Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
ASEE
Paper ID #47672

Beyond OILRIG: Impact of applied redox chemistry modules on cognitive and affective outcomes in a water and wastewater engineering course

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Beyond OILRIG: Impact of applied redox chemistry modules on cognitive and affective outcomes in a water and wastewater engineering course

Abstract

Chemistry is essential to many branches of engineering, including civil and environmental engineering. Based on three years of pre-course surveys for a water and wastewater engineering course, civil engineering (CivE) and environmental engineering (EnvE) majors lack confidence in applying chemistry to solve engineering problems. CivE majors take one basic chemistry course prior to taking water and wastewater engineering, and EnvE majors have historically taken two introductory chemistry courses. According to students' assessments of their learning gains, approximately 50% of students have reported good or great gains in their confidence in applying chemistry because of taking water and wastewater engineering but based on observations in upper-level environmental engineering courses, students are poorly equipped to apply fundamental redox chemistry concepts (e.g., writing half reactions, identifying electron acceptors and donors, calculating electrode potentials). The hypothesis is that the incorporation of two modules on redox chemistry – "the chemistry of the Flint Water Crisis" and "microbial degradation of pollutants" - will improve both affective and cognitive chemistry outcomes in a water and wastewater engineering course.

To test this hypothesis, two new redox chemistry modules were implemented in Spring 2024 in the course Water Quality Engineering at the University of Vermont. These modules interweaved redox chemistry fundamentals (e.g., half reactions, electron donors and acceptors, electrode potential) with big-picture, real-world problems. A total of two 75-minute modules were implemented. Self-reported and observed gains were both analyzed. To assess cognitive outcomes, results of a post-module assessment were compared to a pre-module assessment covering multiple redox chemistry topics. Further, a post-course survey allowed students to report on their own learning gains related to chemistry. Additionally, post-course survey results were compared with two past cohorts to determine if the two new modules impacted learning gains compared to cohorts without these specific modules.

Results of the pre-assessment showed that 40% of students could correctly identify an electron donor and electron acceptor. No students correctly wrote half reactions for oxidation or reduction and most students did not attempt these questions. Likewise, no students were able to calculate the electrode potential of a combined reaction given the electrode potential of half reactions. In total, the pre-assessment confirmed that even students who had completed two introductory chemistry courses retained only minimal information on redox chemistry. After the modules, students were much more likely to attempt the questions, but performance on three of four questions was still poor. The number of students who could correctly identify an electron donor and acceptor decreased from 42% to 33%. While greater than 75% of students attempted to write the oxidation and reduction half reactions, no students got the problems completely correct on either the pre- or post-assessment. The greatest improvement was in a question related to electrode potential. While no students provided a correct answer on the pre-module assessment, 52% of students did this problem correctly on the post-assessment. In the final student assessment of their learning gains (SALG) survey, 59% of students reported good or great gains in their confidence in applying chemistry to engineering problems, which was lower than past cohorts. In total, this study suggests that the minimal interventions were not adequate for addressing poor redox chemistry outcomes. To address this, a new environmental engineering chemistry course has been created that will spend much more time on redox chemistry concepts.

Introduction

Chemistry is essential to the current and future practice of environmental engineering. Pollution control and remediation of water, air, and soils rely on (bio)chemical transformations that must be understood to be applied in appropriate ways. Emerging challenges in environmental engineering (e.g., microplastics, forever chemicals, carbon and nutrient management) are challenges that will require environmental engineers with strong chemistry foundations if the field is to contribute to solving these challenges. The importance of chemistry to civil engineering is less appreciated but will only increase in coming years [1]. With a renewed focus on sustainable and resilient infrastructure, civil engineers will need to develop and preserve materials that form societies roads, buildings, and underground infrastructure. Therefore, chemistry education is fundamental to environmental and civil engineering curricula. Despite its importance, however, chemistry has long been a dreaded topic for engineering and non-chemistry STEM majors [2, 3].

Many chemistry topics are important to environmental engineers. Precipitation-dissolution chemistry is needed to understand drinking water and wastewater treatment processes such as coagulation-flocculation and chemical phosphorus removal. Acid-base chemistry is needed to understand how chemical and biological processes impact pH of drinking water and wastewater. Perhaps the most vital chemistry topic, however -- to both civil and environmental engineers -- is redox chemistry. Redox chemistry explains how pathogens are inactivated through chemical disinfection, how microbes can be harnessed to degrade pollutants, and how hydroxyl radicals fulfill their role as the “detergent of the troposphere” to degrade air pollutants. Redox chemistry also explains how lead leaching can occur in lead pipes that lack adequate corrosion control and how structures without appropriate cathodic protection can fail, sometimes with catastrophic effects. It also explains how CO_2 can be reduced and valorized to beneficial products, chemically or biologically. Redox chemistry – the chemistry that is often minimized by students to “oxidation is losing, reduction is gaining (OILRIG)” – is critical to engineered systems and therefore its teaching in civil and environmental engineering curricula deserves critical attention.

The water and wastewater engineering course used for this study is required for both Civil Engineering (CivE) and Environmental Engineering (EnvE) majors with enrollment between 40 and 60 students per semester. Most students are CEE or ENVE majors and a small number are Engineering (general), Engineering Management, or Environmental Science majors. This course is taught within a civil and environmental engineering (CEE) department at a university with approximately 10,000 undergraduate students. Teaching chemistry-based concepts within this course is thought to be complicated in part due to students entering the course with different chemistry backgrounds: EnvE students were required to complete two first-year courses in general chemistry while CivE students are only required to take one general chemistry course. Redox chemistry was covered in the second general chemistry course which is not required of CivE students.

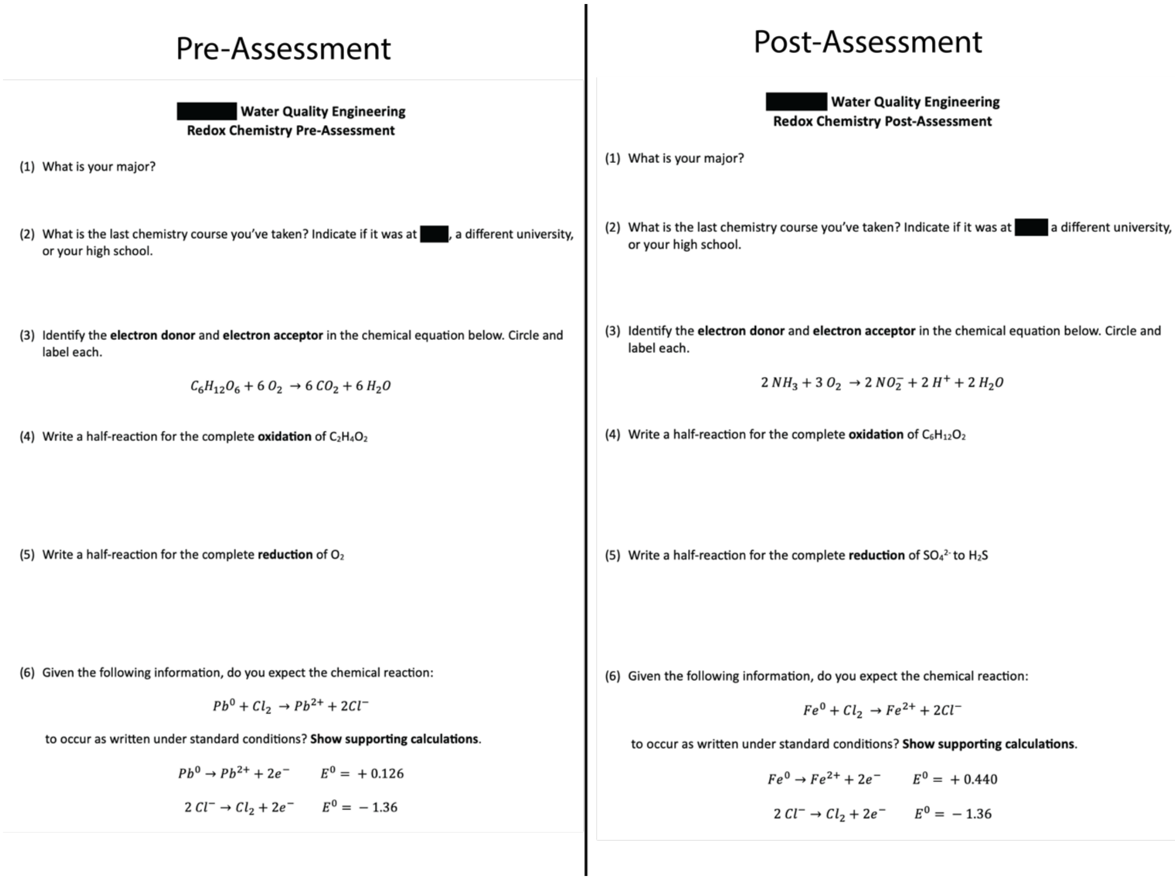
As part of revisiting chemistry education in our civil and environmental engineering programs, we implemented two redox chemistry modules in a water and wastewater engineering course and assessed their impact on student outcomes. The modules were (1) the chemistry of the Flint Water Crisis; and (2) the chemistry of biological transformations in wastewater treatment. These modules represent minimal interventions, taking up two lectures of the water and wastewater engineering course. The central hypothesis was that teaching redox chemistry in the context of environmental issues (e.g., lead leaching, pollutant removal) would improve cognitive and affective outcomes**.** We previously showed that implementation of a robust Flint Water Crisis case study improved cognitive and affective outcomes in a sophomore-level introduction to environmental engineering course [4], but in the current study we aimed to reduce the time spent on content, focus specifically on redox chemistry, and include fundamentals of redox chemistry from wastewater treatment.

Approach

Two modules were developed and implemented for the Spring 2024 cohort of a water and wastewater engineering course. The first module provided background on the Flint Water Crisis and introduced the redox chemistry involved in lead leaching, the formation of disinfection products, and the quenching of residual chlorine that likely played a role in the proliferation of *Legionella*. After discussing the Flint Water Crisis, students were instructed on electron donors and acceptors (e.g., Pb^0 and HOCl), writing half reactions from scratch, calculating the overall electrode potential from a table of half reactions with electrode potential, and converting from electrode potential to Gibbs free energy. In the second module, students were introduced to microbial processes for wastewater treatment, microbial metabolism, and redox chemistry of key microbial transformations including oxidation of organic matter, ammonia oxidation, nitrite oxidation, and denitrification. Both modules reinforced the use of half-reaction tables to calculate the standard electrode potential of redox reactions, and students were instructed specifically on using the table of half reactions from the latest version of the Fundamentals of Engineering Reference Handbook [5].

Both modules included PowerPoint presentations and approximately 50 minutes of lecturing during a 75-minute course period. The remainder of time was spent completing assessments and working on problems in groups. Across the two modules, only 45 minutes of material was different than other cohorts that provided explicit instruction on redox chemistry concepts. These specific changes included (1) introducing students to electrode potential tables and having them work in pairs to calculate electrode potential associated with lead oxidation by chlorine; (2) converting from standard electrode potential to Gibb's free energy change; (3) discussing a table of electrode potentials for common biological transformations in wastewater treatment (e.g., oxidation of glucose, oxidation of ammonia and nitrite, reduction of nitrate to nitrogen gas, and reduction of oxygen to water); and (4) writing half reactions for ammonia oxidation. Prior cohorts were introduced to lead oxidation by chlorine and biological processes, but the redox chemistry concepts were only mentioned briefly, and fundamentals were not applied explicitly (e.g., students were told that chlorine oxidizes lead, and that oxygen is the electron acceptor during nitrification).

To assess cognitive outcomes, pre- and post-intervention written assessments were used. The written assessments were unannounced, and students did not earn points for completing the assessment. Students were allowed 10 minutes to complete the assessment. Questions on the assessments were changed, but the format of the assessment and the difficulty was not changed (**Figure 1**). Consisting of six questions, students were asked to (1) provide their major; (2) provide their highest level of chemistry education; (3) identify an electron donor and acceptor in a complete reaction; (4) write a half reaction for an electron donor; (5) write a half reaction for an electron acceptor; and (6) determine if a reaction will occur under standard conditions given two half reactions and the standard electrode potential for each.



Pre-Assessment

[redacted] Water Quality Engineering
Redox Chemistry Pre-Assessment

(1) What is your major?

(2) What is the last chemistry course you've taken? Indicate if it was at [redacted], a different university, or your high school.

(3) Identify the **electron donor** and **electron acceptor** in the chemical equation below. Circle and label each.

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O$$

(4) Write a half-reaction for the complete **oxidation** of $C_2H_4O_2$

(5) Write a half-reaction for the complete **reduction** of O_2

(6) Given the following information, do you expect the chemical reaction:

$$Pb^0 + Cl_2 \rightarrow Pb^{2+} + 2Cl^-$$

to occur as written under standard conditions? **Show supporting calculations**.

$$Pb^0 \rightarrow Pb^{2+} + 2e^- \qquad E^0 = +0.126$$

$$2\,Cl^- \rightarrow Cl_2 + 2e^- \qquad E^0 = -1.36$$

Post-Assessment

[redacted] Water Quality Engineering
Redox Chemistry Post-Assessment

(1) What is your major?

(2) What is the last chemistry course you've taken? Indicate if it was at [redacted] a different university, or your high school.

(3) Identify the **electron donor** and **electron acceptor** in the chemical equation below. Circle and label each.

$$2\,NH_3 + 3\,O_2 \rightarrow 2\,NO_2^- + 2\,H^+ + 2\,H_2O$$

(4) Write a half-reaction for the complete **oxidation** of $C_6H_{12}O_2$

(5) Write a half-reaction for the complete **reduction** of SO_4^{2-} to H_2S

(6) Given the following information, do you expect the chemical reaction:

$$Fe^0 + Cl_2 \rightarrow Fe^{2+} + 2Cl^-$$

to occur as written under standard conditions? **Show supporting calculations**.

$$Fe^0 \rightarrow Fe^{2+} + 2e^- \qquad E^0 = +0.440$$

$$2\,Cl^- \rightarrow Cl_2 + 2e^- \qquad E^0 = -1.36$$

Figure 1: Pre- and post-intervention assessments

To analyze and compare performance on the pre- and post-assessments, student answers were classified and scored as either (1) no attempt made; (2) attempt made; (3) minor errors; or (4) correct answer. When no work was provided by the student, answers were classified as "no attempt made." Attempts that included some work, even if only minor, was classified as "attempt made." If the answer included greater than half the work necessary to complete the problem and the approach was generally correct, then the answer was classified as "minor error." If the answer was completely correct it was classified as "correct answer." The percentage of total answers falling into each category was used to compare results across each of the four chemistry questions on the assessments. Further, scores on each question were compared based on past chemistry coursework by comparing scores based on the highest level of chemistry completed prior to the water and wastewater engineering course. Students were classified as either completing through General Chemistry I, General Chemistry II, or Organic Chemistry. ANOVA was used to compare the means of these three groups for each of the four chemistry questions.

To assess affective outcomes, results of pre- and post-course surveys were used. Students completed the pre-course survey during the first week of the course. Answers from four questions were used to assess changes in attitudes related to chemistry. Students were asked to select "strongly disagree", "disagree", "neutral", "agree", or "strongly agree" for the following:

(1) You are CONFIDENT that you can use chemistry to solve engineering problems
(2) You are PREPARED to use chemistry to solve engineering problems
(3) You ENJOY using chemistry to solve engineering problems

(4) Chemistry is IMPORTANT for environmental engineering

Further, on an end-of-semester student assessment of learning gains (SALG) survey, students were asked what gains they made in confidence in applying chemistry to solve engineering problems with the response options of “no gains”, “a little gain”, “moderate gain”, “good gain”, or “great gain.” Open-ended responses to the question “Please comment on how this class has CHANGED YOUR ATTITUDES toward this subject” were also analyzed.

Results

In the pre-course survey, students largely expressed their agreement with chemistry being important for environmental engineering with 98% stating that they agree or strongly agree that chemistry is important for environmental engineering (**Figure 2**). Only 32% of students, however, responded that they agreed or strongly agreed that they were confident in using chemistry to solve engineering problems. Similarly, less than 40% of students agreed with the statement that they enjoyed using chemistry. However, greater than 60% of students responded that they were prepared to use chemistry to solve engineering problems. Many students also commented specifically on chemistry when asked “What are you dreading most about this course?” with 17 of 44 students (39%) mentioning chemistry directly. Examples of student comments are provided in **Table 1**. Taken together, these pre-course survey results clearly show that students appreciate that chemistry is important for environmental engineering. While students lack confidence in applying chemistry and do not enjoy chemistry, they feel moderately prepared to use chemistry to solve engineering problems.

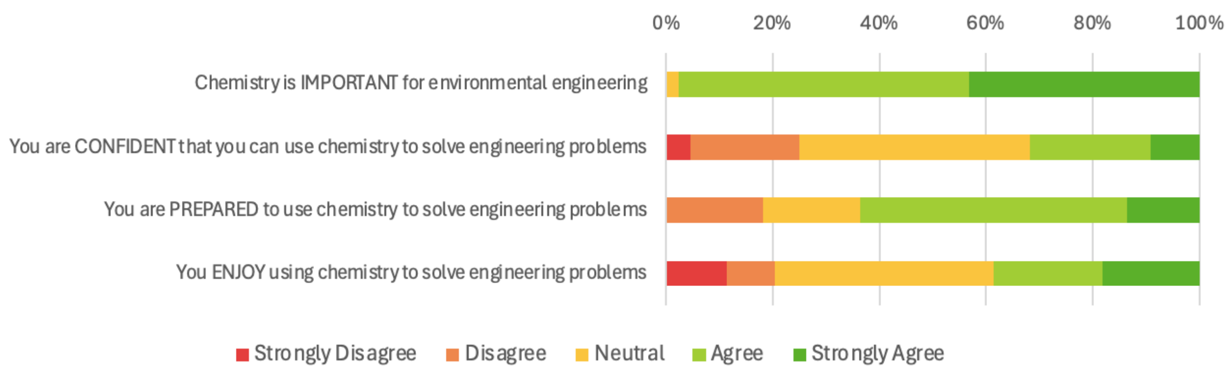


Figure 2: Self-reported agreement with pre-course survey statements (n=44)

Table 1: Responses to pre-course survey question "What are you dreading most about this course?" that included “chemistry” in the response

“I am fearful that the chemistry will take me a will to relearn.”
“I am not really dreading anything about this course yet, maybe doing lots of chemistry, but I am sure I will find areas of the course that I will enjoy and others that are not as fun.”
“Chemistry. I took chemistry in my worst semester here so far and I'm honestly not 100% sure I can recall enough to know what I'm doing for at least a little while.”
“I am a bit nervous that I have forgotten some chemistry necessary for this course. I think that it will take a moment to be confident in some of the more foundational chemistry concepts again.”
“The involvement of chemistry :)”
“Chemistry”
“I didn't do very well in chemistry very so I'm a little hesitant because I know there will be a decent amount of it in this course.”
“needing to know and use chemistry”
“having to use chemistry constintly"
“the chemistry involved with the course”
“Problem sets and being able to apply chemistry, physics, and calculus to solve problems. I am looking foward to lecture and content, but the application of previous classes makes me nervous.”
“I'm very bad at chemistry and this was part of my struggle in environmental systems, so I hope I can overcome this during this semester.”
“And i'm worried about how much ability I have to apply my chemistry knowledge.”
“Using chemistry to solve problems. Chemistry hasn't been my strongest subject”
“I am worried about chemistry, I think I will be fine and that I am making it out to be more diffucult than it is.”
“chemistry”
“…chemistry problems in this class”

A total of 31 students completed the pre-assessments and 21 completed the post-assessment with the majority of students being environmental engineering majors (**Table 2**). As expected, students also varied in terms of the highest-level chemistry course completed prior to the water and wastewater engineering course. Results of the pre-assessment showed that despite 64% of students feeling prepared to use chemistry, few students were able to answer questions related to foundational redox chemistry correctly (**Figure 3A**). On the initial assessment prior to the first module, 42% of students correctly identified the electron donor and electron acceptor in a complete reaction depicting the oxidation of glucose with oxygen as the electron acceptor (**Figure 1**). For writing half reactions, no students answered the questions correctly and less than 50% even attempted the questions. For the final question on using electrode potentials of half reactions to determine if a complete reaction is feasible under standard conditions, less than 10% of students attempted to answer the question.

Table 2: Summary statistics of student majors and chemistry background completing the pre- and post-assessments

	Pre-assessment	Post-assessment
Total Students	31	21
Student Majors		
Environmental Engineering	22	13
Civil Engineering	6	5
Other	3	3
Highest Level of Chemistry		
Organic Chemistry	2	2
General Chemistry II	17	12
General Chemistry I	12	7

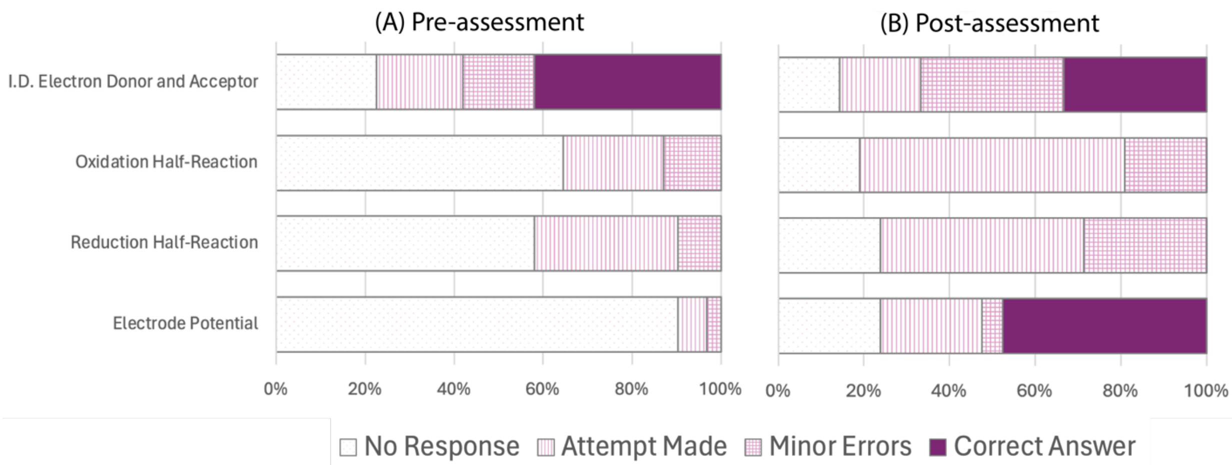


Figure 3: Results of written assessment (A) prior to the implementation of redox modules and (B) after implementation.

After implementation of the modules, performance remained mixed (**Figure 3B**). The number of students correctly identifying the electron donor and acceptor in a complete reaction decreased from 42% to 33%. The number of students attempting the question, however, increased slightly from 77% to 86%. Likewise, the number of attempts made on all other questions also increased. The only question that demonstrated improved redox chemistry competency was the question asking students to determine if a chemical reaction would proceed based on standard electrode potential of its constituent half reactions. While no students answered this question correctly on the initial assessment, 52% answered correctly after the post-assessment. Taken as a whole, the results of the written assessment suggest that gains were made in calculating electrode potential but not in other redox chemistry concepts such as writing half reactions or identifying electron acceptors and donors.

To assess if performance differed based on chemistry background outside of the water and wastewater engineering course, results on all questions were compared based on if students completed second semester chemistry or higher or only a single semester of general chemistry. Differences were expected due to redox chemistry being taught during the second semester general chemistry course, but not in first semester general chemistry. However, there was no clear relationship between chemistry background and assessment performance (**Figure 4**). Students who complete through Chemistry 2 generally performed better on both the pre- and post-assessment, but the only statistically significant difference was for the post-assessment question related to electrode potential ($p < 0.05$). Students who completed through organic chemistry performed much better on the post-assessment than the pre-assessment, but given the small number of students, no significant difference in performance can be ascertained. In total, there were no significant differences on the pre-assessment and only one question related to electrode potential had significant differences in the post-assessment. This suggests that students who complete through Chemistry 2 do not perform notably better at redox chemistry than those who completed just Chemistry 1.

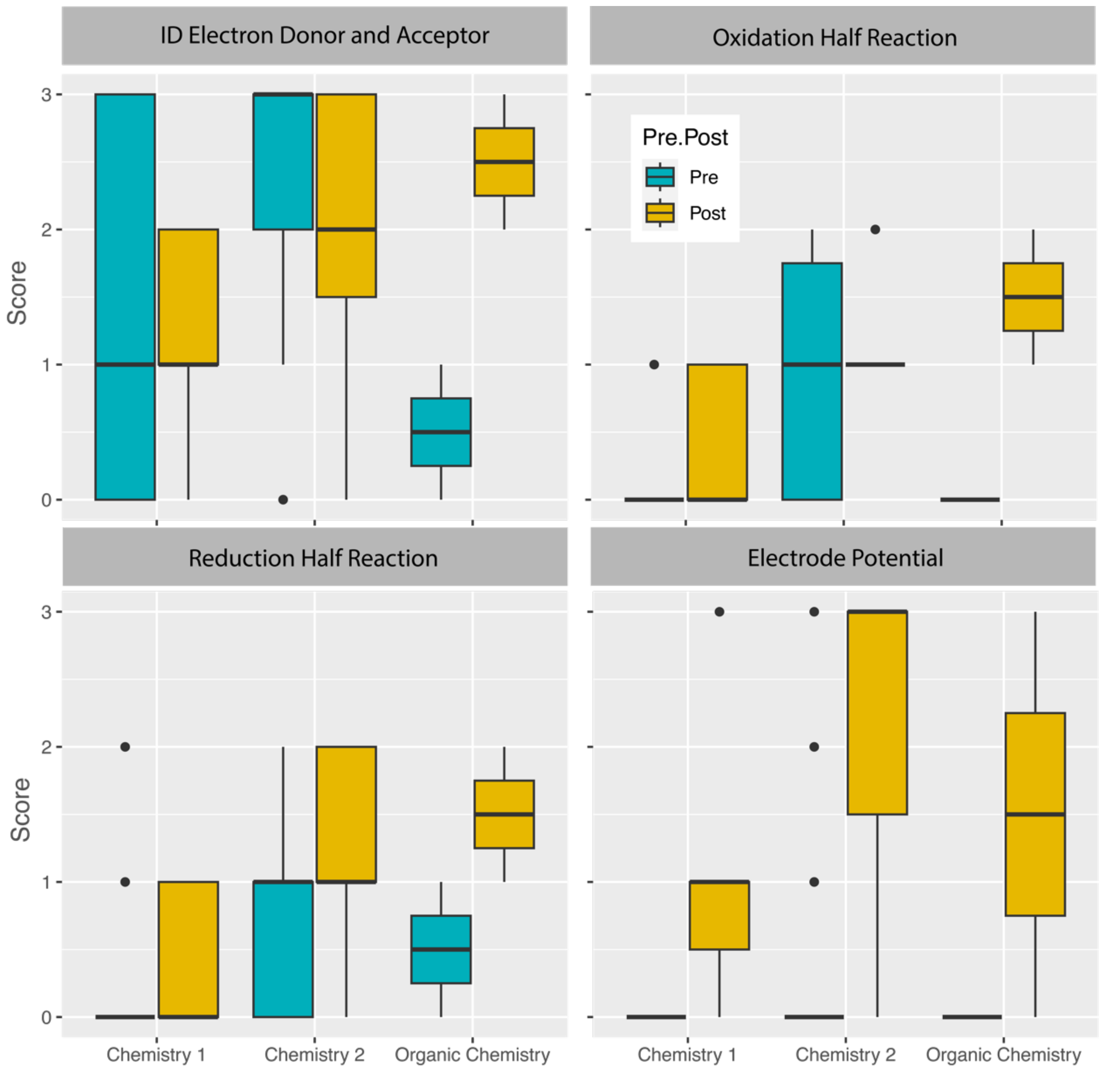


Figure 4: Results of pre- and post-assessment based on chemistry background

To assess if confidence related to chemistry improved throughout the course, we analyzed data from end of semester student surveys. First, we analyzed results to the question "As a result of your work in this class, what GAINS DID YOU MAKE in the following: Your confidence in applying chemistry to engineering problems." Compared to two cohorts without the specific modules, the percentage of students reporting good or great gains in their confidence in applying chemistry decreased from 79% in Spring 2022 and 70% in Fall 2022 to 59% for Spring 2024 when the modules were implemented (**Figure 5**). This demonstrates that the two modules were not adequate for improving student confidence in applying chemistry compared to the general chemistry concepts covered in the course. Responses to the open-ended prompt, “Please comment on how this class has CHANGED YOUR ATTITUDES toward this subject” also provided insights into student attitudes towards chemistry. Of the 34 respondents, six mentioned chemistry in their responses (**Table 3**). Of these six responses, two were negative, suggesting that attitudes may have been negatively impacted, while four were positive, suggesting an improvement in attitudes towards chemistry.

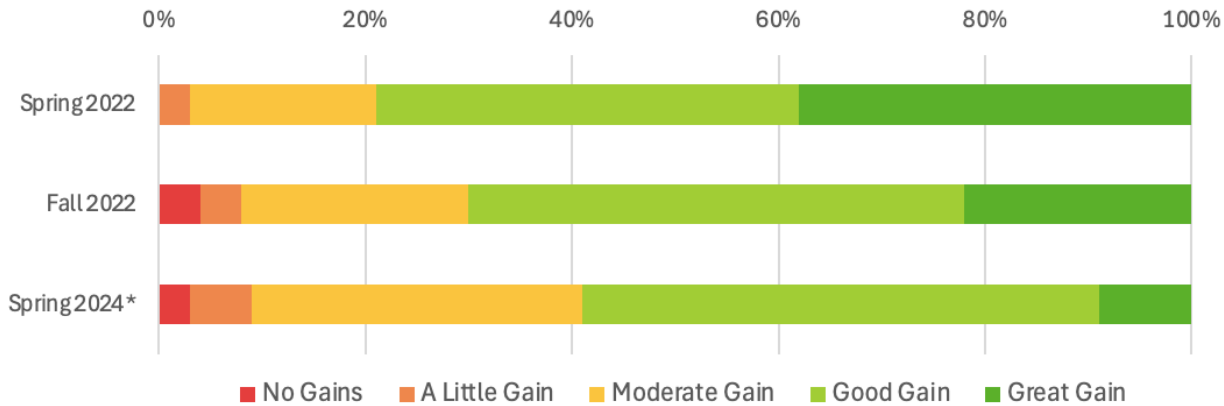


Figure 5: Results of a post-course survey question asking students “As a result of your work in this class, what GAINS DID YOU MAKE in the following: Your confidence in applying chemistry to engineering problems.” The number of responses were 23, 32, and 34 in Spring 2022, Fall 2022, and Spring 2024, respectively.

Table 3: Responses to post-course survey question " Please comment on how this class has CHANGED YOUR ATTITUDES toward this subject.”

“The chem applications are very interesting, and although I struggled to bring back ideas from gen chem, I would like to take more water classes to learn more about the topics covered in thus class.”
“Too much chemistry fro a civil engineer that doesn't have chem two under their belt”
“i am interested in wastewater, but uninterested in chemistry in engineering”
“I think that I am more interested in the topic overall. Seeing some of the applications of chemistry in wastewater made me more excited to learn more and use chemistry knowledge in this context”
“After taking this class, I realized that this is a subject/ field of study that I can see myself getting a career in. I loved using chemistry to solve engineering problems.”
“The chemistry portion of the course we did was very limited, but it did help with understanding conceptually what was happening.”

Discussion

These results suggest that the two modules improved cognitive outcomes related to calculating and interpreting electrode potential, but students did not perform substantially better at identifying electron donors and electron acceptors or writing half reactions. While gains in confidence in using chemistry were reported, the percentage of students reporting good or great gains was lower than previous cohorts. Students who had completed Chemistry 2 (which includes redox chemistry) performed better on the post-assessment question related to calculating electrode potentials than those who had only completed Chemistry 1, however, results for the other three questions were not significantly different regardless of previous chemistry courses. Therefore, while we attempted to improve redox chemistry outcomes through minimal interventions by allocating 45 minutes of class time to explicit redox chemistry instruction, this was not sufficient to make impactful changes in student cognitive outcomes. Students did report gains in their confidence in applying chemistry to solve engineering problems (59% reported good or great gains), but the percent reporting good or great gains dropped compared to past cohorts without the redox chemistry modules.

The limited success of the two modules is likely due to an insufficient amount of time spent on the material and a lack of fundamental chemistry background knowledge. While it may come as no surprise that 45 minutes was insufficient for students who had not previously been exposed to redox chemistry, even students who had completed through Chemistry II and Organic Chemistry were not able to recall redox chemistry when assessed even after recent exposure through the two engineering-focused modules. This points to a larger issue and suggests that students are simply unprepared to apply redox chemistry to engineering problems even if they have covered it as a major topic in previous college courses.

It must also be noted that during the Flint Water Crisis module it was discovered that most students had not heard of the Flint Water Crisis. This was a surprise, since all past cohorts had covered the crisis in an introductory environmental systems course. Therefore, the instruction pivoted in real-time to highlight the social and historical narratives of the crisis which further reduced the amount of time spent on the redox chemistry involved in lead leaching. Interestingly, 82% of students reported good or great gains in their overall understanding of the Flint Water Crisis on the post-course survey, a large increase compared to past cohorts that were previously taught about the crisis before the course. Therefore, moving forward, at least two lectures should be spent on the Flint Water Crisis with one discussing the historical, social, and technical narratives and another discussing the chemistry.

Conclusion and Future Work

This study confirmed significant shortcomings in applying redox chemistry amongst second-year civil and environmental engineering students. Cognitive outcomes assessed based on a pre- and post-intervention assessment identified that students only performed better on a question related to calculating electrode potential from two half reactions. Students reporting good or great gains in their confidence in applying chemistry to solve engineering problems was lower than past cohorts in which the redox chemistry modules were not included. In total, a minimal intervention of two environmental engineering focused redox chemistry modules – one related to the Flint Water Crisis and another related to biological processes for pollutant remediation – were not sufficient to improve cognitive or affective outcomes.

To address continued shortcomings in redox chemistry outcomes, a new required course for EnvE students, Environmental Engineering Chemistry and Microbiology, has been created to provide in-depth instruction on redox chemistry related to both water and air chemistry. This will expose EnvE students to in-depth instruction on redox chemistry. While this will improve redox chemistry learning outcomes for EnvE students, the question remains: how much redox chemistry do CivE students need to know and is it worth the time to ensure fundamental concepts are grasped in a water and wastewater engineering course? Corrosion prevention is essential in a world of aging infrastructure, but rather than fitting it all into a water and wastewater engineering course, we propose implementing these concepts in structural and geotechnical engineering courses so that students interested in these disciplines see the direct application.

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