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# The plastics problem: a qualitative life cycle analysis case study for green and sustainable chemistry education

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In academic and industrial chemistry societies, long-standing professional interests in sustainability education are joined by emergent efforts to incorporate green chemistry, such as those outlined by professional societies' guidelines for degree programs. The new benchmarks indicate minimum expectations as a motivator for departments, educators, and curriculum designers to increase students' participation in the skillsets that comprise green and sustainable practices in chemistry. The road to meeting the challenge of education for sustainable development will be eased by examples of how to actively engage post-secondary students at various scales of instruction in the types of performances that underpin green chemistry and sustainability. This article outlines a multi-week case study from a large-enrollment organic chemistry laboratory course at a large midwestern research intensive university in the United States. In small groups, students are expected to engage in various scientific and engineering practices to (1) construct explanations of the chemistry of polymerization, (2) identify problems with respect to different shareholders, and (3) evaluate different solutions at different points in the life cycle as a "qualitative" life cycle analysis. Embedded in this evaluation are several Sustainable Development Goals (SDGs) to guide the analysis. This approach culminates in students using their evidence-based argument to make a decision and propose specific legislation.

### Sustainability spotlight

This article presents a case study for second-year organic chemistry students to examine the plastics problem through green chemistry principles and the UN Sustainable Development Goals (SDGs). The activity highlights challenges at plastics' beginning-of-life, including monomer sourcing and material properties, and end-of-life issues such as mechanical, chemical, and emerging enzymatic recycling methods. By engaging directly in decision-making, students assess how the plastics problem connects to multiple SDGs. Most teams identified monomer sourcing as relevant to SDGs 1, 2, 3, 4, 5, 7, 8, 11, 12, 13, 14, and 15. The article contributes to SDG 4 by demonstrating theory-aligned, evidence-centered assessment design.

## 1. Introduction

The effects of human-driven phenomena such as climate change, plastic pollution, energy demands, and contamination of water sources have created a climate crisis. To tackle this challenge, the introduction of sustainability to education has resulted in organized efforts to incorporate training in green chemistry principles and sustainability education from K-12 to post-secondary chemistry education. These urgent efforts have been well theorized by the United Nation's Education for Sustainable Development (ESD),[1] supported by a wealth of research in chemistry education.[2–5] Recently, these efforts have been formally incorporated into accreditation standards in the United States from the American Chemical Society (ACS).[6] The "Normal Expectations" suggest the use of case studies to "demonstrate to students the interplay of chemical, environmental health, regulatory, and business considerations that dictate chemical processes and product design." Going one step further, the "Markers of Excellence" involves students evaluating "the environmental, social, and health impacts of a chemical product over the life cycle of the product". These requirements suggest that curricular materials in which students are analysing the life cycle of a product can be an important tool in green chemistry and sustainability educational efforts.

As part of this special issue on the integration of Sustainable Development Goals (SDGs) into the curriculum, we offer an evidence-centred, design-based approach to this integration. In

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this article, we offer a case study designed to engage second-year organic chemistry students directly in a life cycle analysis focused on the two ends of the life cycle: "cradle" or beginning-of-life and "grave" or end-of-life. This case study is the second in a set of three scaffolded case studies. These activities have been implemented as part of a curriculum transformation for the second-year organic chemistry laboratory.[7] We also offer evidence on how students engage in decision-making with respect to relevant SDGs within our principled design approach.[8]

## 2. Case study design

### 2.1 Institutional context

The case study reported below was designed to be implemented as part of a large-enrolment organic chemistry laboratory course at a large midwestern research-intensive university in the United States. This 2-credit course typically serves over 600 students per semester and consists of a 3-hour laboratory period with a 1-hour recitation period per week. The typical student is a science, technology, engineering, or math (STEM) major, including a number of chemistry majors attaining a Bachelor of Arts (BA) degree. This course is the main organic chemistry laboratory course for students interested in health-related professional schools, such as medical school. To accommodate the large enrolment, the course is taught by a team consisting of two fixed-term instructors and 15 graduate teaching assistants. Not all the instructors are experts in green chemistry or sustainability. However, with proper training, evidence-centred curriculum materials can be used on a large scale to engage students in the curriculum.

The case study is positioned as the second of three case studies enacted by teams of students and was designed to be completed over 4 weeks during the 1-hour recitation periods. Students are guided through the activity by weekly assignments using beSocratic, an online system that allows students to construct written and drawn responses to a range of different tasks.[9]

### 2.2 The scenario

Development of the case study was inspired by popular media reporting[10] on the failures of the current recycling regime and recent advances in recycling and monomer sources. Students are given two plastics to consider: a traditional petroleum-based plastic, poly(ethylene terephthalate) (PET/PETE), and a plant-based plastic, poly(lactic acid) (PLA). Both plastics are commonly used in single-use beverage containers, highlighting the students' familiarity with the problem. Students take the role of policy advisers to legislators deciding where to focus scientific funding, by improving the sustainability of either the beginning-of-life problems through alternative monomer sourcing or at the end-of-life *via* improved recycling processes.

### 2.3 Development of the case study using our design framework

We have previously published our framework for developing curricular material to engage students in green chemistry and sustainability topics within the context of a chemistry course.[8] This framework is based on four design principles, defined in Table 1. In the following sub-sections, we will provide examples of how these design principles influenced the iterative design process for the reported case study.

**2.3.1 Design principle #1: supporting the underlying chemistry.** One value this design team holds to be important is that students should be able to use their organic chemistry knowledge to generate causal mechanistic explanations of phenomena. In the case study described below, students repeatedly produce arrow pushing mechanisms and accompanying explanations for parts of the polymerization and depolymerization reactions; these chemistry mechanisms reinforce the synthetic similarity of the two polymers and connect the chemistry content back to the mechanisms learned in the corequisite lecture course. The scaffolding in the case study encourages teams to go beyond the mechanisms and consider other factors that affect the sustainability of the reaction. As we will discuss, this resulted in students accurately analysing the synthetic schemes using the 12 principles of green chemistry.

**2.3.2 Design principle #2: complexity of sustainability issues should increase over time.** As mentioned above, this case study is situated as the second of three case studies in the curriculum. Case study one focuses on the evaluation of synthetic schemes at the bench scale for carboxylic acid derivatizing reactions.[11] Having spent the preceding weeks developing a model for the reactions, to ease the jump in system scale (from bench-top decision making to industrial production scale), we decided to focus on plastics that are made using similar reactions to those studied in the first case study, namely PLA and PET/PETE. Further, to introduce students to the expert-like behaviour of performing a life cycle analysis (and to constrain the cognitive complexity), we chose to focus on only two parts of the analysis, beginning-of-life and end-of-life.

**2.3.3 Design principle #3: engagement with engineering principles to support decision making.** The plastics problem is a large-scale systemic issue with great system complexity; as

Table 1 The 4 design principles that guided the development of the case study and their definitions

| Design principles |
|---|
| Design principle #1: the underlying chemical principles of sustainability phenomena should be emphasized and supported |
| Design principle #2: the complexity of sustainability issues addressed should be increased over time |
| Design principle #3: engagement with engineering practices can support decision-making |
| Design principle #4: focus students' cognitive efforts on the important ideas rather than on esoteric tools and metrics |

such, in this case study, students are not expected to define the overall problem. Instead, using the scaffold of engineering practices, as initially defined in the National Research Council's Framework for K-12 Science Education and further adapted for undergraduate chemistry education,[12] teams are required to define the system's problems found at two time points in the plastic lifecycle (beginning-of-life and end-of-life). This problem definition sets up the green decision making, using green chemistry principles and the UN SDGs to evaluate potential solutions and advocate for which problem to invest public funds for further research.

**2.3.4 Design principle #4: focus students' cognitive efforts.** When initially designing the case study, we had hoped to assess the students' ability to create a mechanism for the nucleophilic acyl substitution at the heart of both depolymerization reactions. They had just developed reaction mechanisms for similar reactions in first case study of this curriculum. In the first iteration, students were asked to draw and explain the full mechanism. Preliminary coding of student mechanism explanations using the protocol described by Crandell *et al.*[13,14] showed that most groups created descriptive instead of causal mechanisms (data not shown). This was surprising as these students were a similar student population, having the same organic chemistry curriculum in their lecture courses as the students in the study by Crandell *et al.* To probe the possible reasons for this observation, informal conversations with the graduate teaching assistants (TAs) were conducted. The TAs reported that students felt rushed to complete the activity in the allotted time. A revision was made based on these observations, the fact that students had spent an entire week developing nucleophilic acyl substitution reactions in the first case study, and the desire to focus on the green chemistry principles and sustainable development goals (SDGs) as part of the decision-making process. The mechanism-related questions were scaled back. Instead of providing a full mechanism, the current iteration asks students to explain a subset of the mechanism at any one time, when initially describing the mechanism (Week 1) or explaining how the enzyme functions (Week 3).

## 3. Case study overview and student responses

### 3.1 Overall goals

The case study was developed using an iterative design approach and the sections below describe the most current iteration we have data for. This version of the case study was implemented in the spring semester of 2024. Data was collected from all five sections of the course taught that semester. Students worked in groups of 3–4 students and data was collected from 141 groups across the five sections. Institutional Review Board approval was obtained (ID# STUDY00004566) and informed consent was obtained from all student participants. Details about coding for specific items can be found in SI – coding schemes.

We begin each week with a slide reiterating the goals of the case study. These five goals are to: (1) construct a molecular-level explanation of how and why each polymer-forming reaction scheme occurs using your understanding of chemistry (in Week 1); (2) define the beginning-of-life problem faced by the polymer manufacturing companies and evaluate the strengths and weaknesses to possible solutions to the problem (also in Week 1); (3) define the end-of-life problem faced by the chemical recycling companies and evaluate the strengths and weaknesses to possible solutions to the problem (in Week 2); (4) define the end-of-life problem faced by the chemical decomposition companies and evaluate the strengths and weaknesses to possible solutions to the problem (in Week 3); and (5) design a solution to the congressperson's problem and communicate your group's solution through a Policy Paper that outlines an evidence-based argument of your choice of which legislative proposal to support (in Week 4).

These are provided to the students as a road map to help them situate themselves in the problem and how each week's activity is building towards the final report, a policy whitepaper. This was added as part of the iterative design process to help students connect the information they collected over multiple weeks together and summarize it in the white paper.

### 3.2 Week 1

In the first week of this second case study, teams of students are introduced to polymers using the biological example of proteins, a call back to the chemistry (amide synthesis) from a previous case study,[11] before being introduced to the two polymers. Students then investigate the syntheses of both PET and PLA at the molecular level (reaction mechanism) and bench scale. In the previous case study, teams developed a mechanistic model of reactions involving carboxylic acid derivatives by creating a more reactive derivative which then undergoes a nucleophilic acyl substitution to create the desired product. In this case study, the initial focus is on the chemical methods (and decisions that impact sustainability) that chemists use to speed up and drive the reactions toward completion. Students use Tables 2 and 3 to compare the two syntheses.

Comparisons start by using the lens of the 12 principles of green chemistry to assess whether a guided selection of metrics is a strength or weakness of the provided synthesis method (and its embedded decisions). After analysis of the pre-selected metrics and principles, students were asked to explore the United Nations Sustainable Development Goals (UNSDGs) and predict and explain how a switch in monomer sourcing would affect UNSDGs.

For the questions related to the 12 principles of green chemistry, many of the students were able to correctly identify

Table 2 Comparison of synthetic requirements for each polymer

| Synthetic detail | PET | PLA |
|---|---|---|
| Temperature (°C) | 197 | 195–230 |
| Solvent | None | None |
| Reaction time (h) | 3 | 2.5 |
| Catalyst used? | Yes | Yes |
| Special glassware | Distillation apparatus | None |

Table 3 Pricing and sourcing for the monomers

| Monomer | Price ($ per ton) | Source |
|---|---|---|
| Ethylene glycol | $33 570 per ton | Petroleum |
| Terephthalic acid | $29 540 per ton | Petroleum |
| Lactic acid | $40 900 per ton | Sugar cane (plant biomass) |

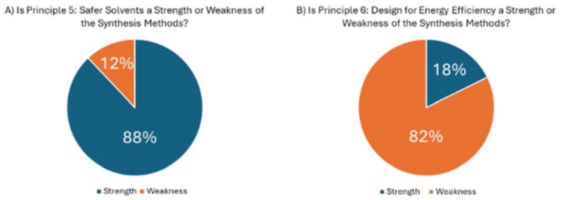


Fig. 1 Student responses regarding synthetic details for (A) safer solvents and auxiliaries and (B) design for energy efficiency ($N = 141$).

(>80% correct, Fig. 1) that principle #5 safer solvents was a strength of the syntheses, as evidence by this team's response:

"We want to follow principle 5 becaus[e] using less solvents would create less overall waste in the synthesis in whatever we are creating. Since neither of the synthesis (PET or PLA) require solvents, we consider the synthesis of each to be a strength."

Another example is of a team choosing principle #6: design for energy efficiency as a weakness of the polymer syntheses:

"The principle of designing for energy efficiency is a weakness of this synthesis because in order to optimize the reaction and produce greater amounts of product, the ambient temperature must be raised above the boiling point of water and well above room temperature."

This is unsurprising given that most chemistry courses focus on reactions at the molecular level or bench scale phenomena, meaning that students are familiar with interpreting chemistry phenomena at those levels.

However, when the focus moved up a scalar level to the effects of monomer sourcing on the UNSDGs, there was much less agreement among responses. Although students identified that changing from petroleum-based monomers (PET) to plant-based monomers would affect 12 out of the 17 UNSDGs, there was no clear consensus for any UNSDG as to whether the change would have a positive or negative effect on the SDG (Fig. 2). For example, some groups claimed UNSDG 8: decent work and economic growth would be positively affected because it would

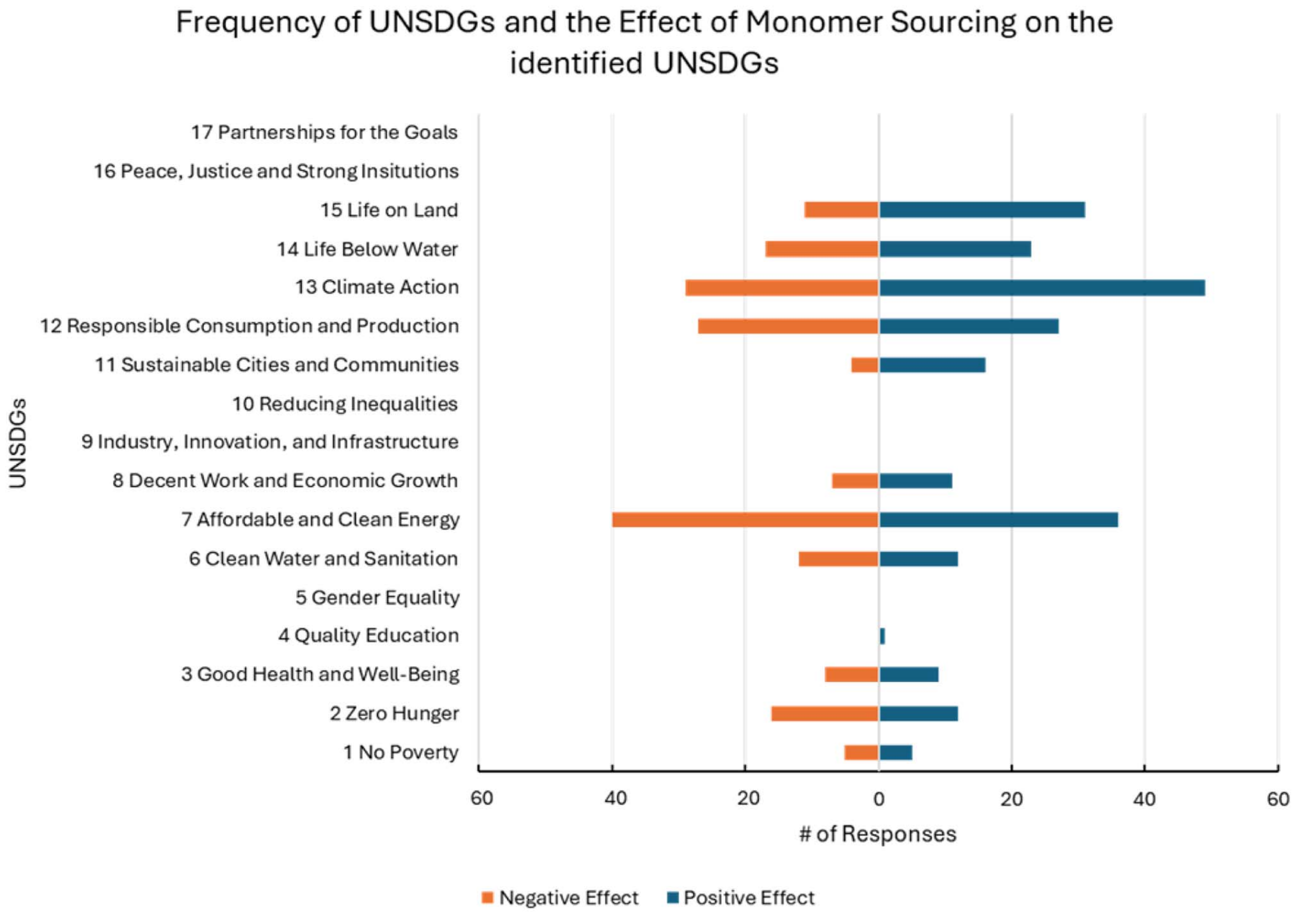


Fig. 2 Distribution of the UNSDGs identified by students as affected by switching monomer sourcing ($N = 408$). See the SI for how data was coded.

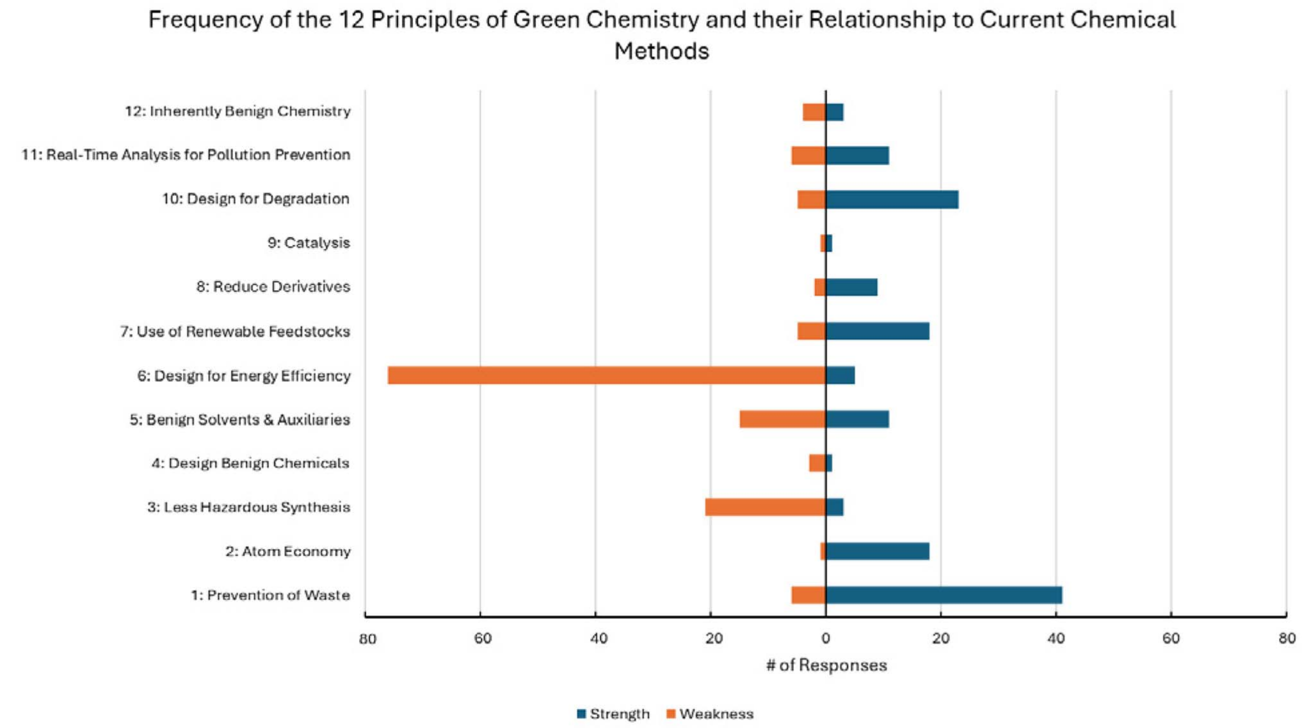


Fig. 3 How students interpreted the 12 principles of green chemistry as a strength or weakness of the current methods of chemical recycling of PET ($N = 289$).

create new jobs as plants to process sugar cane and extract lactic acid were opened, while others predicted a negative effect because of the increased cost of the lactic acid monomer. Another example comes from UNSDG 7: affordable and clean energy where groups tended to focus on petroleum's use as a fuel source, not as a monomer source, and were almost evenly split between positively or negatively affecting the UNSDG. These examples show a larger trend in the student responses towards more surface level answers that were not deeply rooted in chemical principles. This suggests that meaningful interactions with the principles of green chemistry and UNSDGs through the lens of chemistry core ideas are expert behaviours and therefore need to be carefully incorporated into the curriculum. These findings support the argument made in our design framework (design principle #1) and by others that students need to be guided on how to develop these expert-like behaviours and not just assume that they will be able to inherently apply their foundational chemistry knowledge to these complex phenomena,[8,15,16] especially if they are still learning the underlying chemistry core ideas.

### 3.3 Week 2

Week 2 starts off with students reviewing different types of recycling (mechanical *vs.* chemical) and their strengths and weaknesses. With this information they can then make predictions about the greenness/sustainability of aspects of the chemical recycling of PET through the lens of the 12 principles of green chemistry (Fig. 3). Like week 1 (Fig. 1), groups tended to be consistent with each other about how the 12 principles of green chemistry applied to the supplied PET depolymerization reaction. Only four principles (principles 5: design benign chemicals, 9: catalysis, 11: real-time analysis for pollution control, & 12: inherently benign chemistry) resulted in a level of agreement between groups below 75%. Students focused on the temperature and pressures required as being a weakness of the current methods, especially how it requires large amounts of energy (principle 6: design for energy efficiency) and those temperatures/pressures are hazardous (principle 3: less hazardous synthesis). For the strengths of the current methodologies, students were more evenly distributed among the principles, but their responses contained similar themes, mainly preventing waste, be that the plastic itself or other reagents (principles 1: prevention of waste, 2: benign solvents & auxiliaries, 7: use of renewable feedstocks, & 10: design for degradation). Moving from preselected principles in week 1 to an open-ended question in week 2 saw students be able to still analyse bench scale phenomena, like the chemical recycling reaction conditions, through a GSC-centred lens. However, there is still a gap between students' level of understanding and the level of understanding of the intended audience of the principles (working chemists), as evidenced by surface level explanations that only tangentially related to the identified principle. An example that we encountered repeatedly was related to principle 11: real-time analysis for pollution prevention, groups that selected this principle appeared to see pollution prevention and ignore the real-time analysis. This gap was

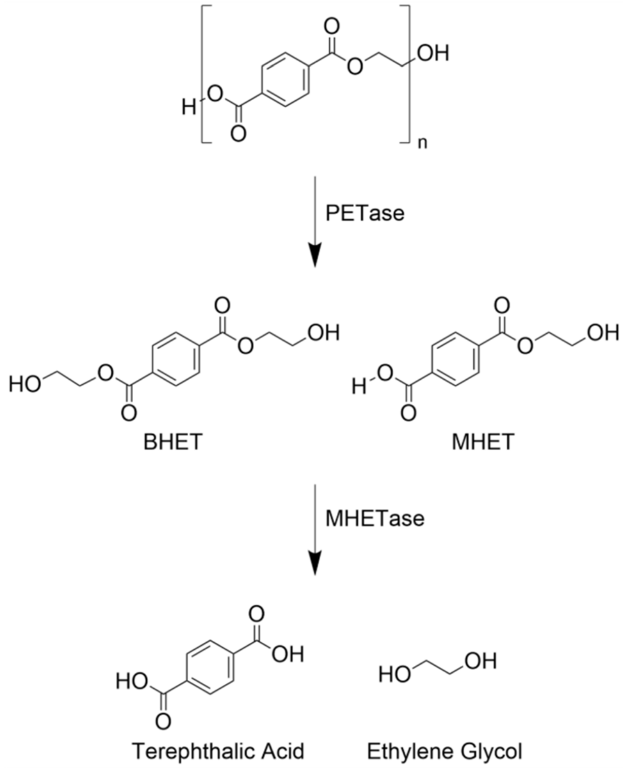


Fig. 4 The enzyme-aided depolymerization of poly(ethylene terephthalate) (PET). PETase chops up PET into smaller units including bis(2-hydroxyethyl) terephthalate (BHET) and mono(2-hydroxyethyl) terephthalate (MHET), allowing MHETase to finish the depolymerization producing terephthalic acid and ethylene glycol.

most evident in principles and UNSDGs that required students to use their chemical knowledge outside of the traditional molecular and bench scales covered in traditional chemistry courses, and supports our design framework's claim that to meaningfully interact with the principles and metrics of green chemistry or sustainability (*e.g.*, 12 principles of green chemistry & UNSDGs) designed for expert audiences, students need to have a solid understanding of the underlying chemical phenomenon. When the core chemical knowledge is not present, students are more likely to parrot back surface level explanations they have previously heard. Teams are then asked to use their predictions to develop an explanation as to why chemical recycling of PET is currently not commercially viable as reported by the popular media.[10]

The rest of week two and week three prompts students to explore alternative end of life options for both plastics, the biodegradability of PLA (week 2) and a bioengineered approach to chemical recycling of PET (week 3). The strength of using PLA is that it is biodegradable. However, the public often uses the terms biodegradable and compostable interchangeably, and so students are tasked with developing definitions for these terms, before exploring authentic data regarding the fate of PLA under composting conditions. The groups are given tables from a 2020 report examining the fate of plastic products in a commercial composting facility in the Netherlands (SI – PLA report tables student facing).[17] They are then guided through analysis of the evidence in the report looking for trends, similarities, and differences in the fate of different PLA based plastics in the report. After the analysis of the provided data, they are given the claim "PLA based plastics are completely compostable" and asked to use their gathered evidence to support or refute the claim.

### 3.4 Week 3

Week three continues the exploration of alternative end-of-life-potential plastic fates with a bioengineered approach to the chemical recycling introduced in week 2. Students are introduced to recently discovered enzymes that depolymerize PET: PETase, which breaks down PET into dimers and trimers, and MHETase, which breaks down the dimers and trimers into terephthalic acid and ethylene glycol (Fig. 4).[18]

Students interested in health-related professional schools are a major subpopulation in our course. This example was included not only as a nod towards the interests of our students but also to highlight, for students, the interdisciplinary nature of green chemistry and sustainability beyond organic chemistry. To prepare for investigating how the enzymes catalyzed depolymerization, students were asked to explain why such enzymes could evolve (Fig. 5). Student responses were coded based on their discussion of the abundance of PET in the environment (abundance), the similar reactivity between the ester functional group in the polymer and other carboxylic acid derivatives, like amides, commonly found in biomolecules (reactivity), or unrelated explanations (non-normative). An ideal response would discuss how bacteria already have enzymes that hydrolyze carboxylic acid derivatives using nucleophilic acyl substitution mechanisms and that a change in those enzymes allowing the bacteria to utilize PET could be beneficial given the extent of PET contamination in the environment, like the student response below:

"The concept of enzymes evolving to break down PET (polyethylene terephthalate) is not far-fetched when considering the biochemical versatility found in nature, especially among microbial communities. Enzymes like esterases and lipases, which catalyze the hydrolysis of ester bonds in biological materials such as fats, share functional similarities with the chemical structure of PET. This similarity suggests that microbial enzymes could adapt to hydrolyze the synthetic ester bonds in PET, especially under the selective pressure of PET-polluted environments. This theory aligns with the observed instances where bacteria have adapted to degrade other man-made substances, such as those involved in decomposing oil spills. Given the environmental prevalence of PET and the adaptive capacity of microorganisms, the development of enzymes targeting PET could be a natural extension of microbial evolution, particularly in ecosystems heavily impacted by plastic waste."

As the case study was implemented into an organic chemistry course, it was slightly disappointing that only ∼50% of responses discussed the similarity in reactivity, but overall ∼75% of responses addressed one or both parts of a complete answer (Fig. 5).

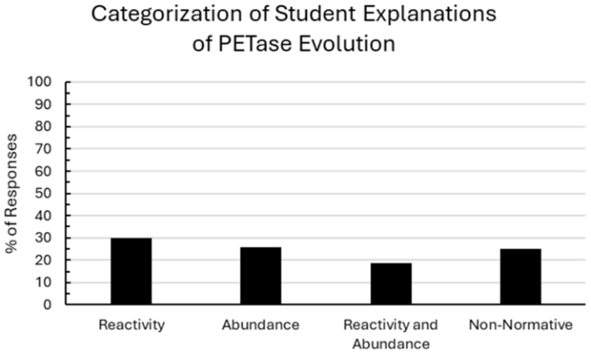


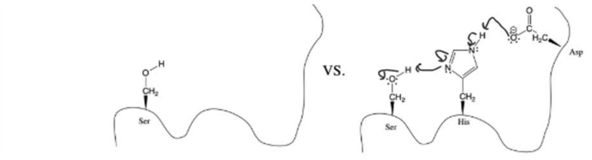
Fig. 5 Distribution of the student explanations for the evolution of PETase ($N = 112$).

Students have developed mechanisms for new acyl substitutions multiple times by this point and are introduced to the enzyme catalysed mechanism while also developing their own arrow pushing mechanism. This leads to the students developing an explanation of how the PETase enzyme catalyses the reaction and to explain observations on the reaction rate if the shape of the active site is changed from an organic chemistry perspective (Fig. 6). Most teams of students could recognize that the catalytic histidine and aspartate residues could increase the serine's nucleophilicity by deprotonating the serine.

After building an understanding of how the enzymes work, the week concludes with students exploring engineering of the enzymes from published data.[18] In a series of three slides students are introduced to creating a flexible peptide linker connecting PETase and MHETase, predicting the effect this will have on the rate of depolymerization, analyzing results to confirm the accuracy of their prediction and using their chemical knowledge to explain the experimental results. Groups, overwhelmingly, correctly predicted that the physical linkage of PETase and MHETase would increase the rate of depolymerization (98%) and interpreted that the results supported their predictions (98%). Their ability to explain the chemistry behind the rate increase was more mixed. A majority of students were capable of producing an answer that discussed how physically linking the two enzymes increased the likelihood that the BHET and MHET produced by PETase collided with MHETase, allowing for the final step of the depolymerization process to occur:

"The significant increase in the rate of depolymerization of PET with the linked enzymes, compared to using them separately, is due to the enhancement of substrate channeling between the enzymes. In a linked enzyme system, PETase and MHETase are basically physically connected, which allows for the transfer of the intermediate product from PETase and MHETase. Since the molecules are very close to one another, it reduces the distance the intermediate needs to travel, thus minimizing the chances of it diffusing away into the solution where it would be less accessible to MHETase. Furthermore, the linked system ensures that the intermediate is immediately available to MHETase in order for further degradation to occur, thus making the depolymerization process more efficient. This transfer between enzymes also ensures that the necessary energy and orientation for the molecules to react are optimize."

Of the groups that did not generate a response about collision rate, their responses tended to be a surface level explanation of how enzymes work.



"The negative charge on the oxygen in aspartate will react and form a bond with hydrogen on histidine. This will cause the bond between the nitrogen and hydrogen to break in which turn creates a negative charge on nitrogen. The pi bond between carbon and nitrogen present in the histidine will turn into a single bond with nitrogen gaining two new lone pair and a negative charge. This negative charge will attract and form a bond with the hydrogen in serine. The hydrogen-oxygen bond will break and the oxygen will have a negative charge. This will create a nucleophilic serine that will be a better nucleophile than just serine."

Fig. 6 An exemplary student annotation of the enzyme active sites and the accompanying explanation for how the active site makes the serine a better nucleophile.

### 3.5 Week 4

Week four is used as a dedicated worktime for students to complete a whitepaper. The assignment is adapted from the white paper template from the MIT Comm Lab.[19] The white paper is intended to bring the congressperson they work for up to speed on the problem and advocate for scientific funding to be steered towards addressing the problems present at the beginning-of-life or end-of-life. Although this is an arbitrary choice, it does mimic real world constraints, in this case limited financial resources.

## 4. Suggestions for adopting this case study

Depending on the course learning objectives and time constraints, reintroduction of students predicting the full reaction mechanism could be useful for instructors looking to adopt this case study. Our initial implementation of the case study occurred during the online learning shift caused by the Covid-19 pandemic. Subsequent research has shown that the pandemic resulted in changes to students' ability to generate reaction mechanisms, but that trend may be reversing as we move closer to pre-pandemic conditions.[20] Reintroduction of the full mechanism prediction questions may be successful in giving the instructor another timepoint to evaluate the students developing use of reaction mechanisms across the organic chemistry course sequence.

The student population of the course where this study was implemented is predominantly non-chemistry majors. In a course with a majority of chemistry majors or a course where students are expected to have a stronger background in sustainability, the life cycle analysis could be expanded. Publicly available data or simulated data sets could be used to perform a more quantitative level of analysis if desired.

## 5. Conclusions

This article outlines a scaffolded case study that engages students in the use of science and engineering practices and green chemistry principles and UN SDGs during key points in the decision-making process. By carefully scaffolding the prompts, the design illustrates that students can apply core chemical knowledge translating from the molecular and bench scales to a larger industrial-scale problem. The trend so far suggests that as students move away from the familiar molecular or bench scale the chemical richness of their answers decreases, suggesting a further need to centre the role of chemistry in larger problems associated with green chemistry or sustainability if they are to be effectively used in chemistry courses to help students develop the necessary critical thinking, analysis, and decision-making skills needed to be successful in the workforce.

## Author contributions

E. L. D. and M. M. C. conceived the larger curriculum transformation project. H. M.-B., E. L. D., and M. M. C. wrote the initial iteration of the case study. All authors participated in data collection and iterative changes to the case study. H. M.-B. wrote the first draft of the manuscript. All authors edited the manuscript and approved its submission.

## Conflicts of interest

There are no conflicts to declare.

## Data availability

Given the nature of human subjects research, data sharing is not covered by our approval from Michigan State University's Institutional Review Board. Data sharing of deidentified student responses can be considered through proper channels upon request, see Michigan State University's Human Research Protections Program (HRPP, at https://hrpp.msu.edu). Data collected from human participants, described in the figures, are not available for confidentiality reasons. All assessment prompts are available in the supplementary information (SI).

Supplementary information: student facing reference material, decision memo template, beSocratic slides for weeks 1, 2, & 3, & coding schemes. See DOI: https://doi.org/10.1039/d6su00001k.

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## Notes and references

1 *Education for Sustainable Development|UNESCO*, https://www.unesco.org/en/sustainable-development/education, accessed 16 December 2025.

2 M. Burmeister and I. Eilks, An example of learning about plastics and their evaluation as a contribution to Education for Sustainable Development in secondary school chemistry teaching, *Chem. Educ. Res. Pract.*, 2012, **13**, 93–102.

3 M. Burmeister, F. Rauch and I. Eilks, Education for Sustainable Development (ESD) and chemistry education, *Chem. Educ. Res. Pract.*, 2012, **13**, 59–68.

4 I. Eilks and V. G. Zuin, Editorial Overview: Green and Sustainable Chemistry Education (GSCE): Lessons to be learnt for a safer, healthier and fairer world today and tomorrow, *Curr. Opin. Green Sustainable Chem.*, 2018, **13**, A4–A6.

5 J. Sjöström, I. Eilks and V. G. Zuin, Towards Eco-reflexive Science Education, *Sci. Educ.*, 2016, **25**, 321–341.

6 Committee on Professional Training, https://www.acs.org/about/governance/committees/professional-training.html, accessed 20 February 2023.

7 M. Zhang, E. L. Day, H. McFall-Boegeman, S. J. Petritis and M. M. Cooper, Incorporation of green chemistry into undergraduate organic laboratory using cooperative project-based experiments and case studies, *Green Chem. Lett. Rev.*, 2023, **16**, 2183781.

8 E. L. Day, S. J. Petritis, H. McFall-Boegeman, J. Starkie, M. Zhang and M. M. Cooper, A Framework for the Integration of Green and Sustainable Chemistry into the Undergraduate Curriculum: Greening our Practice with Scientific and Engineering Practices, *J. Chem. Educ.*, 2024, **101**, 1847–1857.

9 S. Bryfczynski, R. P. Pargas, M. M. Cooper, M. Klymkowsky, J. Hester and N. P. Grove, in *The Impact of Pen and Touch Technology on Education*, ed. T. Hammond, S. Valentine, A. Adler and M. Payton, Springer International Publishing, Cham, 2015, pp. 127–136.

10 *Why Have We All Been Recycling Plastic For 30 Years?: Planet Money*, NPR, https://www.npr.org/2020/09/11/912150085/waste-land, accessed 16 December 2025.

11 E. L. Day, H. McFall-Boegeman, S. J. Petritis, N. Alzamily, M. Zhang and M. M. Cooper, Starting with Synthetic Routes: A Cooperative Case Study to Engage Second Year Organic Chemistry Students in Evaluating Solutions Using Green Chemistry Metrics, *J. Chem. Educ.*, 2026.

12 National Research Council, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, The National Academies Press, Washington, DC, 2012.

13 O. M. Crandell, M. A. Lockhart and M. M. Cooper, Arrows on the Page Are Not a Good Gauge: Evidence for the Importance

of Causal Mechanistic Explanations about Nucleophilic Substitution in Organic Chemistry, *J. Chem. Educ.*, 2020, **97**, 313–327.

14 O. M. Crandell, H. Kouyoumdjian, S. M. Underwood and M. M. Cooper, Reasoning about Reactions in Organic Chemistry: Starting It in General Chemistry, *J. Chem. Educ.*, 2019, **96**, 213–226.

15 H. McFall-Boegeman, S. J. Petritis, J. Starkie, C. E. Schwarz, M. Zhang, M. M. Cooper and E. L. Day, Unpacking Engineering Practices for Curricular Assessment: Aligning Lab Practices and Assessment Items Using the 3D-LAP, *J. Chem. Educ.*, 2025, **102**, 3306–3316.

16 A. Z. Chen, M. D. Peeks and S. H. Kyne, Design, Implementation, and Evaluation of Authentic Learning Activities to Introduce Chemistry Students to Systems Thinking through Green Chemistry, *J. Chem. Educ.*, 2025, **102**, 2283–2293.

17 M. Van Der Zee and K. Molenveld, *The Fate of (compostable) Plastic Products in a Full Scale Industrial Organic Waste Treatment Facility*, Wageningen Food & Biobased Research, Wageningen, 2020.

18 B. C. Knott, E. Erickson, M. D. Allen, J. E. Gado, R. Graham, F. L. Kearns, I. Pardo, E. Topuzlu, J. J. Anderson, H. P. Austin, G. Dominick, C. W. Johnson, N. A. Rorrer, C. J. Szostkiewicz, V. Copié, C. M. Payne, H. L. Woodcock, B. S. Donohoe, G. T. Beckham and J. E. McGeehan, Characterization and engineering of a two-enzyme system for plastics depolymerization, *Proc. Natl. Acad. Sci. U. S. A.*, 2020, **117**, 25476–25485.

19 P. White, D. Chien and D. Pomeroy, *Policy Memo*, https://mitcommlab.mit.edu/nse/commkit/policy-memo/, Accessed 12 March 2026.

20 V. Scammahorn, S. Houchlei, H. Williams and M. M. Cooper, Investigation into the Impact of Online Learning and the Pandemic on Student Use of Mechanistic Arrows, *J. Chem. Educ.*, 2025, **102**, 1755–1764.