



Cite this: DOI: 10.1039/d5su00948k

Received 23rd December 2025
Accepted 25th March 2026

DOI: 10.1039/d5su00948k

rsc.li/rscsus

Using curated chatbots to support students' exploration and awareness of sustainability through essay writing

Morgan J. Clark,  Micke Reynders  and Thomas Holme *

In the context of a written essay assignment in first-year general chemistry that combines chemistry content knowledge and sustainability, students' use of a curated chatbot support resource has been analyzed. The chatbot allows the student to engage in exploration of several potential components of the assignment, including technical requirements, chemistry content, and sustainability contexts. Analysis of both chatbot interactions and student essays found a propensity for students to be guided in their exploration of the UN Sustainable Development Goals by the chemical context of the assignment and some, but not all, students gained a level of understanding that supported a sustainability action perspective.

Sustainability spotlight

This manuscript presents an analysis of student essay writing on topics that connect chemistry and sustainability. Student help-seeking is facilitated by a curated chatbot that includes contextualized chemistry content related to Earth and societal challenges. Although the assignments in this study include a range of connections to the United Nations Sustainable Development Goals, the project itself and this analysis component speak most closely to UNSDG 4, Quality Education. Helping students acquire information about connections between foundational chemistry concepts and sustainable solutions for grand challenges presents a useful direction to enhance sustainability educational outcomes.

Introduction

The United Nations Sustainable Development Goals (SDGs) have proven to be an effective framework for engaging students with pressing global challenges. While learning about the SDGs provides valuable knowledge and raises awareness of these issues, there remains a critical need to strengthen students' competencies related to sustainability. These core competencies, such as systems thinking, problem-solving, critical thinking, anticipatory thinking, self-awareness, and collaboration, are essential for advancing sustainable development.¹ As cross-cutting skills, they enable learners to navigate complexity and contribute meaningfully to sustainability challenges.¹⁻⁴ A comprehensive UNESCO report outlines these competencies and associated learning objectives for each SDG, framing them across three key domains: cognitive, socio-emotional, and behavioral.⁵ These domains consist of knowledge, personal values, awareness, beliefs, and attitudes towards sustainability that contribute to student agency.⁶ As educators, we have a responsibility to equip the next generation of university students with the knowledge and awareness needed to make informed decisions that help shape a sustainable future.⁷

Guerra and coworkers examined university students' awareness of the SDGs and their understanding of sustainability by assessing whether they referenced the environmental, social, and economic pillars in surveys and interviews.⁶ This was achieved through a project-based learning activity, where students worked in small groups to tackle complex real-world problems. The study revealed a gap between personal values and actions, highlighting the influence of professional and situational contexts. Structured activities can thus be incorporated to help students link their knowledge and awareness to actual engagement.⁸ Most studies report on developing students' awareness of sustainability, with fewer studies exploring how students' sustainability-related competence can be developed. Studies are needed that employ innovative pedagogical approaches that integrate artificial intelligence as a powerful tool to tackle multifaceted sustainability issues.

Artificial Intelligence (AI) education and literacy are playing an increasingly important role in developing cognitive, socio-cultural, and affective skills. Such competencies are necessary to prepare students to confidently navigate a digital world and begin with further student exposure to AI tools within the classroom.⁹⁻¹¹ To realize this, educators have incorporated chatbots into their classrooms as metacognitive agents,^{12,13} instructional assistants,^{14,15} and even educational tutors.^{16,17} Chatbots are AI-driven agents that enable students to interact through natural language dialogue, providing on-demand

Department of Chemistry, Iowa State University, Ames, IA, USA. E-mail: taholme@iastate.edu



support and information to improve their learning experience.¹⁸ For example, Wang *et al.* developed a retrieval-augmented generation (RAG) chatbot, ChEdu-GPT, that served as a pedagogical tool for contextual learning by providing personalized learning experiences and enhancing student engagement.^{17,19} The RAG component of Wang *et al.*'s ChEdu-GPT system provided students with instructor-approved content, virtually eliminating AI hallucinations – a common problem with fully generative AI. Tools such as these, with curated, instructor-approved content combined with Large Language Models (LLMs) and machine learning (ML) algorithms, can transform educational environments and enhance the teaching and learning experience.²⁰

Additionally, curated chatbots can help students build sustainability literacy by guiding them as they seek information and explore SDGs through a chemistry lens. These chatbots have been transformative; even still, their design and implementation in sensitive domains, such as sustainability, must be carefully guided by human values. Such a value-sensitive design helps ensure that reliable, accurate content is shared with students.²¹ Although AI can be leveraged for sustainability learning, little is known about how chatbots can be used to foster students' understanding of the SDGs and promote student agency for sustainability in chemistry education.

One challenge for incorporating important rich contexts, such as sustainability in chemistry courses, lies in assessing student learning of such applications. A possibility to address this challenge is associated with embracing communication strategies, such as written essays or similar writing/creative projects that encourage integration of chemistry knowledge with other areas of learning, such as sustainability.^{22,23} In classes such as introductory or general chemistry, however, students often need support resources to bolster their connection-making skills in activities like essay writing.²⁴ With introductory courses often having large enrollments, the need to address student needs at scale plays a role in how support can be provided. Curated chatbots have been shown to be a promising source of writing support for students, even in large-enrollment courses.^{24,25}

Lolinco and Holme developed a curated chatbot, with IBM WatsonX assistant, that served as an instructional aide for a writing assignment about sustainability and chemistry.²⁴ The chatbot contained technical information about the assignment as well as links to sustainability ideas and the SDG webpages. Students generally used the curated chatbot as built and found success in the writing assignment. Analysis of logs generated by student use of the chatbot proved useful in understanding student help-seeking in the context of the writing assignment.²⁵ Since its inception, the curated chatbot has been implemented in several other contexts, including those in this article. In this work, we will focus on how students utilized the sustainability sections of two curated chatbots on (1) the water and carbon footprint (referred to as the footprint chatbot) and (2) Pyrocene, and how the SDGs are reflected in their essays. This research seeks to answer the following research questions:

1. Which SDGs in the Pyrocene and water/carbon footprint curated chatbots did students explore?

2. Focusing on footprint essays, which SDGs were implied or explicitly mentioned by students?

3. What evidence from the footprint essays indicates dimensions of student agency?

Methods

Teaching with curated chatbots

For this study, curated chatbots were introduced in a large general chemistry course to help students with a writing assignment. In the assignment, students were tasked with writing an essay that connects chemistry to a sustainability-related context. These contexts included water footprint, carbon footprint, and the Pyrocene, all of which were incorporated throughout the chemistry course as described in Tables S1 and S2. For the writing assignment, students were free to choose a topic of personal interest if it included chemistry and sustainability within the stated context. Because this assignment generated many questions from students, the curated chatbots were built to address these questions about the technical and content requirements for the essay according to the essay prompt below.

In your treatment of the topic you need to (1) identify which aspect (water footprint, carbon footprint, embodied carbon) you are using in the paper; (2) define the idea (water footprint, carbon footprint, embodied carbon) and how it connects to chemistry in some way and (3) make a connection about how understanding this topic helps inform the idea of sustainability (you can do this by connecting to one of the UN Sustainably Development Goals, for example).

With this prompt and student help-seeking in mind, curated chatbots were developed to include information about several aspects of the assignment. The curated chatbots included components, referred to as “modules”, about (i) technical requirements of the assignment, (ii) content summaries of the main context topic, and (iii) sustainability, as outlined in the SDGs. The structure of each curated chatbot, as detailed in previous work, enables students to access modules on any of these components of the assignment.^{24,25} As shown in the decision tree in Fig. 1, each module starts at a broad level and then delves deeper into information curated by the instructor.

Students were able to access the chatbot through a link in their course management system. Once they accessed the link, they could begin at the top level (level 1) of the curated chatbot and choose one of the provided options (*e.g.*, technical requirements, incorporating chemistry, or sustainability). The options then lead students deeper into the chatbot, narrowing the scope of discovery to a sub-module (levels 2–4). At the end of a sub-module, students are asked whether they would like to continue, learn more about a certain topic, or end their session. Alternatively, students can begin by typing in a query, like a keyword or a specific question, that will lead them to the closest module matching the query.

Importantly, these modules and sub-modules connect to the other modules in ways that students may find helpful. For example, in the case of sustainability information, students could access the sustainability module from the top of the



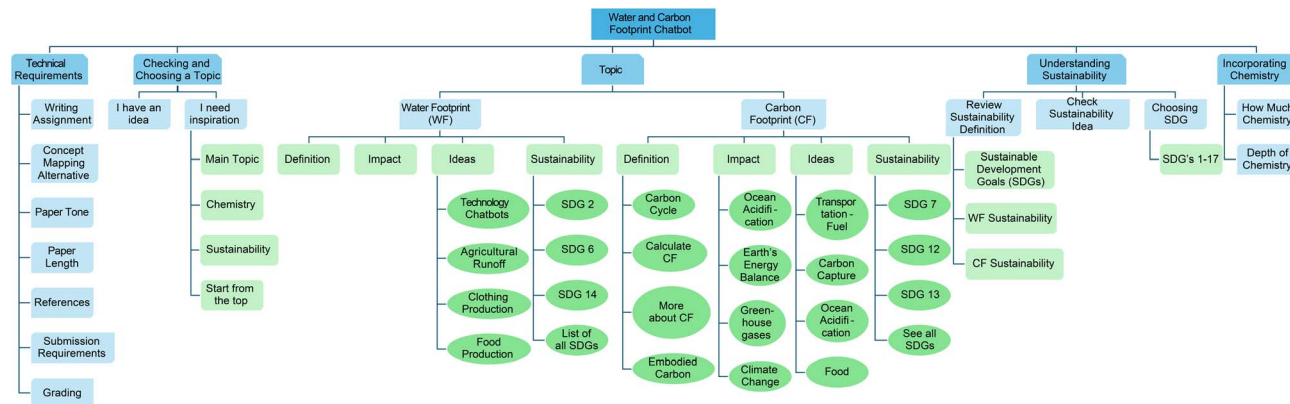


Fig. 1 The carbon and water footprint chatbot navigation depicted as a decision tree.

chatbot as well as through modules on the main chemistry context topic sections. Students were encouraged to use the curated chatbot as a tool to generate essay ideas and address technical requirements, with the incentive of a modest number of points in the course.

All information included in the curated chatbot modules was developed with extensive research by the instructional team. The chatbot uses natural language processing (NLP) to analyze student inputs and machine learning to improve the accuracy of student input matches to specific modules or sub-modules. Generative AI and LLMs were not used, as to limit hallucinations and to provide students with instructor-approved content. This resource was completely optional to use, and all of the technical requirements of the writing assignment were included in a document in the course's learning management system.

Ethics compliance

Data collection for the project followed protocols approved by the university IRB office under (20-444). Artifacts used in this analysis are derived only from students who provided consent for their use, and points associated with chatbot use in the course were awarded independently of whether students gave consent for their work to be used as artifacts.

Sample

All curated chatbots were implemented in a first-semester general chemistry course. Students enrolled in this course were typically science majors. These chatbot users also consented for the use of their data for research purposes. The footprint chatbot was implemented for the first time during the fall 2021 semester during which 236 of the 347 enrolled students interacted with the water and carbon footprint curated chatbot. This implementation was repeated for the same course in spring 2024, where 56 of the 157 enrolled students interacted with the chatbot and submitted an essay. During the following semester, fall 2024, 116 of the 692 students enrolled interacted with the Pyrocene chatbot.

Analysis

Students could explore various modules within the curated chatbot decision tree by clicking on the provided options or by typing their own unique questions. These interactions in the format of a chat were downloaded and anonymized from the IBM WatsonX assistant log files. All anonymized data for each curated chatbot was tabulated in a Microsoft Excel file.

Chatbot interactions

Students chatbot interactions can provide meaningful insights to better understand how they navigated through the chatbot, what content they explored and how deeply they engaged with the content. The depth of engagement can be established based on the amount of time and the number of modules explored. For the footprint chatbot implemented in spring 2024, the engagement was judged as limited when students explored limited modules, asked no questions and had a short interaction time, as fair when they explored at least 2 modules within a reasonable interaction time and as good if they explored multiple modules with a longer interaction time (Table S3).

To address the first research question, the analysis of chatbot interactions, involved counting the number of times students visited the definition of sustainability and/or the SDGs in the footprint chatbot and Pyrocene chatbot to understand what content was mostly explored. The counts were based on whether students visited a particular SDG at least once; repeat visits were not included. This approach was chosen to identify overall patterns in the content students engaged with rather than conducting an in-depth analysis of individual student chatbot actions. These unique student interactions were visualized with Microsoft Excel tree diagrams for comparative analysis. An example of student interactions with the curated chatbot can be found in the SI.

Student essay analysis

To address the second research question, students' written essays were collected, paired with chatbot usage, anonymized, and uploaded to an internal database, Microsoft Copilot. Best



practices regarding informed use and transparency, as outlined by McAfee and Rodriguez were considered during the input, process, and output stages of the analysis.²⁶ Ethics were addressed by anonymizing all student essay data and by using Copilot within the university's managed Microsoft 365 environment, which is designed to meet security and privacy requirements for handling student information. The study used Microsoft Copilot as an extraction tool to identify, capture and structure evidence from student essays that align with the SDGs. This reduced the time needed for the researchers to identify reasonable excerpts, thus allowing for analysis after the output has been cross checked between researchers. It should be noted that the quality of the output depends on the quality of the input and the prompt engineering. The prompt engineering involved defining a clear task, providing details associated with the task and defining the output format.

As shown in Fig. 2, the prompt was designed with the task of identifying both explicit and implicit SDGs mentioned in the student essays. Microsoft Copilot was also directed to provide evidence in the form of a direct quote or phrases as evidence to substantiate when an SDG was implied in a student essay.

Throughout the process, the output was considered, and the strength of the evidence provided was used to make judgments about the validity of the evaluation. From the AI-chosen essay excerpts, only about 3% of the excerpts (9 out of 261) consisted of AI judgments without evidence in the form of essay quotes. These statements for example read "while not directly discussed, the broader environmental impact of carbon emissions may touch on water systems indirectly". For each of these statements the student essay was read and if the SDG was implied in the essay as suggested by AI based on the judgement of both researchers who are knowledgeable in the SDGs, then that SDG was considered as implied. For all the other essays, both researchers considered the direct essay quotes to decide whether the AI-analysis was sound. The outputs were discussed between two researchers to ensure consistency in analysis and to flag any outputs that do not make sense. Flagged outputs are presented in the SI. The SDGs students implicitly or explicitly mentioned in their essays were compared to the SDGs students explored in the curated footprint chatbot that was implemented in spring 2024.

Finally, to evaluate the writing assignment for evidence of student agency, we used Guerra and colleagues' student agency

framework to develop a prompt that helped identify essays demonstrating the three interrelated dimensions of student agency. These included (i) personal values influenced by their knowledge, awareness, beliefs, and attitudes, (ii) actions that include goal setting, planning, monitoring, self-reflecting, and collaboration, and (iii) the context of the action on micro-, meso- and macro-levels.⁶ This framework and its accompanying descriptions were used to develop a generative AI prompt that Microsoft Copilot applied to identify excerpts from students' essays aligning with each dimension of student agency. The prompt included two questions for each dimension, as shown in Table 1. The steps followed to refine the prompt are provided in the SI.

A total of 33 essays that demonstrated at least four of the most frequently visited SDGs (as identified through the essay analysis) were selected for the sample. As these essays represent students with "good" or "fair" usage of the chatbot, they were selected to further investigate the impact of chatbot usage on student essay content. Of these essays, 22 included 4 SDGs and 11 included at least 5 SDGs that were either explicitly stated or implied. This ensured inclusion of essays in which students made multiple, meaningful connections across several of the most emphasized SDGs. The prompt questions shown in Table 1 were then applied to all 33 essays using Microsoft Copilot to generate outputs that included evidence for each dimension in the form of direct quotations or paraphrased statements. The full prompt is provided in the SI. The output was analyzed by two independent researchers who were familiarized with the SDGs to identify patterns or emerging themes. Each researcher independently examined every dimension outlined in Table 1 to explore which dimensions were featured most and least as students connected chemistry to the SDGs in their essays on water and carbon footprint. The researchers then engaged in a structured comparison of their themes and identified overlapping themes consistently supported by the students' essays.

Results and analysis

Throughout the analysis, students' visits to a variety of SDGs within the chatbot and their subsequent incorporation into their essays are discussed. Table 2 outlines the top 6 SDGs that students visited in the chatbot and discussed in their essays, and includes student essay examples to illustrate how authors categorized essay content.

RQ1. Which SDGs in the Pyrocene and water/carbon footprint curated chatbots did students explore?

Pyrocene curated chatbot. The curated content in the chatbot emphasized the relationship between wildfires, fossil fuel combustion, and climate, which created the expectation that SDG 7, 12, and 13 would be explored the most. For the 116 students who interacted with the Pyrocene chatbot, the average interaction time was 9 minutes with 5 students who used the chatbot more than once. Only 7 interactions were judged as limited and 6 as fair. Students could also access the SDGs in the chatbot by visiting the content associated with Pyrocene, which

Please analyze this student essay [word document uploaded] for its alignment with the United Nations Sustainable Development Goals (SDGs). Identify

Explicitly mentioned SDGs: Any SDGs that are directly named or numbered in the essay.

Implied SDGs: SDGs that are not named but are clearly supported by the essay's themes or arguments. Supporting evidence for implied SDGs, include direct quotes or phrases from the essay that demonstrate alignment with each implied SDG.

Present the finding in a clear, organized format.

Fig. 2 Microsoft Copilot prompt used to identify the implicit and explicit SDGs present in students' essays.



Table 1 Questions developed from Guerra's student agency framework for its use in prompt engineering to identify evidence of person values, actions and contexts for sustainability

Dimensions	Generative AI prompt with questions
Personal values for sustainability	Does the student express beliefs or motivations that reflect a personal commitment to sustainability? Do they show self-awareness or confidence in their ability to engage with sustainability challenges?
Actions for sustainability	Does the student demonstrate goal-setting or planning related to sustainability actions? Is there evidence of collaboration, teamwork, or reflection in decision-making?
Contexts of action for sustainability	How does the student describe the influence of their social, cultural, or institutional environment on sustainability actions? Do they show awareness of how they interact with or respond to these contexts?

included a section titled “examples incorporating sustainability,” directing them to SDGs 7, 12, and 13. The most frequently visited SDGs included SDG 7 ($n = 35$), SDG 13 ($n = 32$), SDG 2 ($n = 25$), as well as the definition of sustainability ($n = 40$) as shown in Fig. 3. The sustainability module of the Pyrocene chatbot included the definition of sustainability and

the SDGs. Apart from visiting the definition of sustainability, most students visited SDG 7, 13 and 2 by navigating to the Pyrocene module as opposed to the sustainability module. These three SDGs primarily relate to chemistry content in terms of energy, climate, and the use of wildfires for crop management, as well as additional implications for food security.

Table 2 List of the top 6 SDGs visited by students and mentioned in their essays. This table includes the SDG number, official title, SDG goal as stated by <https://sdgs.un.org/goals>, and an example of how the goals were aligned with student essays

SDG number	SDG title	SDG goal	Student essay example
6	Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all	“Using 1 million gallons of water to harvest only one cow is not sustainable because water is not endless.” – essay 96
7	Clean and affordable energy	Ensure access to affordable, reliable, sustainable and modern energy for all	“Using renewable resources such as solar, wind, or others to create electricity can reduce the amount of emissions since these resources release little to no amounts of greenhouse gases.” – essay 41
9	Industry, innovation, and infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	“For a company, the carbon footprint covers emissions from all its operations, including energy use in buildings, industrial processes, and machinery.” – essay 73
12	Responsible consumption and production	Ensure sustainable consumption and production patterns	“Embodied carbon emissions from concrete stem from every aspect of production including mining raw materials, transportation, kiln operations, and demolition.” – essay 35
13	Climate action	Take urgent action to combat climate change and its impact	“Working to reduce carbon footprint is vital to slow the effects of climate change.” – essay 13
14	Life below water	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development	“Eutrophication is a process that causes harm to marine life and depletes oxygen in the water, nutrient overload in the water. This leads to excessive overgrowth of algae and even dead zones (aquatic life cannot survive).” – essay 82



UNSDG Unique Student Interactions for the Pyrocene Chatbot

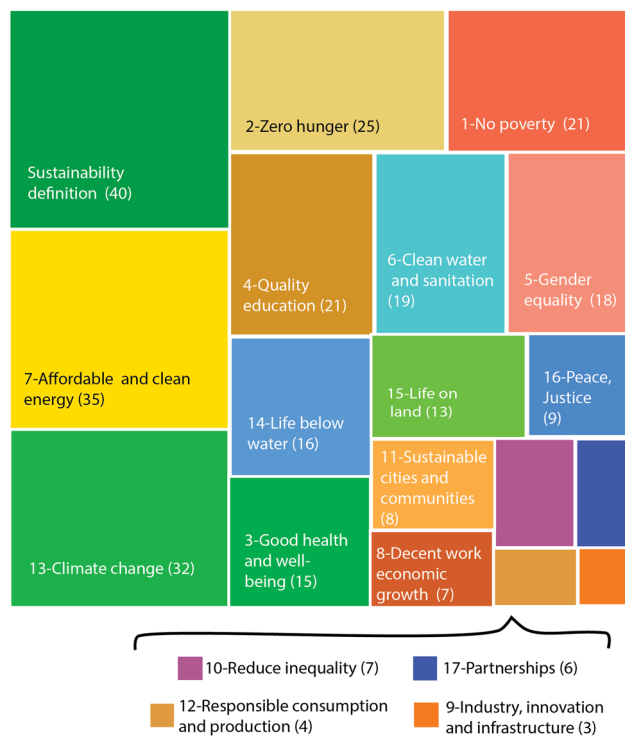


Fig. 3 Tree map of the unique student interactions that students had with the sustainability module in the Pyrocene curated chatbot.

Students also explored SDGs associated with hunger, poverty, and quality education, as indicated by a higher-than-expected number of visits to SDG 1, 2, and 4.

One surprising observation is the few visits to SDGs 3 and 15 regarding the influence of wildfires on life on land and health, particularly in terms of air pollution. This observation could be explained by considering the in-class instructional time allocated to these areas, which was modest. The SDGs least explored with $n = 4$ included SDG 12 (responsible consumption and production) and $n = 3$ for SDG 9 (industry, innovation and infrastructure). This finding shows that even though more visit was expected for SDG 12, students preferred exploring SDG 7 and 13. Highlighting that incorporating responsible consumption and the critical role of industry in future teaching materials can help students understand connections to climate change, fossil fuel use, and the increasing severity of wildfires.

Footprint curated chatbots. In each case for supporting student writing the sustainability module of the curated chatbots includes a review of the United Nations' definition of sustainability, as well as information on all 17 Sustainable Development Goals (SDGs). For spring 2024, the average interaction time of 56 students was approximately 26 minutes with 15 good, 18 fair, and 23 limited student interactions. Also, 12 students interacted with the chatbot more than once. Student engagement on the chatbot interactions for the fall 2021 footprint chatbot is reported elsewhere.²⁴ Fig. 4 provides tree maps that detail the unique student interactions with the sustainability portion of the footprint curated chatbot for the (a) fall

2021 (F21) and (b) spring 2024 (S24) semester. Fig. 4a shows that students visited SDG 6 ($n = 54$), SDG 14 ($n = 37$), SDG 13 ($n = 31$), and SDG 7 ($n = 28$) the most out of all the sub-modules in the sustainability module. Fig. 4b illustrates a similar profile of the top sub-modules, with SDG 6 ($n = 12$), SDG 13 ($n = 8$), SDG 14 ($n = 6$), and the sustainability definition ($n = 6$) being the most prominent. Note also that with the larger group engaging with the chatbot (4a), the number of SDGs visited by any student is larger. With fewer student users in the S24 general chemistry course, the trend still showed that about a quarter of chatbot users visited UNSDG 6, and about an eighth visited UNSDG 13. However, it does appear that a higher proportion of students in the S24 group interacted with the sustainability definition sub-module more than the F21 group.

These modules directly relate to carbon and water footprints, addressing clean water and sanitation, life below water, climate action, and affordable and clean energy, respectively. Although topics such as solubility and thermodynamics are also emphasized in general chemistry, it appears that students wanted more information on how their chosen issues related to the specific SDGs. Other SDGs, such as SDG 12, SDG 9, and SDG 11, had fewer student interactions, suggesting a lack of interest in those topics in the context of the writing assignment or a need for less help in connecting them to chemistry or their chosen subject.

RQ2. Which SDGs were implied or explicitly mentioned in students' footprint essays?

For consideration of this question it is important to recognize that water sanitation and climate were the central concepts associated with the water and carbon footprints. The SDGs mentioned by students in their essays are illustrated in Fig. 5. Interestingly, SDG 12 was present in all of the student essays ($n = 56$), likely because students recognize human activity and consumption as a key driver of climate change and sustainability challenges associated with clean drinking water and the necessary infrastructure. Additionally, the emergence of SDG 9 in student essays, showcases the important role and implications associated with industry.

It was apparent that students who wrote about the carbon footprint or embodied carbon placed emphasis on the SDGs associated with greenhouse gases and climate change, emphasizing the roles of energy, human activities in industry, and sustainability. Students who wrote about the water footprint generally discussed SDGs associated with clean water and sanitation, including the role of agriculture and the impact of various industries on water quality or consumption.

Student essays revealed an emerging understanding of the role of chemistry in technology and innovation, climate and environmental issues, agriculture and food security, as well as industry, production, and consumption. These themes, along with related subthemes and the dominant SDGs referenced, are summarized in Fig. 6.

Interestingly, from the SDGs that aligned with the emerging themes from student essays (SDG 6, 9, 12, and 13), SDG 6 and 13 were mostly explored in the curated chatbot, with fewer visits to



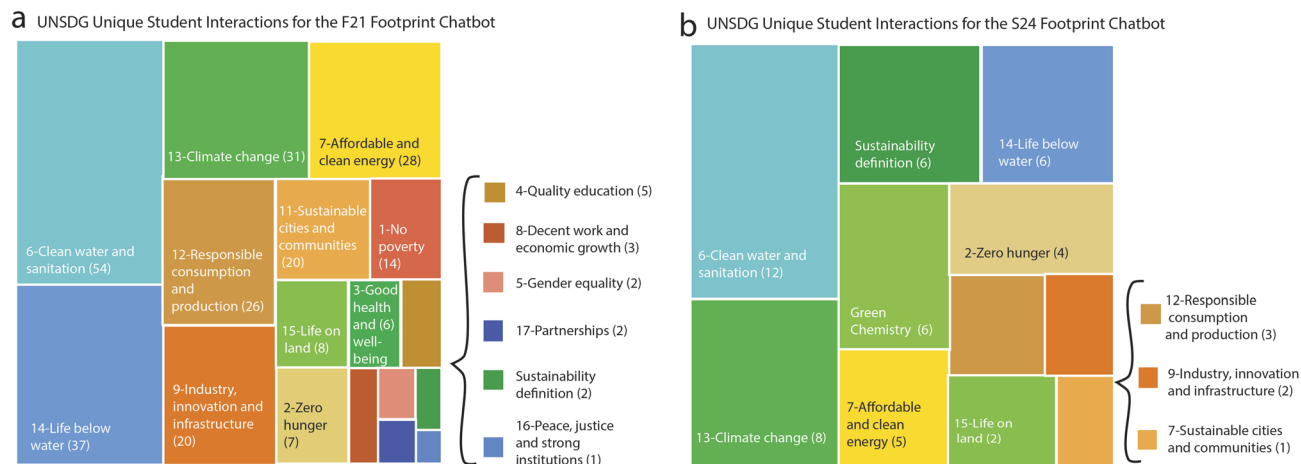


Fig. 4 Tree maps of unique student interactions for the (a) fall 2021 and (b) spring 2024 footprint curated chatbot.

Implicit and Explicit UNSDGs evident in footprint essays (n=56)

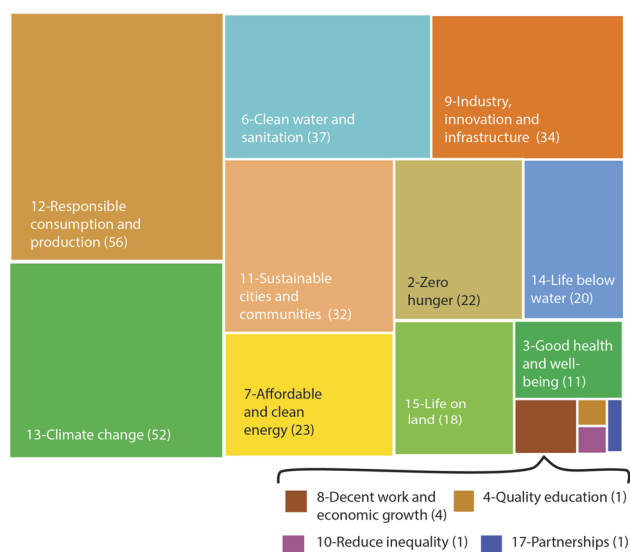


Fig. 5 SDGs that were either implied or explicitly mentioned in student essays based on the Microsoft Copilot analysis.

SDG 9 and 12. This is expected, as the carbon and water footprints relate mostly to water and sanitation (SDG 6) and the greenhouse gases associated with climate action (SDG 13). This is reflected by the 11 out of 36 students who included SDG 6 in their essay and visited the corresponding SDG in the curated chatbot. Similarly, this was observed for SDG 13 with 7 out of the 50 students. Although students did not spend a lot of time exploring curated content on industries (SDG 9) and responsible consumption (SDG 12), they were able to frame it in their writing, revealing an overarching context that connects human decision-making and activities to sustainability. Interestingly, SDG 11 was the least explored in the S24 chatbot, but was implied in many student essays as students referred to urban logistics and sustainable transportation as important aspects of sustainable cities. These discussions included student free

response inquires including, “how many cars there are in America”, “vehicles that use hydrogen fuel”, “the means of transportation” and “moving business towards these more green forms of energy”. In summary, the themes from student essays reflected a range of topics and SDG references, demonstrating their interdisciplinary learning as they connected chemistry to sustainability.

RQ3. What evidence from the footprint essays indicates dimensions of student agency?

Many students incorporated sustainability into their essays by presenting environmental issues, identifying the societal impacts of those issues, and proposing global and local solutions. Although there was little instructional emphasis placed on student agency, these key components of their essays suggest that students showed various dimensions of student agency as defined by Guerra *et al.*'s (2022)⁶ student agency framework. To test this hypothesis, we constructed a prompt for Microsoft Copilot that included questions about personal values, actions, and the context of those actions related to sustainability, as listed in Table 1. In response to the prompt, Microsoft Copilot provided a table that included these dimensions, an evaluation of the dimension, and supporting evidence as demonstrated in Table 3 below.

In the evaluation column, essays were either categorized as [1] demonstrated or strong evidence, [2] partially demonstrated or moderate evidence, or [3] not demonstrated or limited evidence. For this discussion, we will use strong, moderate, or limited evidence. Of the 33 essays analyzed, the majority of students demonstrated strong evidence of personal values ($n = 27$) and the context of their actions ($n = 29$) related to sustainability. However, only ten students demonstrated strong evidence of actions for sustainability, with the majority demonstrating moderate ($n = 17$) or limited ($n = 6$) evidence of this dimension. The students who demonstrated moderate or limited evidence of actions for sustainability, also failed to include ideas such as goal setting or collaborative action in their essays, which are key components of Guerra's framework



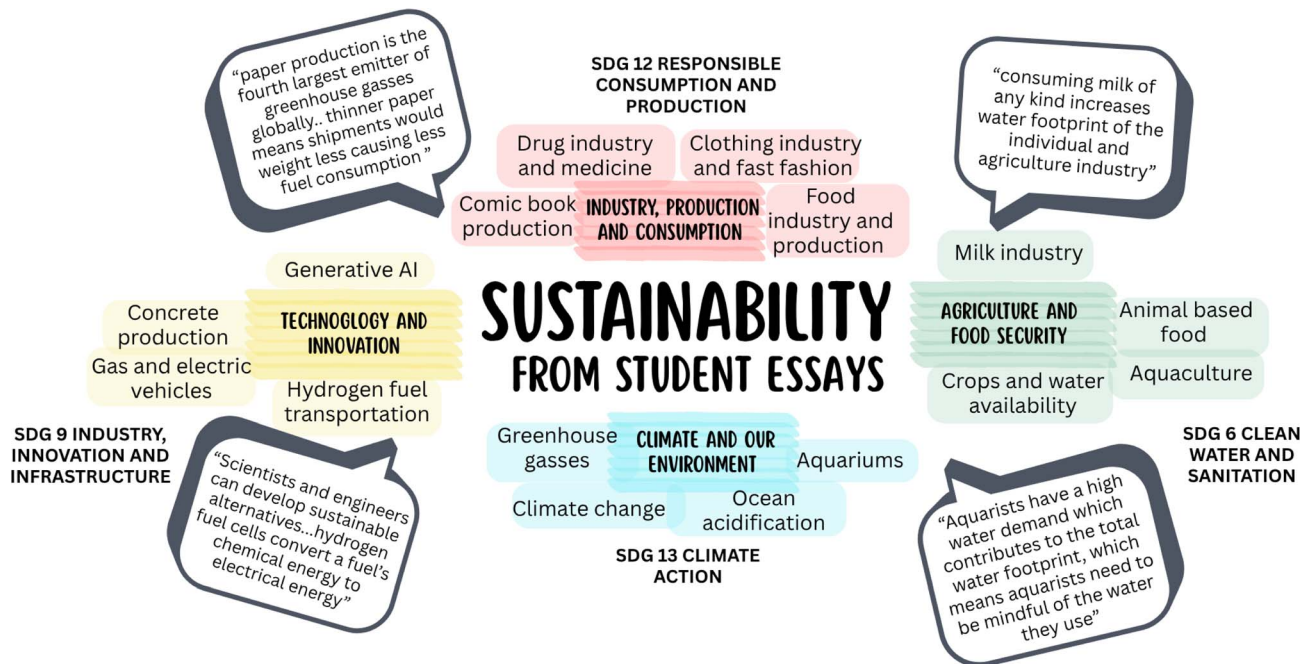


Fig. 6 Key themes that emerged from the Microsoft Copilot analysis essay to explore the implied and explicitly mentioned SDG.

defined explicitly in the Copilot prompt. Of the actions that students did include, most were general or broad statements and did not reflect personal goals or plans. This behavior is expected as the inclusion of sustainability in general was a part of the essay prompt, and students were not explicitly instructed to provide personal sustainable solutions or goals. Examples of direct quotes from student essays for each dimension is provided in the SI.

Personal values for sustainability. The first part of Guerra's student agency framework encompasses personal values related to sustainability. In some cases, these values were reflected in the students' essays as environmental impacts, collective effort, and the value of knowledge. Key themes revealing students' personal values for sustainability are collected in Table 4.

Other examples related to those in Table 4 include student reflections on how the environment is directly affected by damage, while others, like in essay 36, use the current state of the environment as a call to action: "in order to slow further global warming, it is crucial to find ways to reduce our carbon emissions." The essays demonstrate that students recognize that the state of the environment in the future, or even its current state, is a direct result of the efforts that humans make. Students also highlight that to effect change, it will require a collective effort, and that solutions like "reducing transportation-related emissions is essential for sustainable living and preserving the planet for future generations" (essay 100). Comments like these reflect that students see themselves as part of the solution. Students, like in essay 25, remark that their role in the proposed solution includes arming themselves with knowledge and "understanding how the water footprint is related to chemistry" (essay 81). They find value in

knowledge and connecting that knowledge about chemistry to the world around them.

Actions for sustainability. Some student essays showcased evidence of sustainable action. They include a particular focus on practical solutions, collaborative efforts from role players across various scales, and the need for knowledge to understand global issues and their relationship to chemistry. The key themes, along with examples from student essays, are summarized in Table 5.

Students' essays placed most emphasis on providing realistic solutions or options of actions that can be taken to work towards sustainable development. These include decreasing current consumption patterns and providing unique options tailored for various SDGs. As shown in Table 5, these include developing new materials, creating new technology, being innovative, and making better-informed decisions about consumption through awareness, as emphasized in essay 73, also shown in Table 4. For example, one student added that "chemists have developed biodegradable plastics... chemists have found a sustainable way to help reduce this by creating electric powered cars" (essay 74). Several students suggested general actions that can be achieved on a community level with one student (essay 36) providing detailed actions, which include "taking shorter than 10 min showers, reducing the amount of coffee we intake, and recycling everything that we can" and "by taking shorter showers, cutting back on resource-intensive products, and promoting recycling, we can reduce both our water and carbon footprints". Overall, the use of renewable energy and electric transportation was discussed in relation to essays on the carbon footprint, whereas the water footprint primarily focused on actions to reduce water consumption.



Table 3 An example of the output from the Microsoft Copilot prompt on evidence of sustainable agency for student essay 42 (essay passages in blue)

Dimension	Evaluation	Supporting evidence
Personal values for sustainability	✓ Demonstrated	<ul style="list-style-type: none"> - The student expresses a clear belief in the importance of sustainability: “Water footprint and sustainability are connected together because it is such an important part of life on this planet.” - They show motivation to act: “We must do anything we can to minimize and sustain a good water footprint and, most importantly, help ensure that water is available and safe for both this generation and the ones to come.” - There is a sense of self-awareness and responsibility: “Minimizing our water footprint and using our resources safely and respectfully is important not only to the environment but also to humans as well.”
Actions for sustainability	✓ Demonstrated	<ul style="list-style-type: none"> - The student suggests specific actions: “Some ways to help resolve this problem are to recycle, use less plastic, and make better choices about where we are throwing our trash.” - They advocate for civic engagement: “One way to fix some of these problems is to support organizations and charities by using your voice.” - While direct collaboration or teamwork is not explicitly mentioned, the call to collective action implies a recognition of shared responsibility
Contexts of action for sustainability	✓ Demonstrated	<ul style="list-style-type: none"> - The student references local and global contexts: “Iowa has created a harmful ‘dead zone’... Des Moines has one of the poorest water qualities from the high amount of nitrates.” - They connect institutional and environmental factors: “Sadly, our oceans are becoming more acidic and polluted, which is bad for marine life. This causes less tourism, fewer jobs globally, and less food for us to eat.” - They show awareness of social and health impacts: “Not having safe and sanitary water can lead to health problems and deadly diseases.”

Supporting these actions included students' ability to shift focus between important role players from individuals to agencies to larger organizations. On a local to global level, these role players include “Iowan farmers”, “researchers”, “chemists”, “policymakers”, “manufacturers”, “companies”, “groups and corporations”, and the “United Nations”. The student in essay

95 claimed that “The United Nations has curated a set of global goals to combat this issue” and essay 111, “ensuring that those companies follow the guidelines will show a decrease in the carbon footprint for cities”. Students focused mostly on the broader levels of sustainable action with individual examples, such as the comment that reflect both individual and broader

Table 4 Table of themes with their description and example excerpt showcasing personal values for sustainability

Theme	Description	Example excerpt
Environmental impacts	A cause-and-effect relationship between people's actions and the current or future state of the environment	“By contaminating groundwater, especially in poorer countries, the effect can be to prevent people from having access to their basic right to clean water.” – essay 43
Collective effort	Acknowledgement of the need for change as a community and roles as stewards of that change	“It's our job as humans, and especially chemists, to maintain it and steward it as best as we can.” – essay 65
Value of knowledge	The importance of being informed about our own impact on water or carbon footprint and chemistry behind certain phenomena or global solutions	“Education on the chemistry facts and personal adjustments to reduce carbon impact is progress to restore the ecological balance that this beautiful planet once obtained.” – essay 25



Table 5 Table of themes with their description and example excerpt showcasing student actions for sustainability

Theme	Description	Example excerpt
Practical solutions	Solutions or actions that involve human response and innovation for sustainable development	“Choosing renewable sources, being aware of how we produce, consume and dispose of goods, supporting agriculture, and reducing waste.” – essay 73
Role players across scales	Acknowledgement of the key actors or role players on local and global scales that contribute to sustainable action	“Then by understanding this, individuals like policymakers can make decisions on how to conserve more water.” – essay 1
Need for knowledge	Knowledge required to better understand how chemistry relates to global issues and the SDGs	“Map out the whole process of what product is being made... measure when water is being used, how it is being used, how much is being used, and what happens to it after.” – essay 80

collaboration. An example excerpt from essay 42 shows that this student recognized their agency and the role of supporting organizations by stating, “one way to fix some of these problems is to support organizations and charities by using your voice”. Finally, some students recognized the need for knowledge, as it can help students “map out the whole process”. Students added that “knowing this framework [the SDGs], it is crucial that the chemistry connection and pivotal thinking skills are acquired” (essay 25). These excerpts suggest that some students recognized the importance of key role players, collaboration, relevant knowledge, and practical solutions across various scales.

Context for actions for sustainability. According to Guerra's framework, the context of action for sustainability encompasses the role and actions of the individual within the societal environment, which includes social, cultural, and institutional levels as well as their interactions with these contexts. Students' essays demonstrated evidence of these contextualized actions by including a societal focus, data-driven reasoning, and an awareness of broader systems. These themes are summarized in Table 6.

Many of the essays maintain a societal focus as students realized that their own lifestyle may not be feasible or afford the same opportunities for people in different countries or communities. For example, in essay 53, a student notes that purchasing an electric vehicle may be dependent on socioeconomic status, impacting the efficacy of this environmental solution. Expressing these concerns in their essay demonstrates an awareness that socioeconomic status plays a role in environmental efforts. An awareness of these broader systems is then highlighted further when students connect population growth to water pollution. For

example, essay 42 exemplifies the connection between the actions of an agricultural system and its impact on the quality of life in an aquatic system. Students also added connections that were strengthened with data on a local and global scale. As an example, the student who wrote essay 44 claimed that “fast fashion accounts for 10% of all carbon emissions”. Overall, in these essays, students' contexts of action were broad, focusing on larger infrastructure and global solutions rather than personal and community-based solutions.

Implications

Developing sustainable AI has been challenging due to its reliance on non-renewable resources, the large amounts of water required for cooling systems, and the substantial land use for data centers.^{27,28} These issues are especially prevalent in large generative AI models, such as GPT-5, which require extensive training sets and times.²⁹ Researchers and industry partners concerned about the environmental implications of generative AI suggest developing more efficient models using transfer learning or retrieval-augmented generation, thereby reducing energy demand.³⁰

However, these LLMs can be used to focus on sustainability issues, such as climate forecasting or identifying key air pollutants.³¹ Their usefulness cannot be completely ignored because of their impact on the environment. As the field continues to grow, it may be necessary to develop a framework to weigh the costs and benefits of AI models and their use in all disciplines.³²

Table 6 Table of themes with their description and example excerpt showcasing the context of actions for sustainability

Theme	Description	Example excerpt
Societal focus	Includes actions associated with community as opposed to individual impacts	“It isn't always an option for lower income households to make this change.” – essay 53
Data-driven reasoning	The inclusion of numerical information from national or global data sources	“Concrete production accounts for 8% of our global CO ₂ emissions and breaks down emissions by source (e.g., mining, transportation, kiln operations).” – essay 35
Awareness of broader systems	The demonstration of the role that multiple parts play to make a change or impact	“Due to the intense population growth on the planet and the increasing urbanization, water pollution has become an increasing problem.” – essay 32



With regard to education, curated chatbots, such as those introduced in this work, rely on developer input and leverage specialized models trained to optimize performance.³³ These resources are more sustainable than traditional LLMs as they are less energy intensive. As instructors, it is important not only to teach our students about sustainability but also to provide sustainable learning resources for them, and these curated chatbots are a simple way to do so. This study showed that structured activities that incorporate curated chatbots and essay writing, could provide a means to help students connect their chemistry knowledge to the SDGs, whilst developing their awareness and dimensions of agency for sustainability.

Conclusions

In this work, researchers explored students' interactions with a curated chatbot and their reflections on sustainability in a chemistry and sustainability writing assignment. The student's curated chatbot interactions with the sustainability module revealed that they visited SDGs related to their chosen topic. Consequently, SDGs 6, 13, and 7 were frequently visited for essays about water footprint, carbon footprint, and Pyrocene, respectively. Results of a Microsoft Copilot-assisted analysis of the footprint essays showed that students wrote about additional SDGs. They included the topic-related SDGs, but also implicitly or explicitly discussed additional goals like SDG 9 and SDG 12 that connected chemistry to human activities associated with industry and responsible consumption and production. Finally, the student essays were reviewed for evidence of a sustainable action perspective. Through their essays, most students demonstrated personal values and provided context for their actions related to sustainability. However, those actions were limited to broad, global solutions rather than individual, everyday changes.

The student's interactions with the curated chatbot revealed topics that might require more attention during teaching or reflect the issues with which students were most interested. For example, regarding the theme of Pyrocene, the vital role of responsible consumption and the critical role of industry can help students understand connections to climate change, fossil fuel use, and the increasing severity of wildfires, as well as the possible health implications of wildfire smoke and other resulting air pollutants. Noting that these connections may be complex to make during lectures, the curated chatbots provide an additional instructor-approved resource for students as they write essays and explore unfamiliar topics.

In writing of their essays, students included many practical solutions for change and demonstrated a personal responsibility towards those solutions. Sustainable action perspective themes acknowledge the need for and importance of acquiring knowledge for sustainability, highlighting the development of sustainability-related competencies. Through essay writing students were not only able to accomplish this but also use their knowledge of chemistry as a vehicle to imagine change for sustainability from environmental, societal, and economic dimensions. Instructor-approved content in the form of

a curated chatbot supported students in this new way of connecting chemistry and sustainability.

Conflicts of interest

The authors declare that there are no conflicts to declare.

Data availability

The data collected for this work including aggregated results shown in Fig. 2–4 was collected from human participants and are not available for confidentiality reasons.

Supplementary information (SI): includes (1) a description of the teaching design for the course reported on here including a description of the decision trees used in the curated chatbot; (2) details of the methodology used for analysis; and (3) additional details related to that analysis. See DOI: <https://doi.org/10.1039/d5su00948k>.

Acknowledgements

The authors wish to acknowledge students who agreed to the inclusion of their work in a course as artifacts associated with the research in this article. This work is funded by the National Science Foundation (NSF) Division of Undergraduate Education (Grant # DUE-2235600.)

References

- 1 A. Redman and A. Wiek, Competencies for Advancing Transformations Towards Sustainability, *Front. Educ.*, 2021, **6**, 785163, DOI: [10.3389/educ.2021.785163](https://doi.org/10.3389/educ.2021.785163).
- 2 G. de Haan, The development of ESD-related competencies in supportive institutional frameworks, *Int. Rev. Educ.*, 2010, **56**(2), 315–328, DOI: [10.1007/s11159-010-9157-9](https://doi.org/10.1007/s11159-010-9157-9).
- 3 M. Rieckmann, Future-oriented higher education: Which key competencies should be fostered through university teaching and learning?, *Futures*, 2012, **44**(2), 127–135, DOI: [10.1016/j.futures.2011.09.005](https://doi.org/10.1016/j.futures.2011.09.005).
- 4 A. Wiek, L. Withycombe and C. L. Redman, Key competencies in sustainability: a reference framework for academic program development, *Sustainability Sci.*, 2011, **6**(2), 203–218, DOI: [10.1007/s11625-011-0132-6](https://doi.org/10.1007/s11625-011-0132-6).
- 5 UNESCO, *Education for Sustainable Development Goals : Learning Objectives*, UNESCO, 2017.
- 6 A. Guerra, D. Jiang and X. Du, Student Agency for Sustainability in a Systemic PBL Environment, *Sustainability*, 2022, **14**(21), 13728, DOI: [10.3390/su142113728](https://doi.org/10.3390/su142113728).
- 7 A. Oberrauch, H. Mayr, I. Nikitin, T. Bögler, T. Kosler and C. Vollmer, “I Wanted a Profession That Makes a Difference”—An Online Survey of First-Year Students' Study Choice Motives and Sustainability-Related Attributes, *Sustainability*, 2021, **13**(15), 8273, DOI: [10.3390/su13158273](https://doi.org/10.3390/su13158273).
- 8 P. Jääskelä, V. Heilala, T. Kärkkäinen and P. Häkkinen, Student agency analytics: learning analytics as a tool for analysing student agency in higher education, *Behav. Inf.*



- Technol.*, 2021, **40**(8), 790–808, DOI: [10.1080/0144929X.2020.1725130](https://doi.org/10.1080/0144929X.2020.1725130).
- 9 A. K. Erümit and R. Ö. Sarıalioğlu, Artificial intelligence in science and chemistry education: a systematic review, *Discover Educ.*, 2025, **4**(1), 178, DOI: [10.1007/s44217-025-00622-3](https://doi.org/10.1007/s44217-025-00622-3).
- 10 L. K. Allen and P. Kendeou, ED-AI Lit: An Interdisciplinary Framework for AI Literacy in Education, *Policy Insights Behav. Brain Sci.*, 2024, **11**(1), 3–10, DOI: [10.1177/23727322231220339](https://doi.org/10.1177/23727322231220339).
- 11 S.-C. Kong, W. Man-Yin Cheung and G. Zhang, Evaluating an Artificial Intelligence Literacy Programme for Developing University Students' Conceptual Understanding, Literacy, Empowerment and Ethical Awareness, *Technol. Soc.*, 2023, **26**(1), 16–30, DOI: [10.2307/48707964](https://doi.org/10.2307/48707964).
- 12 United Nations Global Compact, Artificial Intelligence and the Sustainable Development Goals: Operationalizing technology for a sustainable future, UN Global Compact, United Nations Global Compact, 2025.
- 13 Y. Guo and D. Lee, Leveraging ChatGPT for Enhancing Critical Thinking Skills, *J. Chem. Educ.*, 2023, **100**(12), 4876–4883, DOI: [10.1021/acs.jchemed.3c00505](https://doi.org/10.1021/acs.jchemed.3c00505).
- 14 M. J. Clark, M. Reynders and T. A. Holme, Students' Experience of a ChatGPT Enabled Final Exam in a Non-Majors Chemistry Course, *J. Chem. Educ.*, 2024, **101**(5), 1983–1991, DOI: [10.1021/acs.jchemed.4c00161](https://doi.org/10.1021/acs.jchemed.4c00161).
- 15 J. L. Araújo and I. Saúde, Can ChatGPT Enhance Chemistry Laboratory Teaching? Using Prompt Engineering to Enable AI in Generating Laboratory Activities, *J. Chem. Educ.*, 2024, **101**(5), 1858–1864, DOI: [10.1021/acs.jchemed.3c00745](https://doi.org/10.1021/acs.jchemed.3c00745).
- 16 A. A. Fernandez, M. Lopez-Torres, J. J. Fernandez and D. Vazquez-Garcia, ChatGPT as an Instructor's Assistant for Generating and Scoring Exams, *J. Chem. Educ.*, 2024, **101**(9), 3780–3788, DOI: [10.1021/acs.jchemed.4c00231](https://doi.org/10.1021/acs.jchemed.4c00231).
- 17 X. Wang, L. Zhang, Y. Mao, D. J. McGillivray and Z. Wang, ChEdu: A Guided AI Teaching Assistant for Chemistry Education and Exam Support, *J. Chem. Educ.*, 2025, **102**(12), 5347–5354, DOI: [10.1021/acs.jchemed.5c00036](https://doi.org/10.1021/acs.jchemed.5c00036).
- 18 E. Korsakova, O. Sokolovskaya, D. Minakova, Y. Gavronskaya, N. Maksimenko and M. Kurushkin, Chemist Bot as a Helpful Personal Online Training Tool for the Final Chemistry Examination, *J. Chem. Educ.*, 2021, **99**(2), 1110–1117, DOI: [10.1021/acs.jchemed.1c00789](https://doi.org/10.1021/acs.jchemed.1c00789).
- 19 P. B. Brandtzaeg, M. Skjuve, K. K. Dysthe and A. Folstad, When the social becomes non-human: Young people's perception of social support in chatbots, *Conference on Human Factors in Computing Systems - Proceedings*, 2021, DOI: [10.1145/3411764.3445318](https://doi.org/10.1145/3411764.3445318).
- 20 E. Kasneci, K. Sessler, S. Küchemann, M. Bannert, D. Dementieva, F. Fischer, U. Gasser, G. Groh, S. Günemann, E. Hüllermeier, S. Krusche, G. Kutyniok, T. Michaeli, C. Nerdel, J. Pfeffer, O. Poquet, M. Sailer, A. Schmidt, T. Seidel *et al.*, ChatGPT for good? On opportunities and challenges of large language models for education, in *Learning and Individual Differences*, Elsevier Ltd, 2023, vol. 103, DOI: [10.1016/j.lindif.2023.102274](https://doi.org/10.1016/j.lindif.2023.102274).
- 21 H. Nguyen, V. Nguyen, S. Ludovise and R. Santagata, Value-sensitive design of chatbots in environmental education: Supporting identity, connectedness, well-being and sustainability, *Br. J. Educ. Technol.*, 2025, **56**(4), 1370–1390, DOI: [10.1111/bjet.13568](https://doi.org/10.1111/bjet.13568).
- 22 T. A. Holme, Using the chemistry of pharmaceuticals to introduce sustainable chemistry and systems thinking in general chemistry, *Sustainable Chem. Pharm.*, 2020, **16**, 100234, DOI: [10.1016/j.scp.2020.100234](https://doi.org/10.1016/j.scp.2020.100234).
- 23 R. I. Perez-Pena and A. E. Vaughn, Chemistry in Your Home Community: Design of a Final Project to Help Empower Students to Explore How Chemistry Connects to Their Home Communities, *J. Chem. Educ.*, 2025, **102**(8), 3708–3715, DOI: [10.1021/acs.jchemed.5c00161](https://doi.org/10.1021/acs.jchemed.5c00161).
- 24 A. T. Lolincó, Using communication tools for chemistry learning to improve literacy, writing, and digital accessibility, PhD Thesis, Iowa State University, ProQuest Dissertations & Theses Global, 2024.
- 25 A. T. Lolincó and T. A. Holme, Developing a Curated Chatbot as an Exploratory Communication Tool for Chemistry Learning, *J. Chem. Educ.*, 2023, **100**(10), 4092–4098, DOI: [10.1021/acs.jchemed.3c00520](https://doi.org/10.1021/acs.jchemed.3c00520).
- 26 S. C. McAfee and J.-M. G. Rodriguez, I Asked ChatGPT to Do My Research: Welcoming Artificial Intelligence to the Chemistry Education Research Team, *J. Chem. Educ.*, 2025, **102**(12), 5082–5094, DOI: [10.1021/acs.jchemed.5c00958](https://doi.org/10.1021/acs.jchemed.5c00958).
- 27 P. Li, J. Yang, M. A. Islam and S. Ren, Making AI Less “Thirsty”: Uncovering and Addressing the Secret Water Footprint of AI Models, *arXiv*, 2025, preprint, DOI: [10.48550/arXiv.2304.03271](https://doi.org/10.48550/arXiv.2304.03271).
- 28 A. Shehabi, A. Newkirk, S. J. Smith, A. Hubbard, N. Lei, M. A. B. Siddik, B. Holecck, J. Koomey, E. Masanet and D. Sartor, 2024 United States Data Center Energy Usage Report, Lawrence Berkeley National Laboratory LBL Publications, 2024, DOI: [10.71468/P1WC7Q](https://doi.org/10.71468/P1WC7Q).
- 29 K. Hao, Training a single AI model can emit as much carbon as five cars in their lifetimes | MIT Technology Review, *MIT Technology Review*, 2019, <https://www.technologyreview.com/2019/06/06/239031/training-a-single-ai-model-can-emit-as-much-carbon-as-five-cars-in-their-lifetimes/>.
- 30 A. Zewe, *Explained: Generative AI's environmental impact*, MIT News, Massachusetts Institute of Technology. MIT News, 2025, <https://news.mit.edu/2025/explained-generative-ai-environmental-impact-0117>.
- 31 E. Strubell, A. Ganesh and A. McCallum, *Energy and Policy Considerations for Deep Learning in NLP*, 2019, <https://bit.ly/2JTbGnI>.
- 32 N. Bashir, P. Donti, J. Cuff, S. Sroka, M. Ilic, V. Sze, C. Delimitrou and E. Olivetti, *On the Limitations of Carbon-Aware Temporal and Spatial Workload Shifting in the Cloud*, MIT, 2024, <https://mit-genai.pubpub.org/pub/8ulgrckc/release/2>.
- 33 IBM Watsonx Assistant transforms content into conversational answers with generative AI, IBM, (n.d.), Retrieved February 9, 2026, from <https://www.ibm.com/new/announcements/ibm-watsonx-assistant-transforms-content-into-conversational-answers-with-generative-ai>.

