

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

Morgan Clark,^a Micke Reynders^a and Thomas Holme^{*a}

Table of Contents

<i>Using curated chatbots to support students' exploration and awareness of sustainability and essay writing</i>	1
<i>Teaching Design</i>	2
Sustainability Content Alignment	2
Chatbot Development and Interactions	4
Chatbot Information and Pyrocene Decision Tree.....	4
Example of Student Chatbot Interactions.....	4
<i>Methodology</i>	6
Essay analysis SDGs	6
Essay analysis Dimensions of Agency for Sustainability	8
<i>Supporting Findings</i>	12
Essay Analysis	12
Additional SDG mentions by students who wrote essays on Pyrocene.....	12
Analysis for Dimensions of Agency.....	13
<i>References</i>	17

Teaching Design

Sustainability Content Alignment

Students in the Fall 2021, Fall 2024, and Spring 2024 courses were equipped with sustainability knowledge throughout the course of the semester. The instructor included examples of sustainability and connected them to chemistry topics. Table SI.1 contains the lecture, chemistry topic, and sustainability example used for the water and carbon footprint sustainability contexts in Fall 2021 and Spring 2024.

Table S1. Table of the sustainability examples used to relate a chemistry topic to carbon and/or water footprint

Lecture	Chemistry Topic	Connections to Sustainability
6	Using Isotopic Abundance	Example of H_2^{18}O vs H_2^{16}O and temperature in deep time ^a
7	Mass to Particles	Water molecules count in a can of diet coke; % nitrogen in nitrate ion ^a
11	Percent Yield	Importance of water properties in how it is used; Define water footprint ^a
12	Solution Definitions	Common pollutant units ^{a,b}
13	Dilution	Water treatment ^a
14	Ionic/Net ionic	Nitrate removal ^a
16	Redox Reactions	Microbial reduction of nitrates ^a
20	Earth's Energy Imbalance	Connection between carbon footprint and energy ^b
21	Coulombs Law and Molecular Energy	Water and energy usage in refining crude oil ^{a,b}
22	First Law	Specific heat of water and its importance ^a
23	Heat flow Example Calculations	Practical importance of water's heat capacity ^a
24	Phase Change Enthalpy	Water vaporization and electricity ^a ; Thermochemistry and carbon footprint ^b
25	Formation of Reaction & Heats of Formation	Combustion energy of hydrocarbons with heats of formation ^b
28	Core / Valence Electrons	Role of oxygen lone pairs in behavior of water ^a
32	Formal charge	Water's shape plays a role in its properties ^a
34	VSEPR theory	ID water is bent ^a
40	Observations related to intermolecular forces (IMF)	Key features of water that lead to high IMF ^a

^aSustainability example relates to water footprint

^bSustainability example relates to carbon footprint

Table S2. Table of the lecture, chemistry topic, and sustainability example used for the Pyrocene sustainability contexts in Fall 2024.

Lecture	Chemistry Topic	Connections to Wildfires
1	Intro	Define idea of pyrocene
2	Models	What could a model for a fire look like? Fuel Models; Charcoal briquette as density example
3	Matter	Crude oil fractionation; Aristotle explanation of fire
4	Quantum model	Fossil fuel produce CO ₂ abundances
6	Using isotopic abundance	Molar masses of common fire reactants
7	mass to particles	ID hydrocarbon from a molar mass
8	balancing chemical equations	balancing combustion rxns; moles of fuel producing moles of CO ₂
9	mass-mass stoichiometry	chemistry of a match head
10	stoichiometry	Complete vs incomplete combustion
11	percent yield	percentage yield in crude oil refining reactions
12	solution definitions	how does water put out a fire?
15	acid/base definitions	combustion as redox
17	CO ₂ levels and temp in deep time	combustion needs vaporization, wildfire vaporization of plant fuels
18	pressure conversions	combustion stoichiometry, pyrolysis
19	partial pressure	Henry's law and CO ₂ dissolving into oceans
20	Earth's energy imbalance	severity trend of wildfires
21	Coulombs Law and molecular energy	compare fossil fuels to wildfire fuels, role of wildfires in CO ₂ levels in atmosphere
22	First Law	high heat capacity of water and putting out fires
23	heat flow example calcs	exothermic character of combustion
25	formation rxn & heats of formation	energy density of wood versus gasoline
26	characterizing light & calcs	color of flame in wildfires and its temperature
33	Bond strengths	role of O ₂ in energy of combustion
35	VSEPR and approx. bond angles	shapes of some plant biomolecules
39	dispersion	dispersion forces dependence on hydrocarbon size

Chatbot Development and Interactions

Chatbot Information and Pyrocene Decision Tree

The majority of how the curated chatbots were developed are included in the previous works. (1) The navigation for the curated chatbots were developed from a decision tree. The decision trees and chatbot navigation for the Footprint curated chatbot can be found in previous work and Figure 1 of the manuscript.(1) Figure S1 is an abbreviated decision tree for the Pyrocene curated chatbot provided to give context to how the curated chatbots are designed.

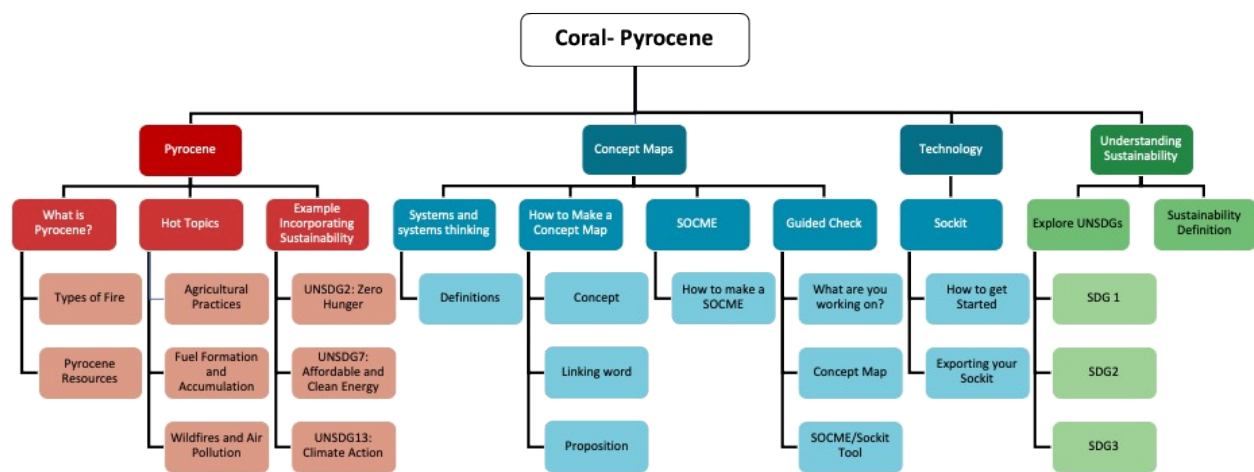


Figure S1. Decision tree for the Pyrocene curated chatbot.

This study specifically reports on chatbot content associated with carbon and water footprints as indicators of environmental impact, with carbon footprints reflecting greenhouse gas emissions and their role in climate change, and water footprints addressing freshwater depletion and water quality concerns. The Pyrocene chatbot content was inspired by the work of Stephen Pyne, who argues that fire has become a driving force in our era as influence by human activities.(2) In this chatbot, emphasis is placed on elements of the fire triangle, wildfires and their impacts.

Example of Student Chatbot Interactions

Students were able to access the chatbot through a link in their course management system. This navigated to a research group home page, with the chatbot embedded into the website. Students could start interacting with the chatbot by typing a phrase or question, or by selecting one of the topics provided.

Figure S2 shows an example of the chatbot log of one student's interaction. The student's actions are highlighted in yellow.

Chatbot Log Example

Participant 01

Interaction 001

Student types "Carbon Footprint Statistics"

- Chatbot routes → **"Carbon Footprint Sustainability"**
 - [information about carbon footprint sustainability]
- Carbon footprint sustainability → **SDG 12: Responsible Consumption and Production**
 - [information about SDG 12]
 - <https://www.globalgoals.org/goals/12-responsible-consumption-and-production/>
 - Would you like to know more about the other SDGs → **Yes**
- Choose SDG → **SDG 3 – Good Health and Well-Being**
 - [information about SDG 13]
 - To learn more, visit <https://www.globalgoals.org/goals/3-good-health-and-well-being/>
 - Would you like to know more about the other SDGs → **Yes**
- Choose SDG → **SDG 1 – No Poverty**
 - [information about SDG 1]
 - To learn more, visit <https://www.globalgoals.org/goals/1-no-poverty/>
 - Would you like to know more about the other SDGs → **Yes**
- Choose SDG → **SDG 9 – Industry, Innovation, and Infrastructure**
 - [information about SDG 9]
 - Learn more at <https://www.globalgoals.org/goals/9-industry-innovation-and-infrastructure/>
 - Would you like to know more about the other SDGs → **No**
 - Would you like to explore any other topics → **No**

End

Figure S2 Example of a curated chatbot log, detailing student choices and interactions with the curated chatbot.

Categorizing Chatbot Interactions

Student interaction categories were established based on the average interactions with the curated chatbot. In the spring 2024 semester, students interacted with the chatbot for an average of 26 minutes and visited 6 modules. These were used as benchmarks to establish the criteria for limited, fair, and good interactions. Limited interactions were those in which students interacted with fewer than the average number of modules for less than

the average interaction time, while good interactions were those in which students interacted with more than the average number of modules for more than the average interaction time. Fair interactions fall in between these categories. The exact criteria for the three categories can be found in Table S3 below.

Table S3. Interaction categories based on average modules visited and average interaction time

Interaction Category	Time	Modules Visited
Limited	< 26 min	< 2
Fair	> = 26 min	< 4
Fair	15 min > x < 26 min	> = 6
Good	> 26 min	> 6

It is important to note that the interaction type is weighted more towards time spent on the modules. This is reflected in the “fair” interaction category, as students may visit fewer modules but spend more time within those modules.

Methodology

Essay analysis SDGs

To ensure that the AI-output identified appropriate excerpts as evidence of implied or explicit SDGs, researcher cross-checking was done. The evidence in the form of direct quotes or phrases was studied by two researchers who checked whether the evidence matched the assigned SDG. If there was not a match between the identified SDG and the evidence provided, then the excerpts were flagged for further checking by reading the student’s essay. The flagged responses are shown in Table S4, where the output in red was excluded from the analysis due to the weak evidence and absence in students essays. The excerpts in green were justified and verified as substantiated in essays.

Table S4. Flagged AI-output responses for identified implicit and explicit SDGs in footprint essays

Student essay	Flagged SDG identified by AI	Evidence	Included or excluded in analysis
94	Implied SDG14	“Consumption of any animal products is going to increase an individual’s water footprint much more than consuming non-animal products.” Implies concern for aquatic ecosystems affected by water use.	Not evident in essay and thus excluded
1	Implied SDG 13	“...we can control our agricultural runoff and plastic waste, which profoundly impacts all ecosystems.”	Action for climate less obvious, action associated mostly with SDG 14 as emphasis is on life below water.

6	Implied SDG 13	While not directly discussed, the essay's focus on environmental pollution and sustainable agricultural practices indirectly supports climate-related goals. The mention of nutrient pollution and ecosystem degradation ties into broader climate resilience efforts.	The mention of improving agricultural practices in terms of water usage and ensuring clean water for future generations- which was considered a suitable climate action mitigation
8	Implied SDG 2	"Agriculture makes up around 70% of the world's water usage..." "As populations increase across the world and countries develop, we can not continue to use water at this level."	In the context this essay discusses cow meat and the impact of the cow industry, which related to SDG2. Therefore it was included in the analysis
37	Implied SDG14	"During this process, it can drain into wastewater, which will then add to the gray water footprint." — This implies pollution of water systems, which can affect aquatic ecosystems.	No evidence in this essay about effects on life below water, thus not included in analysis
42	Implied SDG 13	"Evaporation... can contribute to more precipitation, which can have a substantial effect on water footprint..."	weak evidence that does not make explicit connections to climate change, greenhouse gas emissions, mitigation, adaptation, or policy/action, which are central to SDG 13- thus it was excluded
65	Implied SDG 13	The essay draws parallels between water and carbon footprints but does not directly address climate change or greenhouse gas emissions.	Evidence is weak and thus excluded from analysis
96	Implied SDG 13	While not directly about carbon emissions, the essay's focus on sustainability and resource conservation aligns with climate action goals, especially in reducing environmental impact from food production.	There is evidence in the essay about human response and efforts, such as changing management practices ect. to limit food waste and reduce footprints, thus included in the analysis
115	Implied SDG14	"...reduce water consumption in industries and daily life..." — indirectly supports marine conservation by reducing industrial water use and pollution.	No evidence of aquatic life connection associated with life below water
33	Implied SDG13	While not directly discussing climate change, the essay's focus on water conservation and resource management supports broader environmental sustainability goals, which are integral to climate action.	Evidence is weak as focus is placed on aquariums without broader mitigations and thus excluded from analysis
95	implied SDG 6	While not directly discussed, the broader environmental impact of carbon emissions may touch on water systems indirectly	Insufficient evidence. The paper focuses more on industrial impacts and not explicitly on the impact of water systems
124	explicit SDG 12	"This will contribute to a more sustainable livestock sector and more responsible consumptions and production patterns"	This is a direct quote from the paper and directly aligns with SDG 12, which is "responsible consumption and production"
124	implied SDG 6	While not directly mentioned, reducing methane and improving livestock management can reduce water pollution from manure and runoff, indirectly supporting clean water initiatives	There is no evidence to support this as the paper is focused on livestock production and there is absolutely no mention of clean water initiatives or runoff.

100	explicit SDG 13	Referenced directly: "Goal 13 Department of Economic and Social Affairs"	This essay only referenced this SDG, but did not mention it explicitly in their paper. They included information in a n annotated bibliography, but did not make any direct connections to UNSDG 13. However, there are broad theme of this SDG throughout the paper and an "implied" ranking would be more suitable.
-----	-----------------	--------------------------------------------------------------------------	-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

Both researchers noticed flagged excerpts were readily associated with SDG 13 and 14, as AI identified weak evidence and stated that “this implies”, thus making connections that were not explicit in students’ essays. To ensure both researchers were consistent in judgements, a set of criteria was created to decide whether evidence was sufficient to conclude that SDG 13 or 14 were evident. SDG 14 was usually not evident when students not explicitly discuss the impact on aquatic life. SDG13 required more clarification, as climate action was approached from the perspective that there must somewhere in the essay be mention of ideas that connect to climate change, greenhouse gas emissions, climate related impacts (natural disasters, droughts, floods), mitigation, adaptation, or policy/action, which are central to SDG 13. For example, evidence was accepted as appropriate if essays included any strategies or solutions proposed that could relate to sustainability efforts with a potential link to climate action even if not explicitly mentioned (for example improving water usage for agricultural practices can ensure sufficient water for future generations). When impacts associated with climate change is mentioned that involves consumption of energy and water due to potential impacts or resource management (or climate resilience) and of course climate impacts.

Essay analysis Dimensions of Agency for Sustainability

The prompt engineering was done to summarize the key aspects of Guerra’s framework discussed in this article Student Agency for Sustainability in a Systemic PBL Environment written by Aida Guerra, Dan Jiang and Xiangyun Du in Sustainability 2022, 14(21), 13728 (DOI: <https://doi.org/10.3390/su142113728>). A summary from the article was taken that summarizes each dimension and Co-Pilot was first asked to provide the key points of the summary, then to frame a set of questions associated with each dimension and to then condense it into two key questions per dimension that was used in the prompt. Here follows the conversation:

You said:

summarize the key idea from these 3 dimension and create a prompt that can be used to analyze these from student essays 1. First Dimension: Personal Values for Sustainability This dimension emphasizes epistemic agency as suggested by Damsa et al. [27], meaning engagement in actions that build

awareness and a shared understanding of sustainability. This is the process through which they develop personal values, including beliefs, motivations, interests, and intentions to engage in sustainable practices. This dimension comprises cognitive, affective, and motivational elements such as beliefs, awareness, efficacy, motivation, interests, and attitudes, of which the most influential are self-beliefs and motivation [46,48]. Self-beliefs are learners' perceptions of their knowledge of sustainability, their development of self-awareness in relation to sustainability issues [12], their ability to achieve anticipated goals [46], their attitudes towards sustainability, and their confidence in their ability to take on difficult tasks and overcome challenges as they learn [46]. Motivation refers to learners deriving influences from both intrinsic and extrinsic forces to initiate actions and self-determine problems to study, as well as the direction and intensity of their learning [49]. Learning motivation is viewed as a dynamic or fluid process in which individuals' internal characteristics are interrelated with external contexts [46]. In a PBL environment, students may develop knowledge, awareness, and motivation to promote sustainability through working on real-life problems, which may support them in developing efficacious beliefs and clear goals related to sustainability. 2. The second dimension enhances the regulative and self-regulated characteristics of student agency for sustainability [27]. Behaviorally, agentic students are competent in selecting, organizing, and creating environments to optimize learning [46]. From this perspective, student agency is enacted through setting goals to contribute to or achieve sustainability, making plans for engagement, monitoring their own sustainability-related decision-making processes in complex situations, and self-evaluating their own sustainability-related actions [45]. In a PBL context, this learning process also entails sharing and co-constructing sustainability-related knowledge and actions. This highlights the relational characteristics of agency for sustainability. The collaborative learning process of setting goals and plans, monitoring and adjusting, and self-evaluation and reflection as a group also supports the individual development of knowledge. The negotiation process and compromises within the group may increase participants' motivation. However, a lack of group dynamism may become a constraint on students' development of their knowledge and engagement in sustainability-related actions. Therefore, in a PBL setting, student agency for sustainability is also concerned with students' interaction, communication, and collaboration in the project team and beyond [50]. The relational aspects of this include instructor–student relations, peer support, and a trusting and safe atmosphere [51], along with effective communication, reciprocal positive feedback, and efficient conflict management in team settings [50]. 3. Bandura [24] refers to social environments that enable students to perform well and achieve their goals. In the student agency literature, 'environment' refers to the social and cultural conditions that affect the life of an individual or community. Within the frame of these conditions, students interact with, influence, and are influenced by their surrounding social groups, structures, norms, and/or values. These environments constitute the contexts in which students take sustainability-related actions; they can be considered at micro-, meso-, and macro-levels and are characterized as open, nesting systems that are interconnected and increase in complexity and the number of interactions [52,53,54]. The micro-context comprises the individuals who constitute a given community and the interactions they establish among themselves. Their interactions and activities constitute the context of action [53,54,55]. As an example, Molthan-Hill et al. [55] refer to staff and students' commitment to and engagement in sustainability-related actions and the classroom contexts in which these activities take place. They also consider other micro-level contexts in which sustainability-related actions take place, namely, the program and department levels. In a PBL setting, contextual resources imply reciprocal interplay not only with peers, teams, and instructors, but also with surrounding factors, including the courses students attend and the practices (e.g., policies, programs, or rules) of surrounding communities and institutions, or even the wider sociocultural environment [50,51].

Copilot said:

Copilot

- *Here's a summary of the key ideas from the three dimensions of student agency for sustainability, followed by a prompt that can be used to analyze student essays based on these dimensions:*

▣ **Summary of Key Ideas**

- *Personal Values for Sustainability*
 - *Focuses on epistemic agency—students actively build awareness and understanding of sustainability.*
 - *Involves cognitive, affective, and motivational elements: beliefs, awareness, efficacy, motivation, interests, and attitudes.*
 - *Self-beliefs and motivation are central: students' confidence, goal-setting, and intrinsic/extrinsic drivers influence their engagement.*
 - *In PBL (Problem-Based Learning), real-life problems help students develop sustainability-related knowledge and motivation.*
- *Self-Regulated and Relational Agency*
 - *Emphasizes self-regulation: goal-setting, planning, monitoring, and evaluating sustainability actions.*
 - *Includes collaborative learning: co-construction of knowledge, group reflection, and negotiation.*
 - *Relational aspects are key: peer support, instructor relationships, communication, and team dynamics.*
 - *PBL encourages interaction and shared responsibility in sustainability efforts.*
- *Environmental and Contextual Agency*
 - *Based on Bandura's concept of enabling environments—social and cultural contexts shape student actions.*
 - *Students interact with micro (classroom, peers), meso (program, department), and macro (institutional, societal) levels.*
 - *Sustainability actions are influenced by norms, structures, and values within these nested systems.*
 - *PBL settings involve reciprocal interactions with peers, instructors, and broader institutional practices.*

▣ **Essay Analysis Prompt**

- **Prompt for Student Essay Analysis:**
- **Analyze how the student demonstrates agency for sustainability across three dimensions:**
- **Personal Values** – Does the student express beliefs, motivations, interests, or attitudes that reflect a personal commitment to sustainability? How do they describe their self-awareness and confidence in addressing sustainability challenges?
- **Self-Regulation and Collaboration** – Does the student show evidence of goal-setting, planning, monitoring, or evaluating their sustainability-related actions? How do they engage with peers or instructors in collaborative learning or decision-making?
- **Environmental Contexts** – How does the student describe the influence of their social, cultural, or institutional environment on their sustainability actions? Do they reference interactions at the classroom, program, or societal level?

You said:

which of these dimensions include taking sustainable action?

- *Copilot said:*
- *Copilot*
- *Great question! Taking sustainable action is embedded across all dimensions, but each emphasizes it differently. Here's how they contribute:*

▣ **Dimensions That Include Taking Sustainable Action**

- *Personal Values for Sustainability*
 - *Indirectly supports action through the development of beliefs, motivation, and self-efficacy.*
 - *Students may express intentions and goals related to sustainability, but this dimension focuses more on internal readiness than actual behavior.*
- *Self-Regulated and Relational Agency*
 - *Directly includes sustainable action.*
 - *Students set goals, plan, monitor, and evaluate their sustainability-related behaviors.*
 - *Collaboration and reflection in PBL settings often lead to real-world actions taken by individuals or groups.*
- *Environmental and Contextual Agency*
 - *Enables and shapes sustainable action through interaction with social, institutional, and cultural contexts.*
 - *Students act within and respond to these environments, which can facilitate or constrain sustainability efforts.*

You said:

can you combine all of these and summarize it into key analysis questions to assess students essays for whether they show these dimensions?

Copilot said:

Copilot

- *Absolutely! Here's a consolidated set of key analysis questions that you can use to assess student essays for evidence of the four dimensions of student agency for sustainability, including the systems thinking and socio-environmental competence component:*

☒ *Student Agency for Sustainability – Essay Analysis Questions*

- *Personal Values for Sustainability*
 - *Does the student express beliefs, motivations, interests, or attitudes that reflect a personal commitment to sustainability?*
 - *How does the student describe their self-awareness regarding sustainability issues?*
 - *Do they show confidence in their ability to engage with and overcome sustainability-related challenges?*
 - *Are there signs of intrinsic or extrinsic motivation driving their engagement?*
- *Self-Regulation and Collaboration*
 - *Does the student demonstrate goal-setting, planning, monitoring, or evaluating their sustainability-related actions?*
 - *How do they describe their collaborative efforts with peers or instructors in sustainability projects?*
 - *Is there evidence of reflection or adjustment in response to challenges or group dynamics?*
 - *Do they show awareness of how group processes (e.g., negotiation, feedback, conflict resolution) influenced their learning or actions?*
- *Environmental and Contextual Agency*
 - *How does the student describe the influence of their social, cultural, or institutional environment on their sustainability actions?*

- *Do they reference interactions at the micro (classroom/peer), meso (program/department), or macro (institutional/societal) levels?*
- *Is there evidence of the student responding to or shaping these environments in pursuit of sustainability goals?*

You said:

for aspects 1 to 3 please adjust to only 2 key questions

Copilot said:

- *Student Agency for Sustainability – Condensed Essay Analysis 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?*
- *Self-Regulation and Collaboration*
 - *Does the student demonstrate goal-setting or planning related to sustainability actions?*
 - *Is there evidence of collaboration or reflection in group work or decision-making?*
- *Environmental and Contextual Agency*
 - *How does the student describe the influence of their social or institutional environment on their sustainability actions?*
 - *Do they show awareness of how they interact with or respond to these contexts?*

Evidence of Sustainable Agency

Use the following three dimensions to assess the student's demonstration of sustainable agency. Include specific examples from the essay to support your evaluation.

1. 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?

2. 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?

3. 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?

Output Format

Please present your analysis in a structured table clearly separating each section and including direct quotes or paraphrased evidence where appropriate

Supporting Findings

Essay Analysis

Additional SDG mentions by students who wrote essays on Pyrocene

These SDGs mentioned are aligned with the topics students focused on in their essays. Students who wrote about the carbon footprint and embodied carbon primarily emphasized greenhouse gases and climate change (n = 6), followed by a general discussion of sustainability (n = 4). Fewer students explored sustainability from the perspective of electric vehicles and transportation (n = 3). Other essay topics included ocean acidification, agriculture and food production, concrete, electricity (for which there were n=2), and uniquely, comic books. Most of these essays included SDG 7, 9, 11, 12, and 13, emphasizing the role of energy, the sustainability of cities, the influence of industry, consumption, and climate change. Essays on the water footprint involved a general discussion, mostly about clean water and sanitation (n=8), with sustainability connections made to SDGs 2, 3, 6, 9, 12, 13, 14, 15, and 17. Some of the re-occurring topics included agriculture and livestock (n=5), food industry and animal based food production (n=3), the clothing industry, water treatment and production, aquariums and aquaculture (n=2 for each) and to a lesser extent the milk industry, drug industry and water requirements for generative AI (each n=1). Most of these essays emphasized SDGs 6, 9, 12, 13, and 14. Finally, students who wrote on both footprints linked sustainability mostly to industry-related topics, including livestock (n=1) and food production (n=1), as well as fast fashion and the clothing industry (n=2). General discussions emphasized SDG6, 12, and 13 from the perspective of water consumption. (n=4)

Analysis for Dimensions of Agency

The following excerpts were part of the AI-output after using Guerra's Framework for Dimensions for sustainable agency:

Personal values notes

- **Environmental Impacts but some sort of causal relationships**
 - Students: 3, 43,37,18, 51, 38, 81, 50, 44, 36, 100, 126, 124, 74, 41
 - 43 - "By contaminating groundwater, especially in poorer countries, the effect can be to prevent people from having access to their basic right to clean water."
 - 36 - "Each of us has an impact on the amount of fossil fuels that are burned..."
 - 126 - "In order to slow further global warming, it is crucial to find ways to reduce our carbon emissions."
- **Importance of being informed or having this kind of knowledge and how the chemistry works and the urgency thereof (37)**
 - Students: 24, 25, 49, 55, 73,74,52,81,37,115
 - 81 - "By understanding how the water footprint is related to chemistry it can help to understand how closely it is linked to sustainability, especially in the global goals."

- 25 - "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."
- Using numbers and things to back up their beliefs
 - Students: 65, 18, 44, 100, 25
 - 65 - "Each person globally uses roughly 1000 gallons of water per day."
 - 100 - "If we continue our habits as they are now, the atmosphere will warm by 1.5 degrees Celsius by 2035... we could experience 15x higher mortality rates."
- Personal concerns
 - Students 24, 25, 41, 49, 109, 111, 124, 126, 70, 100, 52, 36, 44, 40, 81, 38, 18, 37, 43, 80, 3
 - 36 - Sustainability is becoming a more important topic today as earth has been negatively impacted in many ways"
 - 70 - "In today's world we spend most of our days running from one point to the next never truly considering the effects of our carbon footprint."
- Referring to the collective effort (our, we with lacking overall in personal responsibility)
- The importance of stewardship
 - 65 "It's our job as humans, and especially chemists, to maintain it and steward it as best as we can."

Actions

- **Practical solutions- Focus on solutions on different scales** - Decreasing current usage (consumptions) and Focus on SDGs
 - 74- The student notes: "Chemists have developed biodegradable plastics... Chemists have found a sustainable way to help reduce this by creating electric powered cars." These are examples of actions, but they are attributed to scientists, not the student.
 - 73- - The essay lists actions such as "choosing renewable sources, being aware of how we produce, consume and dispose of goods, supporting agriculture, and reducing waste."
 - 25- Suggests specific actions: "In an instance where walking or carpooling is feasible, choose to reduce the amount of carbon released from a personal vehicle." and "Reducing the amount of wasted electricity on electronics on 'standby mode'... by unplugging devices or turning off the power strip when not in use."
 - 35- The student discusses solutions such as "optimized production, transportation and reliance on renewable energy" and "carbonation mixing" to reduce emissions, which shows goal-oriented thinking.
 - 41- - The student outlines specific actions: "Using renewable resources such as solar, wind, or others to create electricity... planting more trees... walking or riding a bike... recycling." and "By switching resources and using less fossil fuels when possible, emissions can be positively reduced."
 - 49- The essay references societal actions like the shift to electric cars and tree-planting organizations: "Electric cars were introduced to help society move into more green and safe travel."
 - 55- The essay suggests actions like purchasing or choosing used electric vehicles: "Finding a used one would be even better for the carbon footprint as it does not require a new car to be built."
 - 95- "One example of implementing this would be to reevaluate the combustion reactions we use to power our world."
 - 109- "Recycling, buying less food, transportation..." and "using less energy in a house."
 - 124- "Now, it is important to shift these goals to lessen environmental impacts through artificial selection.", - Highlights planning and strategy: "Combining breeding efforts with

changes in feeding strategies... could yield even greater reductions in methane emissions.”

- 126- “Transportation and electricity are not the only contributors, they are a good place to start in the reduction efforts,” but no direct mention of the student’s own actions or plans.
 - 70-- “Not all hope is lost as there are steps being taken to reduce the carbon foot such as thinner papers... comics are also adopting more digital versions.”
 - 100- “Hydrogen fuel cells... do not emit CO₂ or any conventional pollutants.” and “Vehicles that would use hydrogen fuel would need to have hydrogen fuel cells, which convert a fuel’s chemical energy to electrical energy.”
 - 36-- Suggests specific actions: “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.”
 - 44- “Fast fashion... could be remediated easier than some other contributors.”
 - 50- “Donating and buying secondhand clothing is an effective way to also reuse clothes without making them go to waste.” and “Buying clothes that are more expensive may be better in the long run, as they will last longer.”
 - 38- “Carbon footprints can be specifically reduced through carpooling, downsizing on homes, and unplugging devices when they are not in use.” and “Using sustainable agriculture efforts, improving water resource management, and protecting ecosystems.”
 - 18- “recycling water in order to reduce waste” and “using AI itself to streamline the efficiency of data centers.”
 - 32- “paying attention to how much water we use to carry out actions such as washing our hands, doing laundry, and cooking,”
 - 37- “We can lessen the water footprint... by using waterless dyeing methods, using other materials that do not need as much water to grow, and washing clothes less.”
 - 42- “Some ways to help resolve this problem are to recycle, use less plastic, and make better choices about where we are throwing our trash.”
 - 80- “Creating water treatment facilities that only focus on pushing this recycled water in just the direction of agriculture is important...”
 - 115- “Some examples that can help to reduce one’s water footprint are installing LED light bulbs in homes, using water bottles and biodegradable cups, and even purchasing an electric powered car.”
- **Scale of the role players (broader scales as opposed to individual scales), Agencies and standards, policy-makers chemists also showing collaboration**
 - 95- “The **United Nations** has curated a set of global goals to combat this issue.”
 - 74- “**Chemists** have developed biodegradable plastics... Chemists have found a sustainable way to help reduce this by creating electric powered cars.” These are examples of actions, but they are attributed to scientists, not the student.
 - 24- - Reflects on scientific collaboration: “**Researchers** have already begun to study the genetic markers of these animals.”
 - 100-- Uses credible sources to support sustainable solutions (e.g., US Department of Energy, Clean Air Task Force), indicating research and reflection.
 - 41- Reflects on collective action: “**Groups and corporations** can make an impact by using more renewable resources and less fossil fuels.”

- 111- “Ensuring that those **companies** follow the guidelines will show a decrease in the carbon footprint for cities.”
 - 50- “Consumers can see how the **company manufactures** the products and whether or not they used sustainable criteria.”
 - 81- - Cites collaboration and innovation in agriculture: “...according to an **lowan farmer** this method ‘is as good as it gets.’”
 - 1- “Then by understanding this, individuals like **policymakers** can make decisions on how to conserve more water.”
 - 43- “A solution... could be implementing stricter regulations about wastewater treatment... **pharmaceutical companies** to have on-site independent wastewater treatment facilities supervised by agents of a regulatory agency.”
 - 115- - Reflects on chemistry’s role in sustainability: “Chemists also invented LED light bulbs that conserve energy and water footprints which demonstrates how chemical innovation can lead to more sustainable options.” and “Chemists have come up with a way to reduce one’s footprint by encouraging people to use electric-powered cars.”
 - 3- “bioreactors and streamside buffers that filter fertilizer-borne nitrates...” indicating awareness of practical interventions.
- Example of individual supporting organizations
 - 42- “They advocate for civic engagement: “One way to fix some of these problems is to support organizations and charities by using your voice.”
 - 111- - Suggests specific actions: “To reduce an individual's carbon footprint... start using cars less, use energy-efficient lighting, minimize personal waste...”
 - 111- - Connects actions to broader goals: “Adopting sustainable practices such as using renewable energy for your household...” and “begin taking public transportation...”
 - Knowledge and skills needed
 - 25- “Knowing this framework, it is crucial that the chemistry connection and pivotal **thinking skills** are acquired.”
 - 80- “**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.”
 - 24- “**We can relate** these issues to the UN’s sustainable development goal of taking climate action.” This shows awareness of global sustainability frameworks.
 - 81- - “A major key to stopping, or at least slowing, the release of gases is by **understanding** why so much is being released...”
 - 65- - The essay discusses the importance of water treatment and the need for “proper funding and proper **attention**” and to “our water assessment” and “technological advancements” suggests collective efforts.

Context

- **Focus more on societal aspects**, actions associated with community as opposed to individual impact (example disparities, rural vs urban, industries implicating communities, also challenges between high and low income and solving challenges)
 - 124, 5, 36, 81, 50, 51, 43, 3, 41
 - 53- “Gas vehicles have also been around longer, extending the amount of emissions they’ve given off total, and are easier to get for the average income family.”
 - 53- “It isn’t always an option for lower income households to make this change.” These statements show the student’s understanding of how institutional and economic contexts shape sustainability choices

- 36 - "We are lucky to have clean water unlike so many others."
- 51 - "Some chemicals from the industrial buildings can pollute nearby water sources for towns and cities."
- **Data provided specific to topics**
 - 25, 35, 73, 95, 126, 100, 52, 44, 50, 37, 42, 65, 115, 3
 - 35 - "Concrete production accounts for 8% of our global CO2 emissions" and breaks down emissions by source (e.g., mining, transportation, kiln operations).
 - 44- "Fast fashion accounts for around 10% of all carbon emissions."
 -
- **Awareness of broader systems**
 - 74, 109, 124, 44, 50, 81, 38, 1, 18, 32, 80, 3, 111, 41
 - 38 - "Agriculture is the largest consumer of the world's freshwater resources,"
 - 50 - "Suppliers have also installed closed-loop systems that prevent the wastewater from going back into the community waters while polluted."
 - 32 - "Due to the intense population growth on the planet and the increasing urbanization, water pollution has become an increasing problem."
 - 42 - "Iowa has created a harmful 'dead zone'... Des Moines has one of the poorest water qualities from the high amount of nitrates."

References

1. Lolinco, A. T., & Holme, T. A. (2023). Developing a Curated Chatbot as an Exploratory Communication Tool for Chemistry Learning. *Journal of Chemical Education*, 100(10), 4092–4098. <https://doi.org/10.1021/acs.jchemed.3c00520>
2. Pyne, S.J. *The Pyrocene: How we created an age of fire, and what happens next*. Univ of California Press; 2022 Aug 2.