent thinkers.[109] This prepares them effectively as the future workforce by equipping them to seek more sustainable practices. Lastly, whilst at university, students often participate in extracurricular activities that align with their interests. An offshoot of PBLs could encourage students to continue pursuing their interests in sustainability through sustainability-focused student groups and organising events that disseminate this to the wider community (Fig. S6). Empowering students through this type of pedagogy equips them to actively engage with the subject beyond the classroom.[10]

Similarly to upskilling schoolteachers, university educators also need to be provided with resources to support them in not only sustainability knowledge but also what pedagogy they should use for this subject area. Some resources already exist, such as a course offered by University College London on the online platform FutureLearn which has had nearly 4000 participants enrolled on the three-week course.[110] The online format allows easy access to everyone with an internet connection, thereby increasing its accessibility. However, there is still a cost involved, which may limit the number of participants per educational institution. In contrast, the organisation ‘Beyond Benign’ offers free Green Chemistry curriculum suggestions for any level of education (*i.e.*, elementary school to higher education).[111] Overall, however, fewer resources are available for university-level teachers.

Universities are recognising the importance of sustainability and courses are increasingly incorporating it in their offerings, with a focus on sustainable resources and emerging green technologies. This is an encouraging step towards upskilling future scientists, especially as sustainability is becoming a central component of many scientific careers.[112] However, limited information exists on the extent to which fundamental sustainable practices are being taught in laboratory classes. All students, not only who opt into sustainability-focused modules, should be exposed to sustainable laboratory principles through their education. An initial structure was proposed by Miladinović (2025), who designed a module teaching students about GAC and how to implement it into their work.[75] A real-life example includes the University of Surrey, which offers training in sustainable analytical approaches through a module entitled “Principles of Analytical Chemistry”. Both of these illustrate how sustainability can be meaningfully incorporated into the teaching of core analytical skills, arguably the most natural and effective environment for this.[113] This mirrors the teaching of fundamental theories at school, which are crucial for continued study of the subject.[44] In addition, several universities and professional organisations now recognise the importance of Green Chemistry and the imperative to enhance students' competencies in this field. Table S2 highlights some examples of innovative initiatives and programmes available to under- and/or postgraduate students. Only one course in an LMIC was identified, suggesting there is still a larger focus on sustainable education within HICs. Despite this, two courses are free to attend, and IUPAC offers discounted registration fees for attendees from developing countries.[114] However, travel and accommodation costs still need to be covered, which could decrease the chances for individuals to attend. In contrast, the American Chemical Society (ACS) Green and Sustainable Chemistry School is completely free to attend, with all costs covered, making it accessible to individuals from low-income backgrounds across the Caribbean, as well as Central, North, and South America.[115]

Funding is also beginning to support the development of resources and avenues for sustainable education within the higher education sector. Out of 58 research projects funded *via* the RSC Sustainability Grant in 2024 and 2025, 10.0% focus on education. These projects include initiatives aimed at teaching laboratories, such as developing training tools for students to assess the sustainability of their experiments.[116]

4.2.2 Continued professional development (CPD). When wanting to learn a new skill, a scientist would naturally attend a training course as well as non-educational activities, such as private reading and social interactions.[117] Training throughout a scientific career should also incorporate sustainability as part of CPD.[118] The use of this term introduces a more professional take on lifelong learning.[117] Formal workplace learning has been found to decrease between 2002 and 2017. However, reports indicate that this trend is attributed to more informal channels of education being used rather than formal ones.[119] This supports that workers are identifying topics that are more relevant and important to their specific roles, rather than what is currently being offered. It may be argued that education around sustainability-related topics could fall under this umbrella. If the study of this topic were formally recognised as CPD, then it would further strengthen its importance in the workplace. The same report suggests that adult learning is taken up more largely by wealthier and more skilled workers, confirming that LMICs are less likely to upskill themselves.[119]

Arguably, sustainable practices are a new skill to many, especially those who were not exposed to this during their school and further education, so institutions should be providing the resources that equip everyone to implement these into their work. However, the incorporation of sustainability training needs to be planned with the individual, especially once they reach postgraduate or early career levels. Through this, it allows them to direct their training to relevant areas which interest them and align with their work, which in turn will increase their willingness to engage in the training. Institutions should support individuals in creating their own CPD, which could include organising events that focus on sustainability.[118] This would address the social pillar as it would create safe and inclusive working environments, ensuring social equality and accessibility to greener technologies for everyone.

Whilst school and higher education have a very structured strategy for the dissemination of knowledge, once an individual enters the workforce, upskilling is arguably self-driven. This means there is a stronger shift from learning about sustainability to learning for sustainability.[120] However, suitable material should still encompass suitable pedagogy that educates the individual about sustainability. Vocational education (VE) is a platform that integrates education outside of the current academic curriculum. In line with the approaches outlined in the previous section, VE involves PBL, making it more accessible to the already skilled workforce. Some theory may need to be included, especially for those who are completely unfamiliar with sustainability practices, but overall it provides a practical route to CPD. VE offers modular education models that encompass a flexible curriculum. This flexibility is important as it increases the accessibility of sustainable education, depending on the type of chemistry the scientist practices. For analytical chemists, this can focus on techniques previously mentioned by encouraging them to critically evaluate their own research. This type of educational platform enables broader institutional access, leading to a diverse socioeconomic distribution of CPD.[120] Another potential avenue for engaging individuals with sustainability in the workplace is CBL. This approach is readily used in nursing practice, a practical vocation, suggesting it could be applied to the analytical laboratory.[120] By providing relevant case studies where sustainable laboratory practices can be implemented, scientists would not only learn about sustainability but also its practical application in reducing their carbon footprint.

An example of CBL within the laboratory setting is a dedicated sustainability assessment, similar to a risk assessment, which would allow scientists to assess the sustainability of their planned laboratory activities. Risk assessments are already a routine requirement prior to any laboratory work, meaning this additional step should be easy to incorporate. In most institutions, it is compulsory to undertake training in Risk Assessment and Control of Substances Hazardous to Health Regulations (COSHH) forms; therefore, introducing training on sustainability laboratory practices could be a feasible option to upskill the individual in this area.

Evidently, an aspect of teacher-focused learning is also required, as some scientists may have more expertise within sustainable analytical chemistry than others. Through the dissemination of their knowledge, they will promote sustainability literacy and help embed responsible laboratory practices. A recent course held at a hospital located in Turkey highlighted a notable increase in the participants' knowledge levels. This confirms the importance of providing educational opportunities on this topic.[121] Another practical approach is to incorporate sustainability into laboratory induction training, an already routine and often legal requirement to ensure health and safety standards are met. Institutions seeking the Bronze LEAF award, for example, are required to provide evidence of such training,[122,123] meaning some laboratories may already have elements of sustainability embedded in their induction processes. Another example includes initial training within the laboratory. For instance, if a researcher's first laboratory experience occurs in an environment adhering to Good Laboratory Practice (GLP) or International Organisation for Standardisation (ISO) accreditation standards, the behaviours and expectations established in such settings are likely to be carried forward into subsequent roles, even in laboratories without formal accreditation.[124] This highlights the critical importance of instilling best practices and sustainability-conscious standards from the very beginning of a scientist's career. Similarly, by implementing greenness metrics and sustainability frameworks into routine research, traditional thinking is constructively challenged, prompting critical reflection on established methodologies. This can be achieved through integrating sustainability into SOPs, which not only educates the author but also the next generation of analytical chemists through carrying out the routine work.

The incorporation of sustainability practices and frameworks within workplaces, including educational institutions, is growing. Challenges such as the ‘Freezer challenge’ encourage scientists to take ownership of their carbon footprint.[125,126] This can lead to educating scientists in two main ways: those implementing the frameworks and those working in the accredited laboratories adhering to the frameworks. LEAF is another example of this and was formally launched in 2021. Twenty-three institutions initially piloted the scheme between 2018 and 2020, and it has continued to grow in popularity, with 115 institutions from 15 countries participating as of July 2024.[4,122] It takes approximately 20 to 40 minutes for one individual to complete the Bronze criteria, with the exact time depending on their knowledge.[4] This is a prime example of how sustainability frameworks not only encourage more sustainable laboratory practices but also actively upskill individuals. Furthermore, because audits are conducted internally within institutions, they facilitate the dissemination of knowledge across different groups, enabling sustainable practices to be shared and adopted more widely. Furthermore, MGL requires at least 50.0% of lab members to participate in the scheme, increasing the number of upskilled individuals further. These statistics highlight the powerful tool sustainable frameworks are in educating scientists in sustainable practices. However, these frameworks do not address all three pillars of the sustainable stool. The large cost of participation, outlined previously, means that both the social and economic pillars are not fully addressed. Additionally, frameworks currently available are only designed for British and US laboratories, with little or no translation into other languages.[4] Laboratories in non-English speaking countries or in countries that have little excess resources to spend on these initiatives will therefore miss out on participating and upskilling themselves. Similarly to the UK, European countries are also facing growing pressure from funding bodies to include sustainability accreditation in their applications.[80]

Moreover, sustainable practices are no longer confined to wet laboratory environments, with both frameworks and metrics being available to those working in a dry laboratory environment. An example of the latter is the 'Green Algorithms Calculator', which allows users to calculate the carbon footprint of their codes.[127] Whereas Green Digital Sustainability Certification (DISC) is a certification scheme that measures the impact of digital and computational research.[128] As of September 2025, six teams have successfully completed the inaugural round and received Bronze Certifications. Unlike LEAF and MGL, this scheme is free and open access, making it the first framework to be accessible to all.[128] Another prime example of supporting education of sustainable computing is King's College London, which provides both the support and infrastructure for those conducting software development, computational work and data analysis research. As part of this, they provide guidance on sustainable computing, including strategies for improving energy and hardware efficiency, plus raise carbon use awareness.[129] A similar course exists from the EMBL's European Bioinformatics Institute.[130] Lastly, the Green Software Foundation offers a free training course on how to create 'Green Software'.[131] It is encouraging to see the shift in upskilling computational scientists in sustainability. However, the primary challenge continues to be providing scientists with adequate time to complete these CPD opportunities.

There is also now an influx of groups and networks that are offering resources to upskill scientists through events and training courses.[3] This includes the 'International Institute for Sustainable Laboratories' which hosts an annual education week[132] as well as industry-focused events.[133] The RSC, Medical Research Council and European Molecular Biology Laboratory are also holding conferences to share research outputs relating to sustainability and as a platform to spark discussions.[134] Whilst these are useful resources, employees need to be given the option to attend which in some settings may be difficult, especially if sustainability is not currently being prioritised by their organisation. Furthermore, almost all of them are located in HICs, with none currently being evident in LMICs.[3] This once again highlights how there is an unequal distribution of support available to countries aiming to develop more sustainable analytical chemistry laboratories.

Lastly, disseminating knowledge through publications is critical, as it may help reduce reluctance to implement sustainable practices.[135] A recent publication highlighted that feedback on sustainable practices triggered a 52.8% reduction in leaving the fumehood open.[136] Fumehoods are a major source of energy consumption, with a single unit using roughly the same amount of energy as one home alone.[2] Understanding what has successfully worked for laboratories in a drive to reduce their carbon footprint is a crucial component. Sharing these findings through publications engages the natural curiosity of every scientist and empowers them to bring about change within their institutions. It needs to be acknowledged that implementation efforts are often met with scepticism,[75] particularly from those unfamiliar with strategies that balance environmental responsibility with scientific rigour. This hesitation is further reinforced by the limited evidence available. Publications, therefore, play a crucial role in providing the justification needed to support and advance such changes. This raises the importance of quality over quantity, as well as an openness to adopt sustainable practices without published evidence. Furthermore, many journals now request that authors align their research with the relevant SDGs.[135,137]

5 Recommendations and future directions

Education is a valuable tool in triggering long-term effects. One individual has the potential to implement change through educating those around them, which in turn spreads to the wider community (Fig. S6). Importantly, the role of 'teacher' should not be restricted to only those formally assigned that title; rather, all members of the scientific and educational community share the responsibility of promoting sustainable practices. It is also possible to align the suggested laboratory sustainability interventions to the SDGs (Table 1), confirming that ESDs can be met. Furthermore, to facilitate broader uptake of sustainability within analytical chemistry, several actionable steps can be implemented:

• Localised sustainability education: Develop region-specific curriculum that reflect local environmental challenges, resource constraints, and cultural contexts. It is important to recognise that the knowledge of teachers on these topics varies across regions. A comparison of a LIMC (*e.g.* Indonesia) with HICs (*e.g.*, England and Wales) highlighted a difference in attitude towards the importance of including sustainability in the school curriculum. As a result, students lack awareness and do not achieve the ESDs.

• Open-access teaching materials: Expand free, multilingual resources to ensure equitable access to sustainability education globally. Some resources already exist for English-speaking individuals (*e.g.*, RSC) to teach school children about sustainability related topics. However, further work is needed to ensure an equal distribution of teaching materials across countries as well as the appropriate pedagogy. Education is also required for teachers to strengthen the importance of its incorporation into the curriculum.

• Updates for laboratory sustainability: Encourage institutions to update laboratory infrastructure through energy-efficient equipment, increased use of reusable materials, and adoption of circular waste-management systems. While practices such as recycling, reuse, and repair contribute positively to sustainability, they have certain limitations (*e.g.*, sensitivity and specificity). Charities such as RORO are helping to support these limitations.

• Credentialing and microlearning: Introduce digital badges or micro-certifications in Green Chemistry and sustainable laboratory practice to promote lifelong learning and enhance workforce development. This would be particularly useful for those already working within the analytical chemistry sector, as it could promote an uptake of CPD.

Table 1 Proposed laboratory sustainability interventions to specific Sustainable Development Goals (SDGs), illustrating how laboratory-scale operational reforms contribute to global sustainability targets under the United Nations 2030 Agenda

Laboratory sustainability interventions	Linked SDG(s)				Why it contributes	Reference
	SDG 4	SDG 9	SDG 12	SDG 13		
Inclusion in the curriculum	✓	✓	✓	✓	Embeds sustainability and green analytical chemistry principles in education, equipping future chemists with competencies for sustainable innovation and responsible production	88 and 90
Design of experiments (DoE)		✓	✓	✓	Statistical optimisation reduces reagent consumption, solvent use, and experimental repetition, minimising waste and resource use in analytical method development	53
Greener coding (efficient data processing, low-energy computing)		✓	✓	✓	Energy-efficient algorithms, optimised data storage, and reduced computational redundancy lower digital carbon footprints in analytical data processing	105, 127 and 129
Green analytical chemistry		✓	✓	✓	Applies the 12 Principles of Green Analytical Chemistry (*e.g.*, solvent reduction, miniaturisation, *in situ* analysis) to reduce environmental and health impacts	9, 11 and 13
Sustainable laboratory modules	✓		✓	✓	Practical teaching modules incorporating green solvents, microscale experiments, and waste audits promote responsible consumption and applied sustainability learning	113
Sustainable risk assessments		✓	✓	✓	Incorporates environmental persistence, toxicity, and life-cycle impact into chemical risk assessments, protecting health and reducing ecological harm	139
Sustainable laboratory inductions	✓		✓	✓	Introduces new staff and students to safe chemical handling, waste minimisation practices, energy-efficient laboratory behaviour, and institutional sustainability policies from the outset	3 and 121
Sustainable laboratory accreditations		✓	✓	✓	Formal sustainability standards and environmental management systems (*e.g.*, waste reduction targets, energy monitoring, green procurement) institutionalise responsible production and climate accountability	4 and 125
Green digital sustainability certification	✓	✓	✓	✓	Certification frameworks for sustainable IT practices promote low-carbon computing infrastructure, responsible data management, and innovation aligned with climate and resource-efficiency goals	128

• Compulsory sustainability accreditation schemes: Expand voluntary schemes into a more robust procedure to encourage uptake but also strengthen the need for education. Key learnings from current schemes, such as LEAF and MGL, along with ISO procedures, could be combined to create a self-sustaining programme. This could involve all participants auditing each other, an approach that has allowed LEAF to become a popular and autonomous scheme. As a result, the burden of implementing such a scheme is decreased, which could be beneficial for LMICs.

6 Conclusions

In conclusion, it is essential that all scientists, regardless of age or career stage, receive education in sustainability, with tools and resources tailored to their specific needs. While a range of resources exists to support laboratory sustainability in analytical chemistry, access remains uneven, particularly in low-resource settings. This highlights inequalities that must be addressed to achieve a truly balanced "sustainable stool". A global vision of interconnected, sustainable laboratories powered by education and equitable access could help overcome these disparities.

We recognise that different pedagogical types are suitable for different career stages. Tailoring how sustainability is taught is vital to ensure a long-lasting impact. However, early integration of sustainable practices is also critical. Embedding foundational principles in school and university curricula allows students to grasp sustainability practices, enabling their natural adoption in future careers. This should extend to computational research, given the growing environmental footprint of digital and AI-based approaches. The stool framework offers a balanced and pragmatic model for advancing sustainable analytical chemistry, emphasising the equal importance of environmental, social and economic sustainability. While barriers such as cost, resistance to change, and gaps in training persist, targeted solutions, such as global collaborations, digital innovations, and targeted funding, can facilitate wider adoption. Embedding these principles into education empowers future scientists to critically evaluate the environmental and societal impacts of their work, fostering a culture of shared learning and continuous improvement, advancing toward the UN SDGs.

Ultimately, achieving sustainability in analytical chemistry demands a holistic and system-thinking approach that integrates environmental stewardship, economic resilience, and social equity. Education provides a tool for laboratories of all types, encouraging actions that are environmentally responsible, socially equitable and economically viable. It serves as a call to action for the analytical chemistry community to educate, innovate, and share knowledge, collectively contributing to the pursuit of a more sustainable future.

Conflicts of interest

There are no conflicts to declare.

Data availability

No software or code have been included as part of this perspective. The data supporting this article has been included as part of the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5su00921a.

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