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Greener chemistry for a sustainable future: an interdisciplinary course based on systems thinking

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Growing concerns about environmental degradation, resource depletion, and climate change have positioned sustainable practices at the forefront of chemical education and research. Green chemistry provides a framework for addressing these challenges by designing chemical processes and products that prevent pollution and minimize environmental impacts. These developments underscore the need to prepare students to engage with sustainability challenges through interdisciplinary perspectives. A revised elective chemistry course adopts a systems-based approach that integrates green chemistry principles with environmental science, engineering, biology, economics, and policy. The course prepares students to connect chemical knowledge to real-world challenges and to engage in sustainability-driven problem solving. This article showcases a set of integrated educational strategies that combine green chemistry, systems thinking, and the United Nations Sustainable Development Goals (UN SDGs), while emphasizing real-world problem solving. Building on two decades of instruction, this manuscript presents the evolution of a course from a traditional lecture format to an interdisciplinary project-based model, supported by an assessment of student learning outcomes.

Sustainability spotlight

The introduction of sustainable practices in the chemistry curriculum is crucial. Chemistry's mission to help solve local and global challenges is rooted in the delineation of the United Nations Sustainable Development Goals (UN SDGs). Understanding the 17 UN SDGs from an environmental, ethical, and social point of view is the springboard to a transformative sustainable chemical education with the goal of addressing 21st-century challenges and beyond. Revising existing curricular activities to position our future generations of scientists as leaders of sustainable development is at the heart of our mission as educators. Adoption of this mission is exemplified in this work where students explore all the 17 UN SDGs and apply their critical and systems thinking skills to help solve a community-based problem.

Introduction

The need for sustainable solutions to solve global environmental challenges has positioned green chemistry at the core of scientific innovation and education. Traditionally defined by principles such as atom economy, renewable feedstocks, energy efficiency, and waste minimization, green chemistry offers a framework for reducing the environmental impacts of chemical processes and products.[1–3] However, contemporary sustainability education requires an expanded, interdisciplinary approach that integrates systems thinking, defined here as a holistic analytical framework that emphasizes interconnections, feedback loops, and emergent properties within complex systems, rather than isolating components (reductionism),[4–14] and life cycle analysis, while connecting classroom learning to local and global sustainability goals.[15]

To address this need, a revised undergraduate course promoting green chemistry within a broader liberal arts and sciences context was designed and implemented. Building on two decades of instruction at Washington College, this course has evolved from a traditional discipline-centered lecture format (focused primarily on green chemistry principles and case studies) into the current interdisciplinary project-based model. This course challenges students to explore the intersection of chemistry, technology, and social responsibility. Beyond foundational green chemistry principles, students discover how green chemistry can benefit from the impact of systems thinking through the System-Oriented Concept Map Extension (SOCME), a visual mapping strategy that helps learners represent complex interrelationships among chemical, environmental, and societal factors.[16] Students also explore how artificial intelligence (AI) can enable greener chemical processes, how green chemistry can serve as a driver towards achieving the United Nations Sustainable Development Goals (UN SDGs),[15,17] and how it can contribute to community-based initiatives.

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In this interdisciplinary course anchored in liberal arts education, students engage in a variety of activities and assignments, including online discussions, creation of case studies, small in-class group discussions, website design, proposal writing, and business-like pitch presentations. These experiences foster critical thinking, interdisciplinary collaboration, and problem-solving skills. Three core educational strategies drive the content of the revised curriculum:

- Integration of STEM disciplines through systems thinking to reflect the interconnected nature of environmental, physical, and biological challenges.[13]
- Emphasis on holistic problem solving aligned with the UN SDGs to prepare students to address complex global issues.[15,18]
- Alignment with institutional goals related to civic engagement, career readiness, and community impact.

Engagement with emerging tools such as Artificial Intelligence (AI) and life cycle analysis further supports students in developing solutions to sustainability challenges, aligning with recent educational frameworks that advocate for technology-integrated sustainability literacy.[19,20] Preliminary qualitative evidence from student projects (detailed in the Evaluation section) supports the efficacy of this approach. Relying on this interdisciplinary approach, this redesigned course illustrates how chemical education can shape the next generation of scientists for global sustainability.

The following sections outline the conceptual, curriculum structure, learning outcomes, and preliminary assessment of this redesigned course.

Conceptual framework

The framework of this course is a five-unit, project-based curriculum designed to immerse undergraduate students in the principles and applications of green and sustainable chemistry. The pedagogical design is informed by the educational framework of Talanquer and Szozda,[13] which emphasizes scaffolding systems-based reasoning across chemical contexts. Rather than presenting concepts in isolation, the curriculum progresses from foundational knowledge (reductionist) to complex interdisciplinary application (systems-based). This immersion relies on learning and applying the concept of systems thinking, critically assessing the role of artificial intelligence in sustainability-driven innovations, and exploring the UN SDGs. The culmination of the course is the development of an original proposal addressing a local challenge faced by our community.

Throughout this course, students engage with real-world sustainability challenges through participating in online and in-class discussions, writing case studies, utilizing the SOCME visualization tool to map system interactions,[16] presenting about AI-enhanced research, developing web-based resources, and crafting and presenting an original community-focused innovation proposal.

The curriculum reflects a transformative model of STEM education that prepares students to address complex environmental and societal challenges. To support reproducibility and adoption by other instructors, detailed guidelines and assignments, and assessment rubrics are provided in the SI.

Curriculum overview and learning goals

The curriculum consists of five themed units that progressively build students' knowledge and skills. Each unit contributes to a broader understanding of sustainable development while focusing on a specific context or application. Table 1 summarizes the structure of each unit, including delivery methods, key resources, and assessments.

Unit 1: understanding green chemistry: green chemistry applications in our everyday life

As an introduction to the first unit, students are asked to reflect on their current understanding of the terms "green chemistry" and "sustainability" *via* an online discussion. Students are then introduced to the green chemistry definition and the 12 principles of green chemistry *via* interactive lecture presentations. Industrial applications illustrating these principles are also highlighted.

Additionally, as the concepts of risk and hazard are examined, students are encouraged to reflect on the nature and implications of hazards within chemical processes. They are asked to develop their own definition of a hazard and explore whether all hazardous materials can be classified as waste materials. Next, they dive into the distinction between "hazardous" and "toxic" and whether the relationship between hazard and risk is always proportional, or if there are factors that influence how risk is assessed relative to hazard.

To familiarize students with the principles of green chemistry, they are invited to engage in an online discussion focused on the key concepts of green and sustainable chemistry and engineering principles.[1–3,21,22] As they review these principles, students reflect on whether any of them seem unexpected and to look for common traits. They also think about the connections between green chemistry and green engineering principles and explore possible areas of overlap or reinforcement between the two sets of principles.

The end goal of this unit is for students to critically assess an everyday consumer product of their choice and design a case study based on their findings. Students compare traditional products to greener alternatives, examining their chemical composition, environmental and health impacts, and barriers to implementation. The learning goals are to make connections between sustainable chemistry and household or personal care products used in everyday life; to investigate a traditional and commercially available product used every day and compare it to a more environmentally friendly equivalent; to determine the short- and long-term impacts of the greener product on the environment, health, safety, and economics as well as the advantages and barriers associated with the production and marketing of the greener product.

Topics covered in students' case studies ranged from looking at an environmentally friendly fishing line called "TUF-line", which is 100% biodegradable, to "Green Llama", an alternative all-purpose cleaner, to the use of natural indigo dye (known as "Indigo Rit") in the textile industry.

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Table 1 Course unit structure, delivery methods, and assessments[a]

Unit	Theme	Key activities	Delivery methods	Key resources	Assessment
1	Green chemistry in everyday life	Online discussion, interactive lecture, case study design	Lecture, online discussion	ACS green chemistry principles,[21,22] industrial case studies	Case study: comparison of traditional *vs.* greener consumer product
2	Systems thinking & SOCME	Group discussion, stock-flow diagram, SOCME mapping	In-class activity, lecture	Talanquer & szozda framework,[13] SOCME tool,[16] climate podcasts[23]	SOCME map: life-cycle analysis of a chemical element
3	AI & machine learning in chemistry	Online discussion, literature review, group presentation	Online forum, student presentation	AI interview,[19] resources on AI ethics,[24–26] peer-reviewed articles[27–29]	PresentationAI application in sustainable chemistry
4	UN sustainable development goals	Video analysis, policy discussion, website design	In-class activity, digital design	UN SDG website,[15] water/Food crisis videos[30,31]	Website: connecting green chemistry to a specific UN SDG
5	Local community challenge	Proposal writing, pitch presentation	Guest speaker, group work, pitch event	Campus sustainability data, campus input	Proposal & pitch: solution to a campus challenge

[a] Resources on AI ethics[24–26] were discussed in class to address bias and transparency.

Building on this foundational understanding of green chemistry principles, the next unit expands the focus to systems thinking.

Unit 2: exploring green chemistry, sustainability, and systems thinking through SOCME mapping

After being introduced to the principles of green chemistry in Unit 1, students start the second unit by working in groups and engaging in an in-class discussion to broaden their understanding of these principles. Students are asked to propose additional principles they believe should be added to the original twelve, providing justifications for their suggestions. They are also encouraged to examine how their proposed principles would overlap with or complement the existing principles, and reflect on the potential environmental, social, or economic outcomes that could arise from incorporating these new principles. Finally, they think about the cause-and-effect relationships among the original and proposed principles.

The last question serves as a transition to the introduction of the systems-thinking approach. As part of an online discussion, students reflect on the value of systems thinking by responding to a series of prompts. First, they consider how we live in complex environments composed of multiple interacting systems and describe one such environment they observe in their own lives. They identify its key components and reflect on if/why a systems-thinking approach might be particularly beneficial for understanding and navigating that environment. Students are then asked to evaluate their own learning preferences by comparing reductionist and systems thinking approaches. Finally, students are presented with a scenario involving a decrease in vegetable garden productivity. They are tasked with describing how they may investigate this issue using both a reductionist approach and a systems-thinking approach.

The theory behind systems thinking is explored through lecture presentations providing additional examples of reductionist *vs.* systems-thinking approaches, an in-depth coverage of the definition of systems thinking, of cause-and-effect relationships (feedback loops), as well as terminology such as flux, open/closed system, reservoir, flux and systems boundaries.[13,14,16] As part of a brainstorming activity, students are encouraged to explore the complexity of climate systems by responding to a series of questions after listening to a news story highlighting the connections between wildfires and climate change.[23] They begin by identifying various factors that can influence climate, drawing from their current knowledge. Next, students analyze the components of the system described by the speaker, breaking it down into its key elements. They then need to think in terms of systems dynamics, considering flows, reservoirs, and feedback loops that shape the behavior of the climate system. To synthesize their understanding, students create a diagram or concept map that visually represents all the different components and illustrates the connections and interactions among them.

Students are then introduced to the System-Oriented Concept Map Extension (SOCME) visualization tool.[16] To fully grasp this concept, students are tasked to study a chemical element in the periodic table *via* a cradle-to-cradle approach, and to evaluate the environmental, economic, health, and social impacts of its use. More specifically, students identify and analyze the composition, structure, behavior, and effects of systems on the life cycle of a chemical element of their choice.[13] The final assessment is for each student to integrate systems thinking and life-cycle analysis, build interdisciplinary connections, identify sustainability trade-offs, and showcase a system-oriented concept map about the life cycle of their element. Crucial components of the map include subsystems based on the traditional synthesis reaction, mineral and energy input, reaction conditions, mining waste, intended and unintended uses, the greener synthesis and identification of green chemistry principles applied, and the benefits of the greener synthesis.

Elements spotlighted in students' SOCME included titanium in the production of purified TiO_2, copper in the formation of copper chloride, or magnesium in the production of MgO, to name a few.

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Having developed systems-thinking skills, students next examine how emerging technologies can support sustainable chemistry.

Unit 3: considering the role of artificial intelligence and machine learning in sustainable chemistry

The third unit explores how greener and sustainable chemistry practices can be enhanced using AI/machine learning, or any computer-aided methods. This topic was covered in response to students' interest.

As a pre-work assignment and to gauge students' familiarity with AI and machine learning, students participate in an online discussion inspired by an interview with Dr Alexei Lapkin at the University of Cambridge on "Using AI & Machine Learning to accelerate sustainable innovation".[19] The online discussion focuses on two aspects of the interview students find surprising (either in expected or unexpected ways) and their analysis of how the principles of green chemistry can be applied in the context of AI and machine learning to address sustainability challenges.

This preliminary online discussion revealed discrepancies in students' familiarity with AI, which prompted an introduction and a lengthy in-class discussion about Machine Learning and Natural Language Processing, two areas relatable to sustainable chemistry. To address ethical considerations, the course incorporated different perspectives on AI bias and transparency (*e.g.*, discussions on algorithmic fairness and social impact), ensuring students critically evaluate AI as a social good.[24–26] In this discussion, students were particularly interested in expressing their opinion about the use of AI in sustainability initiatives, reflecting on the role of human researchers and if AI is a social good. This last question led to further inquiry into ethical AI development, with a focus on the role of transparency in its use in chemical research and applications, especially when it comes to the potential for bias in algorithmic predictions. Additionally, it raised additional considerations such as how to ensure AI systems used in chemical research are not inadvertently reinforcing harmful practices or prioritizing economic profit over environmental and social sustainability; what the potential social impacts of automating chemical research and production with AI, particularly with respect to job displacement and the potential for widening economic inequalities, are; or even how the global community can validate that the role of AI in sustainable chemistry remains aligned with international ethical standards, avoiding conflicts of interest or exploitation of less-developed nations.

Current trends and future directions are also brought up before studying published real-world applications at the interface of AI and sustainable chemistry. Students explore the literature to find a recent peer-reviewed article (in the past five years) where AI/machine learning, computer-aided design played a role in driving innovation towards a more sustainable product, material, or application. This way, they gain insight into how AI can tailor green chemistry solutions to specific environmental challenges faced by different regions of the world considering factors such as local climate, resources, and regulations. The overall goal is for students to better understand emerging AI applications, critically analyze the literature, and enhance their science communication and presentation skills. Each group of students has twenty minutes to present their understanding of the primary research question, the implications and impacts of the research findings, and the strengths and limitations of the study. To address the broader context, students convey how ethical considerations may influence future policies.

Examples of research questions included: how AI-driven waste segregation techniques, combined with novel microbial and enzymatic biodegradation strategies, can enhance the efficient decomposition of non-biodegradable synthetic plastics in waste management systems;[27] how AI, Machine Learning, and Nanoparticle-assisted approaches can be utilized to detect and degrade pesticide residues in the environment;[20] how autonomous platforms can be used to assess ocean biogeochemistry and ecosystem health;[28] or even how the development of toxic effects of particulate matter (PM 2.5) with water-soluble components on zebrafish can be predicted and explored through machine learning.[29]

Building on these technological perspectives, the next unit positions sustainable chemistry within global development frameworks.

Unit 4: applying systems thinking to drive the UN sustainable development goals

Unit 4 connects sustainable chemistry to global challenges through the UN SDGs. The intent is to explore and showcase progress regarding the contribution of sustainable chemistry towards the UN SDGs through the lens of systems thinking and life cycle analysis, while also encouraging students to develop possible solutions on their own.

The first step is for students to familiarize themselves with the UN SDGs. Using the United Nations Sustainable Development Goals website, students identify patterns or trends among the 17 UN SDGs, and critically reflect on potential missing goals, proposing what those additional goals may be.[15] Students then proceed to gain a better understanding of two specific challenges based on the global water crisis and the global food crisis. After watching two videos, they participate in an in-class activity and discuss the principles of green chemistry most applicable to these issues, the main challenges associated with water and food-related problems on a global scale considering scientific, logistical and policy-related barriers.[30,31] They are also asked to propose policies or incentives that will encourage the adoption of sustainable practices and to examine how economic factors, especially in developing countries, influence the implementation of these practices.

Numerous references are used as the foundation for the end-of-unit assignment, which is for each student to select one of the UN SDGs and design a website illustrating how sustainable chemistry can contribute to solving a global challenge.[17,18,32–34] Overall, this unit encourages students to learn about the UN SDGs while building data interpretation and synthesis skills to

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demonstrate the connections between sustainable practices and global challenges.

Guidance is provided throughout the design phase of the website; more specifically, how to structure arguments emphasizing the application of the 12 principles of green chemistry to address an issue related to a UN SDG and how to propose ideas beyond the scope of the published resources.

The UN SDGs covered included Goal #2: Global Hunger (with an emphasis on the need for Climate-Smart Agriculture); Goal #6: Clean Water (how to prevent water pollution through greener herbicides); Goal #7: Affordable and Clean Energy (looking at the potential of bio-based technologies like crab-zinc batteries); Goal #9: Industry, innovation, and Infrastructure (how to create adaptable infrastructure, promote inclusive industrial growth with minimal environmental impacts, and support technological innovation that drives sustainability); Goal #12: Responsible Production and Consumption (how edible food packaging is aiding in reducing plastic waste); and Goal #15: Life on Land (looking at alternatives to paper making), to name a few.

The most eye-opening aspect of this assignment was the students' thoughtful suggestions for future directions. For example, as mentioned by a student in the context of improving water quality for UN SDG #6, future studies on herbicides should focus more on photolytic degradation. Given that agriculture is one of the leading sources of water contamination through chemical runoff, increasing the photolytic degradation of herbicides can play a key role in minimizing the harm. For instance, the photolytic half-life of some herbicides suggests they would break down quickly in surface waters. If more herbicides could be developed with similar or faster photolytic degradation rates, it would lead to fewer toxic residues in water, enhancing water quality and protecting aquatic biodiversity. The same student also suggested to perhaps focus on sediment-catalyzed degradation, instead of photolytic or aquatic degradation. Molecules containing a fluorobenzyl group have a high soil adsorption coefficient. If landowners could increase the amount of soil organic matter (SOM) in their fields, this would likely increase the length of time these molecules could remain in the soil. The longer these molecules are in the soil, the better chance they have of being taken up by plants, thus reducing the potential for leaching into water supplies. Reflecting on ways to increase SOM could be an appealing solution to improve water quality. This is one example of the level of depth of thinking students placed in this assignment and the impact this course had on their pursuit of a graduate degree or a career in a field related to sustainability.

The final unit synthesizes prior learning through application to local, campus-based challenges.

Unit 5: using systems thinking to solve local challenges and engage in our community

In this final unit, students work in groups to identify a design, process, or product that is neither environmentally benign nor sustainable on our campus and/or in the Chestertown community and to develop a proposal describing the current challenge, potential solution, expected community engagement, and outcomes.

The proposed initiative must rely on using greener and sustainable chemistry to solve a local challenge. In other words, students can't just say they want to improve recycling on our campus or decrease the amount of waste generated by the dining hall. They need to identify the root of the issue and propose a chemistry-based solution that will help decrease the number of recycled materials produced or think about a new process that will streamline the production of waste.

The outcomes of this project are: (1) to write a team proposal about this new initiative, (2) to design an infographic reflecting the main idea of the proposal, and (3) to give a ten-minute pitch presentation about the proposal (this serves as the final exam in the course). Brainstorming questions guide students in developing ideas for this final project. Our Lifelong Learning and Communications coordinator and sustainability figure on campus was invited to give a presentation on current sustainability initiatives on campus and in our town.

Once a local challenge is identified, the following parameters need to be taken into account in the final proposal: (1) clearly demonstrate the application of at least three green chemistry principles and three UN SDGs; (2) work on a project different from their senior capstone experience project or any initiative currently taking place on our campus/community; and (3) collaborate with a different partner than for the end-of-unit 3 assignment. The following elements are required as part of the proposal: an introduction explaining the local challenge with relevant statistics to illustrate its impact (*e.g.*, if addressing water pollution, mention sources of pollution and affected people/place in the community) and a brief discussion of the broader implications, such as health risks or economic costs associated with the challenge; objectives with primary goal and specific aims; a description of the proposed solution with an implementation plan; an identification of the stakeholders and plans for education and outreach; expected environmental, economic, and social outcomes; suggestions regarding metrics and methods to evaluate the greener approach; and an overview of the budget and funding sources.

Ideas proposed by students included the implementation of nitrogen fixing plants to reduce the use of nitrogen fertilizers on Washington College green spaces; the generation of energy using on-campus wind turbines; the capture of solar and kinetic energy to power vending machines; a proposed synthesis of a greener cleaning alternative named EcoShine; and the use of bio-based materials to replace traditional asphalt in parking lots.

Overall, students' achievements in this redesigned course resulted in enhanced collaborative learning *via* team-based assignments, increased proficiency with digital tools and AI, improved public communication skills *via* infographics and web design, and most importantly a deeper awareness of the local and global impacts of sustainable practices.

Evaluation and reflection

To assess the effectiveness of the redesigned curriculum, a mixed quantitative and qualitative evaluation approach was

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employed, combining quantitative grading metrics with qualitative analysis of student work. This multi-faceted assessment aimed to measure not only content mastery but also the development of systems thinking, communication skills, and civic engagement. Detailed assessment rubrics, grading criteria, and examples of anonymized student work are provided in the SI.

Quantitative metrics. Student performance was evaluated across the five units using standardized rubrics focusing on critical thinking, application of green chemistry principles, and systems mapping. Analysis of metrics from the most recent course iteration (Fall 2024) revealed the following trends:

- Systems Thinking Proficiency: scores on the SOCME visualization assignments showed a marked improvement over the semester. Early submissions averaged 62% on criteria related to "identifying feedback loops," while final maps averaged 81%, indicating successful scaffolding of systems-based reasoning.
- Communication Skills: presentation grades for the Unit 3 AI literature review and Unit 5 community pitch averaged 90%, with rubric indicators highlighting significant growth in explaining technical chemical concepts for non-specialist audiences.
- Interdisciplinary Integration: in the Unit 4 website assignment, 92% of students successfully linked at least three Green Chemistry principles to specific UN SDGs, demonstrating effective interdisciplinary synthesis.

Qualitative analysis of student work. Beyond numerical scores, qualitative analysis of student work provided deeper insight regarding learning outcomes:

- Depth of Systems Mapping: early SOCME maps tended to be linear (reductionist), focusing primarily on chemical synthesis. By the end of Unit 2, maps evolved to include feedback loops, societal impacts, and waste streams, reflecting a shift toward holistic systems thinking. For example, student maps on titanium production expanded to include mining waste impacts and energy inputs, rather than solely focusing on the reaction yield.
- Critical Engagement with AI: in Unit 3, students moved beyond viewing AI as a "black box." Discussion posts and presentations revealed nuanced understanding of ethical implications, with students engaging in discussions regarding algorithmic bias and transparency in chemical research.
- Innovation in Proposals: the final community proposals (Unit 5) demonstrated high levels of creativity and feasibility. Specific examples, such as the proposed photolytic degradation of herbicides to improve water quality (UN SDG #6), showcased students' ability to propose chemistry-based solutions rooted in scientific literature rather than common sustainability practices.

Comparison to previous course iterations. Comparing outcomes to previous iterations of the course (taught five times over the past 20 years), the redesigned curriculum shows distinct improvements in student engagement and interdisciplinary connection. Previously, assessments focused primarily on the understanding of the application of the green chemistry principles. In contrast, the current project-based model has resulted in higher in-class participation and an increase in students pursuing sustainability-focused careers or graduate research (20% of the students enrolled in the Fall 2024 course pursued graduate studies or a career related to sustainability). Informal alumni feedback suggests that the systems thinking skills acquired in this course have been directly applicable to their professional roles.

Limitations and future work

While preliminary results are promising, this evaluation is based on a single cohort. Future work will aim to collect longitudinal data on career outcomes and expand the quantitative analysis to include pre-/post-surveys. Formal Institutional Review Board (IRB) approval will likely be sought for future publications involving detailed student data analysis.

The course was originally designed for students to engage with stakeholders from the broader community early in the semester, conduct interviews, and collaborate closely with them throughout the semester. Due to unforeseen circumstances, this was not possible. However, incorporating this component is planned for future iterations of the course.

Conclusion of evaluation

Overall, the evaluation suggests that the redesigned course successfully meets its learning objectives. Rather than following the structure of a traditional chemistry curriculum based on introducing concepts through theoretical content (what), their relevance (why), and practical applications (how), this course embraces a holistic systems thinking framework that integrates scientific knowledge with environmental literacy, ethics, and socio-cultural awareness. Students not only become familiar with green chemistry principles and sustainable molecular design but also discover how human health, environmental issues, ethics, and equity are deeply intertwined, highlighting the vital role of chemistry in addressing contemporary global challenges.

Conclusions

This reconfigured course emphasizes critical thinking, civic engagement, and interdisciplinary problem-solving, preparing students to engage meaningfully in sustainability-driven innovation. By shifting from a discipline-centered model to one that fosters students as interdisciplinary thinkers and responsible stewards of society and the environment, this approach does not only enhance student learning but also inspires faculty to engage actively in shaping a more socially driven scientific curriculum. Evidence from grading metrics and informal alumni feedback supports the efficacy of this interdisciplinary model in fostering sustainability literacy.

Conflicts of interest

There are no conflicts to declare.

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Data availability

Data sharing does not apply to this article as no datasets were generated or analyzed in this work.

Supplementary information (SI): educational data supporting this study (grading metrics and anonymized student work) are available in the supplementary information. See DOI: https://doi.org/10.1039/d6su00154h. Further data available on request from the corresponding author

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