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A sustainability approach to inquiry-based experiential chemistry education in pre-college programs

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Pre-college programs offer valuable opportunities for high school students to engage authentically with science by applying chemical principles to real-world challenges. This study examines two such initiatives, Momentum Lab and Impact Lab, which integrate inquiry-based, experiential learning to advance environmental awareness and scientific literacy. Momentum Lab featured a forensic science module that combined chemistry and biology to investigate a simulated wildlife crime, illustrating the societal relevance of chemistry in healthcare, environmental monitoring, and justice systems. Impact Lab explored global sustainability through three thematic modules focused on: (i) climate change, sea-level rise, CO_2 absorption, and ocean acidification; (ii) soil and water quality, nutrient cycles, and ecological consequences of fertilizer runoff; and (iii) biodiesel synthesis *via* transesterification, highlighting green chemistry's role in renewable energy and waste valorization. Together, these activities demonstrate how inquiry-based learning can connect chemical concepts to pressing global issues while fostering engagement, curiosity, and applied problem-solving skills among learners. The overall patterns observed suggest that experiential chemistry education has strong potential to strengthen students' understanding of sustainability and inspire future participation in STEM pathways.

Sustainability spotlight

This study advances sustainability-focused chemistry education through two pre-college programs at Wentworth Institute of Technology that integrate systems thinking and the UN Sustainable Development Goals (UN SDGs). The Momentum Lab used forensic science investigations to highlight chemistry's role in health, justice, and environmental stewardship, aligning with UN SDGs 3, 4, 15, and 16. The Impact Lab explored climate resilience, soil health, water quality, and renewable energy, connecting chemistry to UN SDGs 6, 7, 11, 12, 13, 14, and 15. Through experiential learning and collaboration, these programs position chemistry as a tool for addressing global challenges and provide a scalable, inquiry-based framework for sustainability-focused STEM education.

Introduction

Our world faces significant global sustainability challenges, including climate change, resource depletion, pollution, and environmental health degradation.[1] This has created a demand for a generation of scientifically literate citizens who can make informed decisions and develop innovative solutions grounded in sustainability principles. Sustainability-focused thinking emphasizes understanding the interconnect between environmental, economic, and social systems, and applying scientific knowledge to develop solutions that minimize harm and promote long-term resilience. In chemistry education, this involves contextualizing chemical principles within global challenges such as climate change, resource management, and pollution, while aligning learning objectives with frameworks like the United Nations Sustainable Development Goals (UN SDGs) and the principles of green chemistry.[2,3] Education plays a pivotal role in this transformation, and chemistry, often called the "central science",[2] is uniquely positioned to address these issues through its broad applications. However, traditional science curricula often fail to connect abstract concepts to real-world contexts, leaving students disengaged and unprepared for the complexities of sustainability beyond the classroom. To bridge this gap, educators are increasingly promoting early STEM engagement and active learning strategies to foster critical thinking and interdisciplinary problem-solving skills.[4,5]

STEM engagement through inquiry-based chemistry activities

The recognized benefits of early STEM engagement are well known, but maintaining student interest throughout high school remains a significant challenge. Evidence shows that interest in STEM careers in the United States often decreases between middle and high school if not reinforced,[6,7] whereas globally, only a small minority demonstrates high proficiency in science. To address this, pre-college programs have emerged as

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an effective intervention to increase young people's interest in STEM subjects. Research indicates that participants in pre-college STEM programs are more likely to pursue STEM majors compared to non-participants.[6,7]

Inquiry-based chemistry activities play a critical role in sustaining this engagement by allowing students to explore real-world problems through hands-on experimentation and collaborative learning. Such approaches have been shown to improve conceptual understanding, foster critical thinking, and enhance confidence in applying scientific principles to authentic contexts.[4,5] By integrating sustainability themes and the United Nations Sustainable Development Goals (UN SDGs) into these activities, educators can make chemistry relevant to societal challenges, thereby increasing motivation and persistence in STEM pathways (Fig. 1).[3,8]

Recent frameworks, including those from the International Union of Pure and Applied Chemistry (IUPAC)[9,10] emphasize that active learning is essential for sustainability education to address interconnected global challenges.[10,11] The 12 Principles of Green Chemistry[12] provide a foundation for designing safer, more sustainable processes.[13] Integrating these principles into inquiry-based activities promotes active learning and aligns chemistry education with the United Nations Sustainable Development Goals.[11,14] Evidence indicates that active learning strategies reduce achievement gaps among underrepresented students and improve exam performance compared to traditional lectures.[4,15] Similarly, inquiry-based approaches enhance confidence in applying science to real-world problems (Fig. 2).[5]

Connecting chemistry to sustainability in high school

There is a growing interest in sustainability among young people; however, high-school chemistry curricula often remain abstract and insufficiently connected to societal and environmental challenges. Research by Celestino[16] shows that incorporating systems thinking and sustainability principles into high-school chemistry helps students recognize the relevance of molecular-level concepts to global environmental issues. Similarly, Hoffman and Dicks[17] demonstrate that embedding the UN SDGs and Green Chemistry Principles into secondary chemistry curricula enhances student engagement and

Fig. 1 The 2030 United Nations Sustainable Development Goals (https://www.un.org/sustainabledevelopment/news/communications-material/).

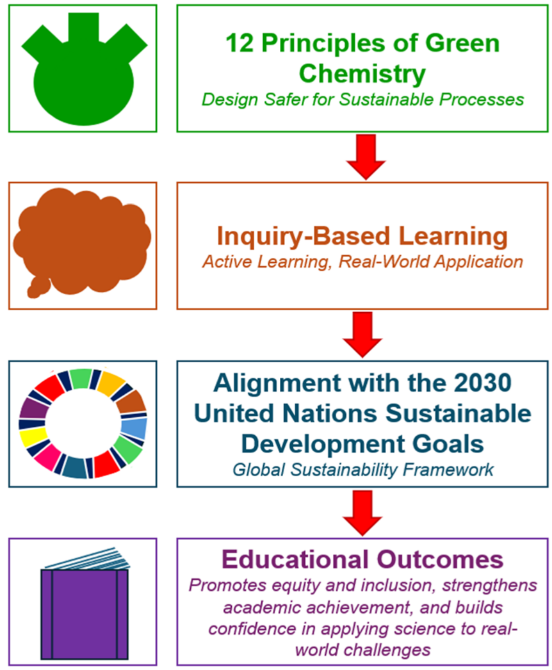

Fig. 2 Framework connecting green chemistry principles, inquiry-based learning, and the 2030 United Nations Sustainable Development Goals to foster inclusive educational outcomes.

strengthens conceptual connections to sustainability.[18] Inquiry-based, hands-on learning experiences, such as the fuel-cell investigations developed by Grandrath and Bohrmann-Linde,[19] which connect electrochemistry to clean-energy transitions, further illustrate how experiential chemistry activities can make sustainability challenges tangible for learners.[6,7]

Pre-college STEM programs provide a powerful platform for these approaches. Hansen *et al.*[20] report that structured STEM learning communities significantly enhance students' sense of belonging, a key psychological predictor of persistence in STEM pathways. Beauchamp *et al.*[6] show that authentic research experiences and mentorship increase scientific interest and STEM major selection among underrepresented youth. In addition, Kuchynka *et al.*[7] demonstrate that participation in pre-college STEM academies strengthens science identity and university belonging, both of which contribute meaningfully to long-term STEM engagement. Together, these studies show that sustainability-focused, inquiry-driven experiential chemistry education within pre-college programs can cultivate both scientific competence and the motivation needed for future sustainability-oriented careers.

Case study: Wentworth Institute of Technology

Wentworth Institute of Technology, located in Boston, places a strong emphasis on experiential learning. Each summer, the university hosts two immersive pre-college programs, Momentum Lab and Impact Lab, designed to engage high school students in hands-on learning that fosters critical thinking, problem-solving, and collaboration. Both programs encourage interdisciplinary approaches to address real-world challenges through practical projects.

Momentum Lab is an innovative one-week commuter program for 9th and 10th-grade students. It introduces students to interdisciplinary exploration in science, engineering, and design through a central academic theme. In 2025, the theme was Connected Care: Technology in Human Health. The program enrolled 39 students and offered interactive workshops that connected classroom concepts to real-world applications.

Impact Lab, by contrast, is an advanced two-week commuter program for 11th and 12th-grade students with a strong interest in STEM. Impact Lab featured a range of STEM courses, including engineering, computer science, and product design, alongside chemistry-focused activities that addressed sustainability challenges. In 2025, the program focused on Chemistry and Sustainable Cities: Climate Resilience for a Better Future. Impact Lab enrolled 136 participants across two sessions, 89 in Session I and 53 in Session II, each lasting one week. Session I introduced students to foundational STEM disciplines through inquiry-based learning and design thinking. This session emphasized engineering, technology, and sustainability, preparing students to tackle global challenges. Session II built on this foundation with STEM and innovation-focused activities that explored real-world applications of science, technology, and engineering. This session highlighted impact, entrepreneurship, and problem-solving.

Within the theme of sustainable cities, students examined chemistry's role in urban resilience. Topics included climate change and rising sea levels, urban heat islands and soil health, and biodiesel production. Through laboratory activities, case studies, and collaborative projects, students explored how chemistry can mitigate these issues.

This paper describes the design and implementation of chemistry-centered activities in Wentworth's Momentum Lab and Impact Lab and evaluates their role in promoting sustainability awareness among high school students. By situating these programs within the broader discourse on sustainability in chemistry education, this work provides insights into how pre-college experiences can advance scientific literacy and foster global citizenship.

Momentum Lab: connected care: Technology in Human Health

The 2025 Momentum Lab theme Connected Care: Technology in Human Health track, selected faculty members led sessions designed to introduce students to academic majors and demonstrate their relevance to human health technologies. The workshops aimed to actively engage participants in practical, hands-on activities aligned with the program theme while simultaneously highlighting career pathways and job opportunities in related fields. Another key objective was to create cohesion across the different workshops and faculty member contributions, to ensure a seamless and synergistic learning experience for all students. Each session, attended by 15 students, included interactive activities to explore emerging technologies and their societal impact. Within this framework, the chemistry component was designed to illustrate how chemical principles underpin health care innovations. The author developed a CSI-themed forensic activity in which students investigated chemical principles and techniques applied in forensic science and medical technology. This approach emphasized the interdisciplinary nature of chemistry and its contribution to sustainable health care systems.

Crime scene investigation: the case of leo the missing leopard

The activity "Crime Scene Investigation: The Case of Leo the Missing Leopard" is an inquiry-based learning experience that bridges forensic science, chemistry, and medical applications within a sustainability and conservation framework informed by the United Nations Sustainable Development Goals (UN SDGs) and the 12 Principles of Green Chemistry. Students assume the role of forensic investigators tasked with solving a wildlife crime, applying scientific principles, particularly chemistry, to reconstruct events and identify the culprit.

This forensic science activity introduced students to analytical chemistry through a simulated crime scene investigation. The scenario involved a missing leopard from a fictional zoo, with students tasked to identify the culprit using the provided evidence. Chemistry is central to forensic science, underpinning techniques such as UV fluorescence for detecting body fluids, chemical extraction and purification in DNA analysis, and gel electrophoresis for molecular profiling. These same principles extend to medicine and healthcare, where DNA technologies support diagnostics, personalized medicine, and disease prevention. By showcasing these integrated contributions, the activity demonstrates how chemistry-driven forensic methods support both medicine and justice while advancing sustainability through biodiversity protection and fostering quality education. This approach situates science within global challenges, fostering awareness of ecological and ethical responsibility, and the societal role of science in sustainability and justice.

The learning objectives of this activity were for students to apply interdisciplinary scientific concepts with a particular emphasis on the role of chemistry in forensic science. Students developed an understanding of the ecological and societal implications of wildlife crime through sustainability and justice frameworks, while strengthening critical thinking, collaboration, and evidence-based reasoning skills. In addition, the activity aimed to connect chemistry and forensic science techniques to the UN SDGs (Fig. 3).

Teaching strategy and inquiry-based design. The activity adopted an inquiry-based learning model that emphasizes active engagement and interdisciplinary integration. Students worked collaboratively in authentic roles as forensic investigators, solving a wildlife crime through hands-on techniques such as UV analysis, DNA profiling, and bone examination. This experiential approach encouraged problem-solving and deep learning.

Fig. 3 The activity poster for Momentum Lab (AI-generated).

Chemistry served as the anchor discipline, providing analytical techniques, such as chemical fingerprinting, spectroscopy, and trace element analysis, that underpin modern forensic science and enable the solving of crimes through chemical evidence. These techniques were presented not only as tools for investigating wildlife crime but also as approaches that inform sustainable practices. By linking the activity to global challenges and UN SDGs 3, 4, 15, and 16, forensic chemistry was situated within broader ethical and societal contexts. This integration promotes sustainable thinking by demonstrating how chemical evidence can guide conservation strategies, prevent illegal exploitation, and contribute to long-term ecological resilience. Furthermore, chemistry plays a critical role in health by enabling the detection of toxins, contaminants, and disease-related biomarkers, showcasing its wider applications through techniques such as chromatography, spectroscopy, and molecular analysis. This is highly beneficial for students, as it highlights the relevance of chemistry across diverse real-world contexts beyond the laboratory.

The CSI activity also enabled students to build transferable skills. Collaboration was integral, with students working in pairs and presenting findings, reinforcing communication, teamwork, and shared reasoning. Each stage incorporated problem-solving and logical thinking, equipping learners with adaptable competencies applicable across disciplines and real-world sustainability challenges. Critical thinking was prioritized as students interpreted data, such as fingerprints, blood splatter, hair strands, and gel electrophoresis results, while applying chemical principles to justify conclusions using evidence-based reasoning and ethical considerations. Overall, students not only learned about the application of chemistry and scientific techniques but also understood their societal relevance.

Student feedback. Formal written feedback was not organized in time for the Momentum Lab; however, verbal feedback gathered from all participating students after the activity was overwhelmingly positive. Students consistently emphasized three key strengths:

(1) Hands-on activities: the session was praised for its emphasis on applied problem-solving and practical engagement with sustainability concepts.

(2) Collaborative environment: the activity fostered creativity and peer learning through the team-based activity, which encouraged interdisciplinary dialogue and cooperative problem-solving.

(3) Real-world relevance: the activity was designed to address authentic sustainability challenges, enabling students to connect theoretical chemistry knowledge and techniques with actionable solutions.

While these impressions are based on informal feedback rather than formal evaluation, they suggest that experiential, collaborative, and inquiry-based approaches can support sustainability education and highlight the potential benefits of integrating technical knowledge with practical application.

Impact Lab: sustainable cities: climate resilience for a better future

The Impact Lab program consisted of two intensive sessions covering multiple themes. The author participated in Session I for three days, under the theme Sustainable Cities: Climate Resilience for a Better Future. Within this theme, three lessons were designed to integrate theoretical foundations with practical applications, demonstrating how chemistry can drive sustainable solutions in urban environments and play a vital role in climate resilience. The overarching goals of the lessons were to embed chemical sciences within sustainability discourse, advance climate resilience through innovative materials and energy systems, foster peer collaboration, and empower students with the knowledge and tools needed to implement sustainable practices as future leaders.

This session explored the pivotal role of chemistry in creating climate-resilient urban systems. Students examined advanced materials for infrastructure, focusing on low-carbon and durable construction solutions. Air and water quality management was addressed through chemical processes for pollution control and remediation. Energy sustainability was introduced through innovations in batteries, solar cells, and hydrogen technologies, alongside circular economy strategies for waste valorization.

The lessons were held in the afternoon and integrated three critical themes that connect chemistry to sustainability challenges. The first lesson, Climate Change and Rising Sea Levels, focused on investigating the different air, water, and soil pollutants, chemical processes that are energy-intensive and polluting, fossil fuels, and material innovations that support coastal adaptation and mitigation strategies for the rise in sea level. The second lesson, Urban Heat Islands and Soil Health, examined how chemistry reduces heat stress in urban environments while enhancing soil quality to support green infrastructure and sustainable agriculture. The third lesson, Biodiesel Production and Evaluation, provided students with hands-on experience in synthesizing renewable fuels (reconnecting this experiment to fossil fuel mitigation that was introduced in the first lesson), illustrating the role of green chemistry in advancing sustainable energy solutions and waste valorization. The three lessons were enriching and comprised mainly of introductory science ice-breaker activities, short theoretical lectures, and interactive class discussions (discussion prompts were provided), real-world case studies, and stimulating laboratory activities. This approach was to portray that chemistry is not confined to theoretical constructs but is a cornerstone for sustainable urban development and climate resilience (Fig. 4).

Day 1: climate change and rising sea levels

Day 1: Climate Change and Rising Sea Levels, students investigated the science behind climate change, ocean acidification, and rising sea levels through interactive demonstrations and experiments. This lesson helped students connect fossil fuels and greenhouse gas emissions to global warming and its effects on oceans and coastal cities through rising sea levels caused by melting glaciers. Students also learnt about the importance of coastal resilience mitigation. The experiments focused on the chemistry behind ocean acidification through climate change, by observing how carbon dioxide reacts with water to form carbonic acid, which lowers the ocean's pH and impacts marine ecosystems.

The learning objectives for this lesson were for students to be able to articulate the chemical interaction between carbon dioxide and water that leads to the formation of carbonic acid, and explain its significance in ocean acidification. Develop an understanding of the ecological consequences of decreasing ocean pH and investigate how melting ice contributes to rising sea levels. Finally, students had to apply their knowledge to design and model an environmentally friendly and effective sea wall as a strategy for enhancing coastal resilience.

The detailed activity structure and workflow for the Climate Change and Rising Sea Levels session, including resources and set-up, demonstrations, experiments, and design challenges with time allocations, are provided in the SI (Table S1).

Day 2: urban heat islands and soil and water health

Day 2: Urban Heat Islands and Soil and Water Health, students investigated soil and water as an ecological community, analyzed soil and water biodiversity, explored nutrient cycling and fertilizer, and understood its impacts on soil ecosystems. This session connected chemistry to sustainability by examining soil properties, including pH, nutrient content, and nitrogen chemistry in plant growth. Experiments on fertilizer runoff highlight consequences of agricultural practices, linking chemistry to food security and environmental health. Water and soil samples were also analyzed to assess the presence of microorganisms and determine factors that affect them.

The learning objectives for this session were for students to identify organisms present in soil and water samples and understand how they can vary due to different factors. Students were to test soil for nitrogen content and analyze the impact of fertilizer runoff and how it can affect soil and water quality and overall ecosystem health.

The detailed sequence of activities for Day 2: Urban Heat Islands and Soil and Water Health, including resources and set-up descriptions and time allocations, is provided in the SI (Table S2).

Fig. 4 The activity poster for Impact Lab (AI-generated).

Day 3: biodiesel production and evaluation

Day 3: Biodiesel Production and Evaluation, students synthesized biodiesel from vegetable oil and evaluated its properties through standard tests, connecting chemistry to sustainable energy solutions. This session focused on green chemistry and renewable energy, demonstrating transesterification, a chemical process that converts triglycerides into biodiesel.[21] Students assessed their produced of biodiesel fuel quality through different quality assessments. There were also discussions throughout the session on how chemistry innovations and the use of alternative fuels can reduce reliance on fossil fuels and mitigate climate change.

The learning objectives for this session were for students to understand the chemical process of transesterification and its role in converting triglycerides into biodiesel. Gain practical experience in producing biodiesel from vegetable oil and methanol and conduct biodiesel standard quality assessments, such as the 3/27 solubility test, emulsion test, and cloud point determination. Finally, students critically evaluated biodiesel as a renewable energy source and considered its potential to reduce reliance on fossil fuels and mitigate climate change.

The detailed activity structure and workflow for the Biodiesel Production and Evaluation session, including resources and set-up, time allocations for each component, is provided in the SI (Table S3).

Student feedback on Impact Lab activities. To assess the effectiveness of the Impact Lab in delivering sustainability-focused learning, structured surveys were administered immediately after the completion of the Impact Lab activities. These surveys captured both quantitative and qualitative responses, providing insights into student satisfaction, engagement, and perceived value of the interdisciplinary approach.

Table 1 provides a summary of quantitative feedback from all nine students enrolled in the author's class. The data combine ratings of satisfaction with faculty interaction and the likelihood of applying to another program.

Table 1 Student satisfaction for Impact Lab activities

Metric	Category	Percentage
Faculty interaction satisfaction	Extremely satisfied	80%
	Somewhat satisfied	20%
Likelihood to apply for another program	Extremely satisfied	80%
	Somewhat satisfied	20%

In addition to the quantitative results, qualitative feedback was analyzed to capture students' perceptions of the learning experience. Open-ended responses to the question "What aspects did you enjoy?" were reviewed using a thematic approach to identify recurring patterns. Three key themes emerged, and representative comments illustrating these themes are provided below:

(1) Interactive teaching – incorporating games and hands-on experiments to reinforce sustainability concepts.

Representative comments:

"Interactive teaching and Professor Poya's class."

"Having the afternoon lab session after the morning lecture was also nice to break up the day and keep it interesting."

(2) Chemistry integration – linking chemical principles to climate resilience and urban sustainability challenges.

Representative comments:

"I loved that I got the opportunity to truly learn about sustainability by looking through Boston's city… strongly related to chemistry, which I enjoyed."

"The labs in the afternoon, especially the ones that involved chemistry."

(3) Supportive engagement – creating an inclusive environment where students felt comfortable asking questions.

Representative comments:

"I enjoyed all the field trips and labs that we did."

Students expressed verbally that engagement in these programs has increased their desire to explore STEM pathways in future academic and career choices.

Discussion

Contextualizing chemistry for sustainability

Embedding sustainability within chemistry education is essential for preparing young learners to address interconnected global challenges. Pre-college programs are essential avenues for this work and must move beyond isolated content delivery to foster sustainability and its broader societal impact, using chemistry as a tool.

The Momentum Lab and Impact Lab exemplify how experiential learning can contextualize chemical principles within authentic scenarios to support the United Nations Sustainable Development Goals (UN SDGs). To illustrate these approaches, Table 2 summarizes the Momentum Lab and Impact Lab programs, their themes and activities, the relevant chemistry fields and concepts covered in the lessons, and their alignment with specific UN SDGs.

Experiential learning in pre-college programs

The Momentum Lab introduced forensic chemistry through a wildlife crime investigation, employing UV fluorescence, polymerase chain reaction (PCR) techniques, fingerprint analysis, and simulated DNA profiling. These activities linked biochemistry, analytical chemistry, and forensic chemistry to real-world applications, including genetic testing for personalized medicine, drug purity analysis, and crime scene investigations.[22,23] This approach extends beyond technical proficiency to ethical and ecological considerations, reinforcing chemistry's relevance to biodiversity protection and justice.[13] These connections align with UN SDG 3: Good Health and Well-being, UN SDG 4: Quality Education, UN SDG 15: Life on Land, and UN SDG 16: Peace, Justice, and Strong Institutions.

The Impact Lab focused on sustainability themes across three sessions, each integrating distinct chemistry domains and real-world applications.[10] Day 1 addressed climate change and rising sea levels through concepts in environmental and physical chemistry, including sea-level rise, CO_2 absorption, and ocean acidification. These were linked to carbon capture technologies and ocean health monitoring, supporting UN SDG 11: Sustainable Cities and Communities, and UN SDG 13: Climate Action.[8,24] Day 2 examined urban heat islands and soil and water health, drawing on soil and water chemistry, fertilizers, and nutrient cycles. Day 2 aligns with UN SDG 6: Clean Water and Sanitation, UN SDG 14: Life Below Water, and UN SDG 15: Life on Land.[25,26] Day 3 focused on biodiesel production and evaluation, applying organic, analytical, and green chemistry principles such as esterification and transesterification to renewable energy solutions, biodegradable plastics, and energy-efficient materials, supporting UN SDG 7: Affordable and Clean Energy, and UN SDG 12: Responsible Consumption and Production.[27,28]

Collectively, these experiential modules demonstrate how pre-college chemistry learning can extend beyond technical proficiency to incorporate ethical, societal, and environmental considerations. By grounding instruction in authentic sustainability challenges, both programs contextualized chemical principles in meaningful ways that promoted relevance, engagement, and interdisciplinary thinking.

Inquiry-based learning and instructional design

The instructional design of the Momentum and Impact Labs was intentionally grounded in inquiry-based chemistry learning, emphasizing iterative cycles of investigation, evidence evaluation, and revision. Rather than merely presenting chemistry content within sustainability contexts, the activities

Table 2 Overview of the Momentum and Impact Lab activities and their associated chemistry fields, and relevant UN SDGs

Program	Activity	Chemistry focus	Key concepts	Relevant UN SDGs
Momentum Lab – connected care: Technology in Human Health	Crime scene investigation: the case of leo the missing leopard	Biochemistry Analytical chemistry Forensic chemistry	DNA analysis Spectroscopy Trace evidence analysis	3: Good health and well-being, 4: quality education, 15: life on land, 16: peace, justice and strong institutions
Impact Lab – sustainable cities: climate resilience for a better future	Day 1: climate change and rising sea levels	Environmental chemistry Physical chemistry	CO_2 absorption Ocean acidification	11: Sustainable cities and communities, 13: climate action
	Day 2: urban heat islands and soil health	Agricultural chemistry Environmental chemistry	Fertilizer nutrient cycles Water and soil chemistry	6: Clean water and sanitation, 14: life below water, 15: life on land
	Day 3: biodiesel production and evaluation	Organic chemistry Analytical chemistry Green chemistry	Esterification Transesterification Renewable energy	7: Affordable and clean energy, 12: responsible consumption and production

required students to formulate hypotheses, collect and interpret data, compare results with predictions, and refine explanations in response to feedback. These iterative feedback loops and opportunities to explore interconnections between chemical, environmental, and societal systems align with multidimensional inquiry frameworks that highlight conceptual, epistemic, social, and procedural domains of learning.[29,30]

By prompting students to navigate uncertainty, justify decisions, and engage in evidence-based reasoning, the program reflected guided inquiry models shown to support scientific process skills—particularly for learners who are new to inquiry-oriented approaches. While we refrain from claiming direct development of inquiry skills, students' participation in this structured inquiry environment may support the emergence of holistic problem-solving abilities, consistent with research showing the value of authentic, iterative, and student-centered investigation for enhancing scientific communication and critical thinking.[31,32]

Student competencies and sustainability thinking

The Momentum Lab and Impact Lab were programs that promoted active engagement, collaboration, and evidence-based reasoning amongst students. Such competencies were emphasized in global sustainability education frameworks, such as the international recommendations from IUPAC on sustainability education.[10,33] Students demonstrated sustainable thinking by connecting chemical processes to environmental and societal outcomes, a skill critical for navigating complex global systems.[34] Feedback from both programs was unanimously positive from participants, which indicated that these activities made chemistry feel relevant to real life and helped connect science to global issues. Students have reported increased confidence in applying chemistry concepts to practical problems and expressed enthusiasm for sustainability-focused learning.[35,36] While knowledge gains were not directly assessed, participants' feedback suggests that experiential approaches contributed to greater engagement, motivation, and perceived relevance of scientific concepts. Given the limited evaluation methods and the absence of formal assessment of conceptual understanding, these findings, future work would incorporate structured evaluation tools to strengthen evidence of impact.

Study limitations

Several limitations must be acknowledged. First, the instructional design integrated multiple inquiry-based components, including iterative reasoning, hypothesis refinement, and sustainability-focused investigations, into a cohesive learning experience. Results were not analyzed at the level of specific components, so inquiry features that most strongly influenced student outcomes cannot be determined. Second, the limited sample size, short program duration, and lack of formal pre/post assessment constrain claims regarding learning gains or skill development. To enhance interpretive rigor, Creswell and Miller's[37] validity procedures were applied, including triangulation of data sources, thick description of classroom interactions, and peer debriefing. While these strategies strengthen trustworthiness, the absence of component-level analysis and comprehensive assessment remains an important direction for future research.

Future directions

The integration of sustainability themes into pre-college programs demonstrates the powerful role of experiential learning in bridging chemistry disciplinary knowledge with broader societal challenges. The lessons presented in this study served as effective interventions for increasing young learners' interest in STEM while situating chemical concepts in authentic contexts that reflect real-world environmental and societal issues. The recommendations outlined in Table 3 are intended to guide both the further development of the Momentum and Impact Labs and the design of pre-college STEM programs more broadly. While these suggestions emerge from observations within the two programs, they also align with established best practices in inquiry-based chemistry education, sustainability education, and experiential learning.[29–32] As such, these

Table 3 Suggested future directions for enhancing pre-college STEM programs

Future direction	Description
Extend program duration and depth	To make these pre-college programs more meaningful and impactful, future programs should extend their duration and depth, moving beyond short workshops to day-long or week-long modules so that students can fully grasp concepts in sustainable chemistry and its relevance in solving global issues[29,30]
Integrate real-world data and technology	Integrating authentic data, technology, and digital tools in these pre-college programs can further increase simulation in connecting concepts with research to enhance scientific rigor[31,32]
Build strong community and industry partnerships	Build community and industry partnerships with local agencies, institutions, and companies, so that they can provide authentic case studies and learning opportunities for students[32]
Embed interdisciplinary connections	Interdisciplinary links should be embedded in pre-college programs to link chemistry with other STEM subjects, and social sciences subjects as well. Incorporating various subjects into a blended pre-college program will present a multi-dimensional view of its importance[29]
Implement longitude impact assessment	Longitudinal assessment strategies could be carried out, such as pre- and post-program surveys and follow-up interviews with participants. This will help track their learning progress and sustained interest in STEM[29,31]
Offer clear career pathways	Presenting clear career pathways and exposure to green careers through these programs can inspire students to select their major area of study and make career decisions[32]
Scale and adapt for diverse educational contexts	Programs can be scaled and adapted for diverse settings such as flexible hybrid or online teaching formats. This will ensure wider accessibility and impact[29,32]

recommendations apply not only to future iterations of the Momentum and Impact Labs but also to similar pre-college learning contexts and scalable models implemented across diverse educational environments. Collectively, they provide a forward-looking pathway for developing chemistry education that embeds sustainable practices, promotes systems thinking, and cultivates the mindset and problem-solving capacity needed for future STEM leaders to address complex global challenges.

Conclusion

The Momentum Lab and Impact Lab programs demonstrate how inquiry-based, experiential chemistry education can meaningfully engage pre-college learners and spark sustained interest in STEM. By situating chemical concepts within authentic, real-world sustainability challenges, these programs bridge the gap between classroom learning and global societal needs, positioning chemistry as a catalyst for sustainable development. Through activities centered on specialized themes, students engaged in evidence-based reasoning, ethical reflection, and practical problem-solving, competencies essential for navigating the complexity of modern sustainability issues. These findings underscore the potential of experiential chemistry education to cultivate critical thinking, responsible decision-making, and a deeper appreciation of chemistry's role in shaping a more sustainable future. Integrating programs like the Momentum and Impact Labs into pre-college curricula not only supports sustainability education and inquiry-based learning but also helps prepare the next generation for careers aligned with the United Nations Sustainable Development Goals and the broader pursuit of global well-being.

Author contributions

The author is fully responsible for the preparation and content of this manuscript.

Conflicts of interest

The author declares no conflicts of interest.

Data availability

This article is based on original pedagogical design and conceptual development by the author. No datasets were generated or analyzed during the study. All relevant information regarding the project structure, educational approach, and implementation is provided within the manuscript.

Fig. 3 and 4 used in this work were generated using Microsoft Copilot (AI-based image generation tool) and are available upon request from the corresponding author. The use of AI tools was solely limited to image generation for Fig. 3 and 4 and did not influence the conceptual or analytical aspects of the study or the writing of the manuscript. All intellectual and creative contributions remain the author's own.

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