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Connecting chemistry concepts with environmental context using student-built pH sensors

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ABSTRACT

Educational research supports incorporating active engagement into K-12 education using authentic STEM experiences. While there are discipline-specific resources to provide students with such experiences, there are limited transdisciplinary opportunities that integrate engineering education and technological skill-building to contextualize core scientific concepts. Here, we present an adaptable module that integrates hands-on technology education and place-based learning to improve student understanding of key chemistry concepts as they relate to local environmental science. The module also supports disciplinary core ideas, practices, and cross-cutting concepts in accordance with the Next Generation Science Standards. We field-tested our module in three different high school courses: Chemistry, Oceanography and Advanced Placement Environmental Science at schools in Washington, USA. Students built spectrophotometric pH sensors using readily available electronic components and calibrated them with known pH reference standards. Students then used their sensors to measure the pH of local environmental water samples. Assessments showed significant improvement in content knowledge in all three courses relating to environmental relevance of pH, and to the design, use and environmental application of sensors. Students also reported increased self-confidence in the material, even when their content knowledge remained the same. These findings suggest that classroom sensor building and collection of environmental data increases student understanding and self-confidence by connecting chemistry concepts to local environmental settings.

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sensor building; pH; spectrophotometry; environmental change; place-based education

Introduction

Literature context

Recent education reforms have encouraged implementation of authentic STEM (Science, Technology, Engineering and Mathematics) experiences in K-12 education: those with real-world context that reflect actual methods that scientists and engineers use to conduct scientific research (National Research Council, 2012; NGSS Lead States, 2013). Authentic STEM experiences help students develop scientific knowledge via active engagement in practices which encourage them to think and act like scientists and engineers (Lee & Butler, 2003). The Next Generation Science Standards (NGSS) promote authentic STEM experiences through three-dimensional engagement with *disciplinary core ideas*, *science and engineering practices* and *crosscutting concepts* that span a multitude of scientific fields (NGSS Lead States, 2013). While such opportunities for K-12 students are growing, due in part to the increasing development of NGSS-aligned curricula, there are limited transdisciplinary educational modules that integrate STEM concepts across disciplines (National Research Council, 2009; Honey et al., 2014). Therefore, a present need exists for the development and assessment of transdisciplinary STEM curricula, particularly those that incorporate engineering and technology (Honey et al., 2014).

Engineering- and technology-based education help facilitate integrated and authentic STEM experiences. Engineering-based education engages students in active, hands-on learning connecting core STEM concepts through design and building solutions that address scientific challenges (Honey et al., 2014). Moreover, these active, hands-on learning experiences have demonstrated increases in student content knowledge and understanding of scientific concepts (Freeman et al., 2014). Such experiences through engineering activities encourage student creativity and cooperative problem-solving, enhancing student achievement, self-confidence, and attitudes toward STEM (Honey et al., 2014). A technology-based education provides students exposure to and experience with the tools and skills that drive technological advances necessary for STEM innovation to address scientific challenges. Technology-based activities also connect scientific concepts with societal relevance (Bennett et al., 2007), leveraging students' interest in technology in their everyday lives (Walia et al., 2007). Similar to engineering-based education, technology use in

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the classroom has been shown to positively correlate with student achievement and attitudes toward STEM (Liu, 2005). For example, sensor-based lab activities in life sciences (Walia et al., 2007; Iskander & Kapila, 2011), computer-assisted instruction in Earth science (Chang, 2000), robotics initiatives (Tims et al., 2011), and use of Makerspaces, student centers with technological tools to support creativity and design, (Hsu et al., 2017) have increased student achievement and helped develop student confidence in STEM. Teaching STEM in a transdisciplinary way, grounded in real-world technologies and context increases the relevance of material for students (National Research Council, 2009; Honey et al., 2014).

Place-based educational approaches can help address the need for more integrated authentic K-12 STEM experiences by providing real-world context for scientific concepts. Place-based education emphasizes connections between classroom learning and places that students consider familiar and important (Sobel, 2004; Semken et al., 2017). These approaches can be especially meaningful in the geosciences, as they provide students with the environmental context to apply and ground transdisciplinary STEM knowledge (Semken et al., 2017). Locally-relevant environmental phenomena can serve as "anchoring" events that help students frame their understanding of a scientific concept (Theobald et al., 2015; Thompson et al., 2018). Moreover, emphasis on locally relevant, real-world context in previous studies has yielded increased student comprehension, positive attitudes toward science (Bennett et al. 2007), and greater appeal to underrepresented student groups (Semken, 2005; DeFelice et al., 2014; Semken et al., 2017). Many communities face locally-relevant environmental challenges that require innovative STEM solutions, which can serve to provide such real-world context. For example, in Washington State, water quality monitoring and development of water treatment systems were implemented to address oyster die-offs at local shellfish farms due to ocean acidification (Barton et al., 2015). Educators can use these challenges as meaningful and informative contexts to engage student interest. As educators work toward incorporating curricula to meet NGSS standards, resources and examples will be needed to support this engagement. Contextualizing learning with engineering, technology, and placed-based approaches offer students and educators unique opportunities for authentic, transdisciplinary STEM experiences that emulate scientific and engineering practices.

Purpose and learning objectives

Our goal was to develop an educational module that combines technology-based and place-based elements to provide students with a transdisciplinary and authentic hands-on STEM experience. Engaging students in hands-on sensor building serves as an excellent means to address this goal because it promotes transdisciplinary learning by introducing students to engineering design, construction and function of technological devices, computer programing and tools to test scientific hypotheses (Hotaling et al., 2012; Kelley & Grünbaum, 2018). Sensor building facilitates authentic STEM experiences by engaging students in methods practiced by scientists, who regularly use sensor-based platforms to measure environmental parameters, such as pH in natural waters. Spectrophotometry is the one of the preferred methods used by scientists to measure pH in both freshwater environments (French et al., 2002) and marine environments (Clayton & Byrne, 1993; Dickson et al., 2007). Scientists commonly use sensor-based techniques for local and global environmental monitoring and have even built custom low-cost DIY spectrophotometric pH sensors to meet their research needs (Yang et al., 2014). With easily accessible and inexpensive electronic components, it is more feasible than ever before for students to engage in simple sensor building. Furthermore, sensor building initiatives facilitate environmental literacy, lend real-world context to STEM concepts, and enable students to observe and investigate local effects of global environmental change in their own communities (Hotaling et al., 2012; Kelley & Grünbaum, 2018).

Here, we present a field-tested sensor building module, adaptable for a variety of subject classes, that integrates hands-on technology education and a place-based approach to enable students to apply chemistry concepts to their local environments. The module is also aligned with NGSS goals (see Table 1). Student learning goals include: (1) to describe pH and explain spectrophotometry principles, (2) to develop skills in sensor building and sensor use and (3) to apply knowledge of pH and sensors to an environmental context. Additionally, we designed our module to 'demystify' technology and make it more approachable for students with varying comfort and prior experience with technology. Constructing sensors from raw components can help address the lack of understanding of the function of commercially available sensors students typically use in the classroom (Hotaling et al., 2012). We emphasized multiple entry points for knowledge acquisition to increase accessibility (e.g., through hands-on design, collaborative group work and the need for a diverse set of skills).

Students built a simple spectrophotometer, used it to describe the relationship between red and blue light absorbance and pH across a range of standards by creating a calibration curve. They then used their calibration curve to assess the pH of a water sample from a local body of water. In the module, students built spectrophotometers and measured pH using a method analogous to, albeit less accurate than, a preferred method of environmental scientists (Clayton & Byrne, 1993; French et al., 2002; Dickson et al., 2007). We assessed whether this sensor-building experience presented in a local environmental context helped achieve learning goals by measuring content knowledge and self-confidence in students who completed the module using pre- and post-test assessments.

This module was initially developed for use in an undergraduate introductory ocean technology course, through a graduate student teaching assistantship. It was later adapted for the high school level and piloted at two high schools in 2017, where initial discussion-based feedback was collected from teachers and students to improve the module. Through

Table 1. NGSS disciplinary core ideas, science and engineering practices and crosscutting concepts addressed by the module in conjunction with the corresponding model component that supports that standard.

	NGSS Standard (Grades 9–12)	Module component
Disciplinary Core Ideas	PS4.B: Electromagnetic Radiation	Students learn about light absorbance and transmittance and use a Beer's law simulation to understand how their spectrophotometric sensor works.
	PS4.C: Information Technologies and Instrumentation	Students build their own sensor and learn how technology and instrumentation support scientific questions.
	ESS3.D: Global Climate Change	Students learn how scientists use sensors to monitor climate change and ocean acidification. Students collect data using their sensor within the framework of monitoring their local environment to record changes.
	ETS1.C: Optimizing the Design Solution	Students build and troubleshoot a sensor to collect environmental data. They consider strengths and limitations of their sensor.
Science and Engineering Practices	Planning and Carrying Out Investigations	Students conduct an investigation using their sensor to identify the pH of an environmental sample.
	Analyzing and Interpreting Data	Students analyze their data using their calibration curve and interpret it in the context of their local environment.
	Using Mathematics and Computational Thinking	Students create a calibration curve and use the relationships they create between pH and light absorbance to assess environmental samples. They are also introduced to basic coding to communicate with their sensor.
Crosscutting concepts	Patterns	Students use their calibration curve to describe the relationship between pH and light absorbance.
	Cause and effect	Students explain how their sensor works and how differences in light intensity cause the sensor readings to change. Students learn about the causes and effects of ocean acidification.
	Stability and Change	Students learn how sensor building and environmental monitoring help detect changes related to natural variability and climate change.

a collaboration with an undergraduate oceanography service-learning course, a student helped further improve the module and assessment by incorporating collected feedback and helped teach the final module as a course project. Improvements to the module based on student and teacher feedback included reducing lecture components, simplifying written instructions, adding more visuals to lab guides, and building in more opportunities for discussion among students to process and engage with the material. The implementation described here is the final revised iteration of the module.

Methods

Student population

We worked with students from two high schools located in coastal communities near Puget Sound, Washington, USA. At one school, five Chemistry classes (96 students) implemented the module following an acid-base chemistry unit in May 2018. The module was also implemented in January 2019 at another school in two Advanced Placement (AP) Environmental Science classes (45 students) during a unit on bodies of water, and in four Oceanography classes (68 students) as a part of an ocean chemistry unit. At both schools each class consisted of roughly 15-25 students. Additional student demographic data were not collected.

Concept introduction

Students were first introduced to environmental sensors by engaging in a short discussion using the guiding question: *What is a sensor and why might we want to use them to study the environment?* The discussion was facilitated by a teacher with students first discussing the prompt in small groups, then as a whole class. Small student groups (2-3 students each) were organized by the teacher prior to implementing the module and remained the same throughout the duration of the module. Students then watched a video we created on the use of sensors in oceanographic science explaining how student-built sensors operate in much the same way (video available: https://interactiveoceans.washington.edu/story/From_Cruise_to_the_Classroom). After the video, students returned to the guiding question to add to their previous ideas. Small group work and discussion-based learning was emphasized throughout the module as it enables students to process information by giving and receiving feedback, develops social practices of scientists and encourages critical thinking (Driver et al., 2000).

A 15-minute mini-lecture (see *Presentation Slides* in Supplemental Materials) was then presented by the teacher to the students to introduce three major concepts: (1) pH, (2) the environmental relevance of pH and, (3) the properties of light that are foundational to the function of spectrophotometric pH sensors. For concept 1, students were reminded of the pH scale and prompted with questions to discuss their everyday experiences with pH, distinguishing between acids and bases and the importance of measuring pH. For concept 2, pH was given environmental context using ocean acidification as an example. Ocean acidification is of local importance to coastal communities in Washington State, where the schools are located, affecting livelihoods, economies and cultural resources (Feely et al., 2012, Barton et al., 2015). Students were presented time-series data on the CO_2 concentration of the atmosphere from Mauna Loa Observatory, the partial pressure of CO_2 in ocean water and the corresponding ocean pH from oceanographic Station ALOHA (data available through NOAA PMEL Carbon Program: https://www.pmel.noaa.gov/co2/file/Hawaii+Carbon+Dioxide+Time-Series). Students were then prompted to discuss, in small groups and then as a class, the relationship between these variables, and the causes and implications of local environmental pH change. For concept 3, students were introduced to methods used to measure environmental pH, e.g., spectrophotometry, and basic principles of absorbance and transmittance of light through a medium that govern how spectrophotometers work. Discussion questions for concepts 1-3 are listed in the *Lesson Plan* document in Supplemental Materials.

Students explored the relationship between the absorbance and transmittance of different color light through different color solutions using an online PhET simulation of Beer's Law that was analogous to the spectrophotometric pH sensor design (https://phet.colorado.edu/sims/html/beers-law-lab/latest/beers-law-lab_en.html). PhET simulations have been shown to support authentic STEM experiences by helping students think critically about physics concepts (Wieman et al., 2008). Students explored the online simulation in small groups using an in-class worksheet (*Simulation Worksheet* in Supplemental Materials), enabling them to discover relationships between light absorbance and transmittance they would later use when interpreting their sensor data. Teachers facilitated the concept introduction, mini-lecture, simulation exercise and related discussions.

Sensor construction and application

Students worked together in previously formed small groups. Each student group was provided a color-coded kit containing all the necessary sensor components, such that the technology would be more accessible for students who had not had prior exposure to electronics (Figure 1a, *Sensor Parts List* and *Instructor Setup Guide* available in Supplemental Materials). Student groups worked through the *Sensor Assembly Instructions* document (see Supplemental Materials) in a self-guided manner to construct a spectrophotometric pH sensor from the sensor kit (Figure 1b). Once assembled, students confirmed their sensor was operational by connecting the sensor to a laptop to communicate with it. Students communicated with sensors using Beagle Term, an app for Google Chrome that emulates a serial terminal enabling students to send commands directly to the sensor (Han & Lim, 2016). Students were prompted to type two lines of code, which returned the transmittance of light from the LED to the light sensor. At this step, students engaged in troubleshooting if necessary by correcting common errors, such as loose or incorrect wire connections (see *Instructor Troubleshooting Guide* and *Presentation Slides* in Supplemental Materials). After confirming sensors were operational, student groups completed a short checkpoint discussion with an instructor (see *Lesson plan* in Supplemental Materials). Students were required to explain how the sensor functioned and the significance of the data returned by their sensor prior to using the sensor. Checkpoint questions were incorporated into the module to facilitate comprehension through informal discussion and enable the instructor to assess student understanding midway through the module.

Student groups then worked through the *Lab Procedure* document (see Supplemental Materials) where the sensor was used to measure the transmittance of red and blue light through five standard pH solutions: pH 3, 5, 7, 9, and 11. The lab procedure was designed to guide students through the use of the sensor with clear visual aids to reduce barriers to understanding the material, and to enable groups to work at their own pace. Standards were colored with red cabbage juice, a pH indicator dye (Figure 1c). Students then input their data into the pre-built MS Excel *Student Datasheet* (see Supplemental Materials) to create a calibration curve for their sensor (Figure 1d). The datasheet was pre-built to encourage students to focus on the patterns generated from their data and to ensure that a lack of experience using MS Excel would not be a barrier to data interpretation.

Using their calibration curve, students identified the unknown pH of a seawater sample collected locally from Puget Sound (sample collection instructions in *Instructor Setup Guide*). This local seawater sample was also used as a connection to the earlier discussion of ocean acidification in the concept introduction. After identifying the pH of a local sample, groups reported their measurements to calculate a class average. Students were then asked to discuss findings, the sensors' strengths and limitations, and how the sensor function compared with the online Beer's Law simulation in respective small groups and then as a class. Students also identified additional local environments (e.g., streams, lakes, marine areas) in which to use their sensor, and they proposed sampling regimes of these environments to address questions of interest. Final discussion questions were facilitated by instructors and are listed in the *Lesson plan* (see Supplemental Materials). Total class time needed to implement the module was approximately three hours, one for the concept introduction, one for sensor construction, and one for sensor application and use (more details in *Lesson Plan* in Supplemental Materials). Complete materials to conduct the module can also be found at http://publicsensors.org/K12modules/pHsensor/.

Assessment of student learning

We evaluated student learning over the duration of the module using pre- and post-test assessments (Figure 2). Learning assessments were developed through personal communication with a K-12 education research associate at the University of Washington College of Education. Assessment questions prompted both written and diagrammatic explanations related to the application and environmental relevance of pH rather than recalling information from the classroom lecture. Students were also asked to self-report their confidence level when answering content knowledge questions.

Students answered assessment questions on the following concepts: (1) pH basics, (2) environmental pH monitoring tools, (3) impacts of environmental pH changes, (4) causes of environmental pH changes, (5) properties of light necessary to understand spectrophotometric principles, and (6) sensor design. Pre- and post- assessments were blindly scored, using methods similar to Chan et al. (2012), with a scale of 0-4 for the following criteria: 0 - blank, 1 - attempted but incorrect, 2 - partially correct with some incorrect logic, 3 - correct but incomplete, 4 - correct and complete. Self-reported confidence in the material was also scored on a 0-4 scale, where students were asked which statement they identified with most: 0 - blank, 1 - "I have no idea," 2 - "I have some idea, but mostly unsure," 3 - "I feel comfortable but not confident," 4 - "I feel very

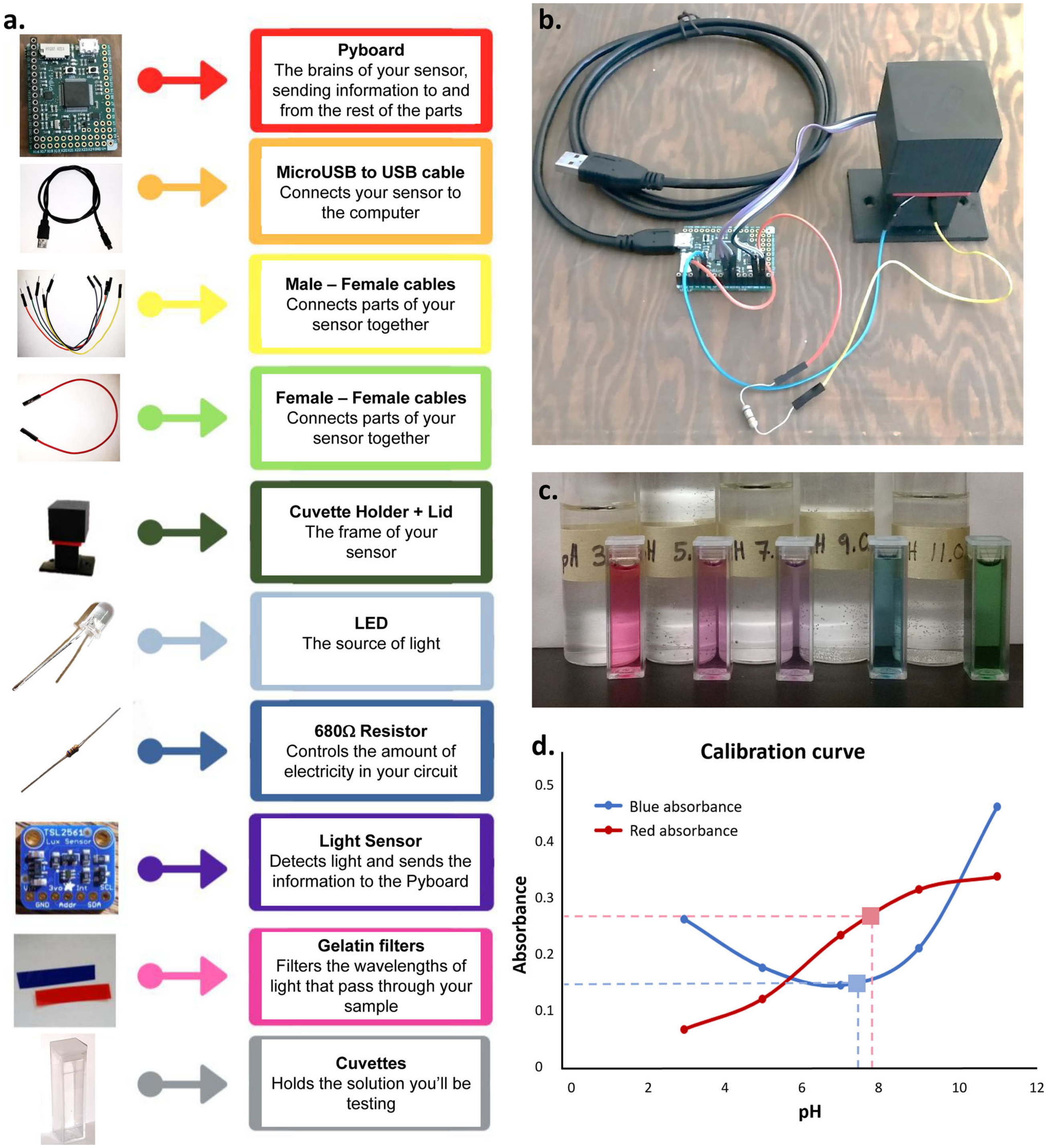
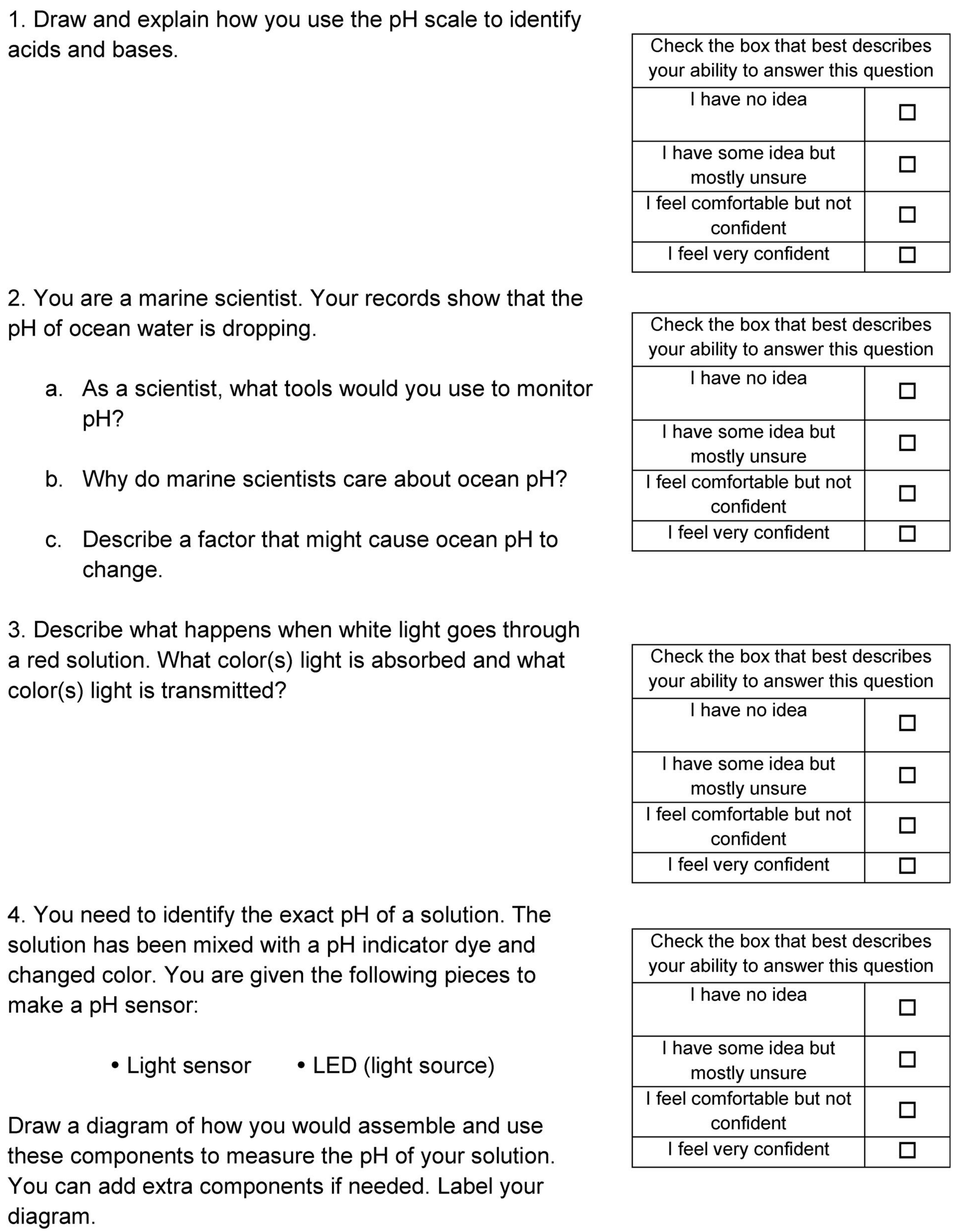


Figure 1. (a) Color-coded materials students use to build their spectrophotometric pH sensor, (b) a student-constructed sensor, (c) pH standard solutions mixed with red cabbage juice as an colorimetric pH indicator and (d) the calibration curve generated from the *Student datasheet* MS Excel spreadsheet using above pH standards which described the relationship between the absorbance of red and blue light and the color (pH) of a solution. Pink and blue squares represent the intersection point of the calibration curve with student-generated absorbance data for an environmental sample of unknown pH. Dashed lines on the calibration curve show how students interpolate the pH of their environmental sample from absorbance values. Students take the average pH from their red and blue light approximations.

confident." One Oceanography class of 17 students did not take the post-assessment so corresponding pre-assessments were removed from the analysis. Comparison of pre- and post-assessment scores were assessed with a non-parametric Wilcoxon rank sum test using R version 3.4.1 (R Core Team, 2017) to detect changes in mean scores before and after students completed the module. Significance was determined at an $\alpha = 0.05$ threshold.

After completing the module, we facilitated discussions and asked students to provide informal feedback on their experience completing the module in small groups, then as a whole class. We also had informal conversations with teachers for anecdotal feedback after the module was completed. Discussions were not formally recorded. Chemistry teachers independently solicited written student feedback on the degree to which they found the module engaging and enjoyable.



1. Draw and explain how you use the pH scale to identify acids and bases.

Check the box that best describes your ability to answer this question	
I have no idea	☐
I have some idea but mostly unsure	☐
I feel comfortable but not confident	☐
I feel very confident	☐

2. You are a marine scientist. Your records show that the pH of ocean water is dropping.

   a. As a scientist, what tools would you use to monitor pH?

   b. Why do marine scientists care about ocean pH?

   c. Describe a factor that might cause ocean pH to change.

Check the box that best describes your ability to answer this question	
I have no idea	☐
I have some idea but mostly unsure	☐
I feel comfortable but not confident	☐
I feel very confident	☐

3. Describe what happens when white light goes through a red solution. What color(s) light is absorbed and what color(s) light is transmitted?

Check the box that best describes your ability to answer this question	
I have no idea	☐
I have some idea but mostly unsure	☐
I feel comfortable but not confident	☐
I feel very confident	☐

4. You need to identify the exact pH of a solution. The solution has been mixed with a pH indicator dye and changed color. You are given the following pieces to make a pH sensor:

- Light sensor
- LED (light source)

Draw a diagram of how you would assemble and use these components to measure the pH of your solution. You can add extra components if needed. Label your diagram.

Check the box that best describes your ability to answer this question	
I have no idea	☐
I have some idea but mostly unsure	☐
I feel comfortable but not confident	☐
I feel very confident	☐

Figure 2. Student assessment questions used to collect information on student content knowledge and confidence in the material before and after completing the module.

Results

In all courses (Oceanography, AP Environmental Science and Chemistry), assessment scores showed significant increases in student understanding of (1) properties of light governing spectrophotometry principles and (2) sensor design (Figure 3a, c, and e). Students in all classes exhibited low prior knowledge of properties of light governing spectrophotometry principles with average pretest scores of 0.78, 0.56 and 1.75, out of a maximum possible score of 4.0, for Oceanography, AP Environmental Science and Chemistry respectively. Students exhibited similarly low prior knowledge in sensor design with average pretest scores of 0.98, 0.71 and 1.35 in these courses respectively, suggesting limited prior exposure to spectrophotometric

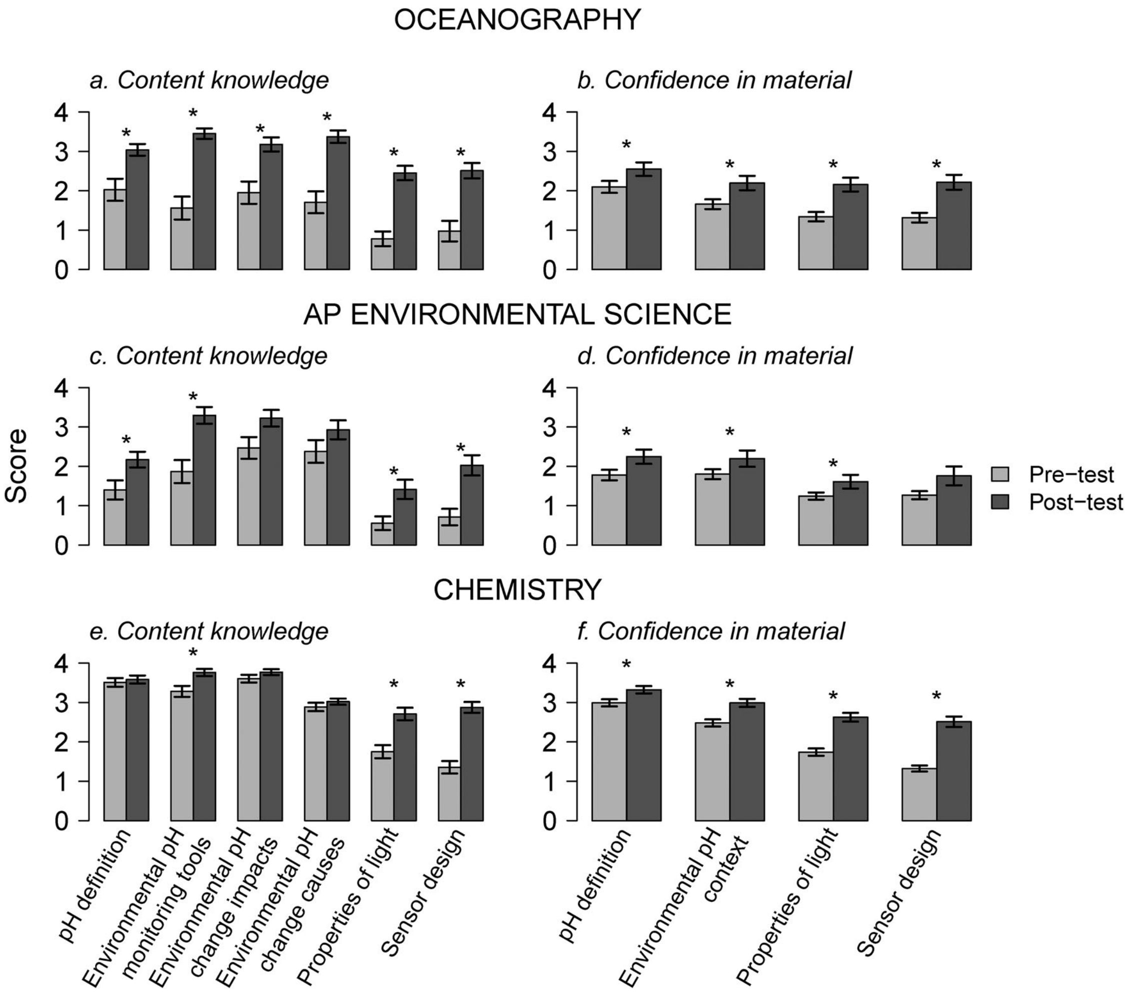


Figure 3. Student assessment data by course. Light gray bars represent student scores before completing the module and dark gray bars denote student scores after completing the module for each assessment question. Asterisks denote significant improvements in score and confidence. Error bars denote the standard error. Data is presented from 51 students in Oceanography, 45 students in AP Environmental Science and 96 students in Chemistry.

instrumentation and technology. However, post-test scores indicated that students in all courses demonstrated significant improvement in their understanding of these two topics. Average student scores in properties of light governing spectrophotometry principles increased by 1.67, 0.85, and 0.96 in Oceanography, AP Environmental Science and Chemistry classes respectively. Similarly, average scores in sensor design increased by 1.52, 1.31, and 1.53 in these courses.

Students in all courses also exhibited an increased understanding of environmental pH monitoring tools (Figure 3a, c, and e). In this assessment category, average pretest scores were lower in Oceanography (1.56) and AP Environmental Science (1.87) than in Chemistry (3.28). Despite these differences in prior knowledge across disciplines, students in all courses showed improved content knowledge in this category with significant average score increases of 1.89, 1.42, and 0.48 in Oceanography, AP Environmental Science and Chemistry classes respectively.

Students in all courses reported increased self-confidence in all assessment categories (Figure 3b, d, and f). Students generally exhibited low initial self-confidence in (1) properties of light governing sensor function and (2) sensor design. In these two categories respectively, students demonstrated low average pretest confidence scores of 1.34 and 1.31 in Oceanography, 1.24 and 1.27 in AP Environmental Science, and 1.74 and 1.32 in Chemistry. After completing the module, students exhibited increases in self-confidence in both categories, which accompanied the above-described significant increases in content knowledge. In properties of light governing spectrophotometry principles, average confidence scores significantly increased by 0.82, 0.37, and 0.89 in Oceanography, AP Environmental Science and Chemistry classes respectively. In sensor design, students demonstrated average score increases of 0.91, 0.49, and 1.19 in these classes respectively, with statistically significant increases in Oceanography and Chemistry. Student confidence scores increased significantly in all other assessment categories as well, sometimes even when there was no associated significant increase in content knowledge. Average post-test confidence scores increased by 0.44, 0.46, and 0.33 in fundamental pH concepts, and 0.54, 0.39, and 0.51 in environmental context of pH for Oceanography, AP Environmental Science and Chemistry classes respectively.

Cross-course comparison

In Oceanography courses, students exhibited significant increases in their content knowledge in all assessment categories with corresponding significant increases in their confidence in the material (Figure 3a and b). Oceanography students demonstrated significant content knowledge gains with average score increases of 1.02 in fundamental pH concepts, 1.89 in environmental pH monitoring tools, 1.23 in environmental pH change impacts, 1.66 in environmental pH change causes, 1.67 in properties of light governing spectrophotometry principles, and 1.52 in sensor design.

In AP Environmental Science, students exhibited significant increases in their content knowledge in all assessment categories except (1) impacts and (2) causes of environmental pH change (Figure 3c and d). Pretest scores were higher in these categories, 2.47 and 2.38 respectively, than in the other assessment categories where average pretest scores were below 2.0. Students exhibited increased post-test scores in these categories, but they were not significant. Despite non-significant content knowledge increases in these two categories, students demonstrated significant increases in self-confidence in environmental pH context with an average confidence score increase of 0.39. In the remaining content knowledge categories, students demonstrated significant score increases. Average student scores increased significantly by 0.77 in fundamental pH concepts, 1.42 in pH monitoring tools, 0.85 in properties of light governing spectrophotometry principles and 1.31 in sensor design.

Chemistry students did not demonstrate significant increases in their understanding of (1) fundamental pH concepts, (2) impacts of environmental pH change or (3) causes of environmental pH change (Figure 3e and f). Students showed considerable prior knowledge in these three topics with high pretest averages of 3.51, 3.6 and 2.89 respectively, unlike in the other two courses. In these categories where content knowledge was already high, Chemistry students did not demonstrate significant score increases after the module. However, students exhibited significant increases in confidence scores in all categories, including those without significant content knowledge increases. In the remaining categories, Chemistry students exhibited significant increases in their understanding of sensors and their application to the environment. Average post-test scores increased significantly by 0.48 in environmental pH monitoring tools, 0.96 in properties of light governing spectrophotometry principles and 1.53 in sensor design.

Feedback

From whole-class discussions conducted after completing the module, students generally found the module enjoyable and engaging. This was supported by written student comments in the Chemistry classes. Quotes reported here refer to written comments which were independently solicited by teachers from Chemistry students only. Chemistry students described the module as "fun," "cool," "awesome" and "interesting." Many students made specific references to enjoying building sensors, reporting that they "liked the hands-on aspect of building the sensors" and "building the spectrophotometer was fun." The integration of technology was also cited as an enjoyable experience with students commenting that "it was fun making electronics and working with programming" and the module "involved using technology that is not usually used which was engaging." However, some students reporting feeling "frustrated" and "confused" with the use of technology because of "technical issues" and the need for troubleshooting, although "enjoying trying to fix things" was also mentioned. Despite some references to frustration, students reported the approachability of the module and the sensor stating it was "easy to understand," "simple and easy to follow" and "not at all hard to do."

Chemistry students also reported that the module was an integrative experience that "combines engineering and science" and provided an authentic STEM opportunity, in which they "felt like a scientist" and "learned how to build a sensor and record different pH levels like scientists." Students also mentioned the relevance and importance of the context provided in the module, citing it was "cool to see a real-life application of what we are learning," "it had applications for future everyday use" and there was a "good connection between class and real-world science." See Appendix 1 in Supplemental Materials for the complete list of Chemistry student quotes that were received.

In our informal conversations with teachers, they expressed enthusiasm for including hands-on technology opportunities in their courses and noted the broad applicability of the module in other natural and physical science courses. Teachers commented that the nature of the module appealed to a diversity of students and engaged some who were typically more reserved. Though we do not have a formal record of all teacher comments, one teacher expressed in an email that "having students in my class become engineers of their own pH meters helped them understand better how pH works in our oceans and why monitoring pH is important."

Discussion

Student outcomes

The pH sensor building module provided students with an authentic STEM experience. Through this experience, students were exposed to accessible technology that helped them learn and apply chemistry concepts. Our assessment results suggest that students largely met the learning goals of the module by demonstrating significant learning gains in fundamental pH concepts (significant score increases of 1.02 in Oceanography, 0.77 in AP Environmental Science), spectrophotometry principles (significant score increases of 1.67 in Oceanography, 0.85 in AP Environmental Science, 0.96 in Chemistry), sensor design (significant score increases of 1.52 in Oceanography, 1.31 in AP Environmental Science, 1.53 in Chemistry) and the environmental applications of sensors (significant score increases of 1.89 in Oceanography, 1.42 in AP Environmental Science, 0.48 in Chemistry). Students also developed skills in sensor building, with feedback suggesting that the hands-on experience was important for their learning. Student assessments showed increased self-confidence in both new and familiar material, determined from pretest responses. This demonstrated the benefit of such active sensor building experiences, even when students had considerable content knowledge. This adds further evidence that technology-based approaches connect classroom chemistry concepts to environmental contexts and increase student knowledge and self-confidence. Observed increases in student confidence during our module and anecdotal student feedback corroborate previous studies (Bennett et al., 2007) showing that connecting learning to society through technology improved student attitudes toward science.

Comparison of the different subject courses

Implementations of our sensor building program in high school Chemistry, Oceanography and AP Environmental Science courses enabled us to test its efficacy across multiple disciplines. The module was successfully integrated into three different subject courses with significant student learning gains in all three, demonstrating its ability to support student learning in a diversity of subjects. The module was therefore adaptable and relevant, with the place-based approach contributing real-world context for students in all three courses. Not surprisingly, Chemistry students demonstrated the most prior knowledge of pH, with a high pretest average of 3.51. The module directly followed an acid-base chemistry unit in this course, suggesting Chemistry students had had the most recent exposure to pH and retained a proportion of this knowledge set. Oceanography students increased their content knowledge in the greatest breadth of topics after completing the module, including foundation pH concepts. AP Environmental Science students also demonstrated increases in content knowledge in foundational pH concepts. pH was likely not a new concept for students in these courses, but it was presented outside of a traditional chemistry course which may have presented an additional challenge in transferring their prior knowledge. Students across all disciplines also increased their confidence in all assessment categories. This suggests hands-on sensor building opportunities are capable of building student self-confidence in STEM concepts in various disciplinary settings.

Broadening the place-based approach

A key component of our module was its place-based approach. Students tested water samples from their local environment and reflected on specific locations where their sensor would enable them to address scientific questions in their own local communities. Here, the module was presented in the context of ocean acidification, a locally-relevant phenomena common in coastal Washington near the schools. However, students who participated in the module also proposed sensor-based monitoring in non-marine environments such as local streams, lakes, and the school pool. These proposals demonstrated the flexibility of the module to meet local interests of the students. They also demonstrate student understanding of the range of applications even though the module was framed around ocean acidification. To adapt the module to non-marine contexts, instructors can have students test the pH of samples from any local waterway using the student-built sensor. Additionally, instructors can substitute any locally-important example for slide 4 in the *Presentation Slides* (Supplemental Materials) to adapt the module to a local environmental concern in need of ecological monitoring. The adaptability of our module to local environmental needs expands authentic STEM opportunities among diverse student populations, supporting achievement and retention of underrepresented students in the geosciences (Semken, 2005; DeFelice et al. 2014; Semken et al., 2017).

Supporting the goals of NGSS

The spectrophotometric pH sensor module provided students with an authentic and integrative STEM experience that emulated how professional scientists investigate environmental change. The module provided students with increased content knowledge in core NGSS physical science, Earth science and engineering concepts through the construction and use of a sensor that enabled them to engage in authentic science and engineering practices. Specifically, the module was modeled after actual scientific protocols used to make spectrophotometric pH measurements and conveyed to students that scientists often build their own instruments, including for this particular purpose (Yang et al. 2014). Overall, the module contributes to a growing body of resources for teachers that incorporate authentic STEM experiences and evidence-based teaching practices which meet NGSS standards.

Limitations

We documented many successes of the module. However, there are some limitations to the data interpretation. Student learning gains were reported across three different disciplinary courses. Differences in learning gains and module effectiveness across the three classes were attributed to specific fields of study associated with the course. However, classes differed in several other ways that may have influenced assessment results, such as different instructional approaches that may have introduced additional variability in our data. Demographic data and student educational history may have also helped explain differences in assessment scores; however, we did not collect these data. Additional data regarding student grades and performance in the course would have been informative to interpret our results and situate the benefits of the module in the larger framework of a course.

Students self-reported increased confidence in the material in all three courses. Confidence scores may have been affected by external variables for which we did not account, such as gender or educational experience (MacPhee et al., 2013). In some instances, students exhibited a significant increase in confidence without an associated significant increase in content knowledge. While we interpreted this positively - that students increased their confidence even in concepts they understood well - this may also be a result of student metacognitive skills and difficulty in self-assessment (Kruger & Dunning, 1999).

We used student quotes to support assessment interpretations. However, we received written feedback from Chemistry students only. Oceanography and AP Environmental Science students expressed similar comments in whole class discussions, but these were not formally recorded. We have assumed Chemistry student quotes to be largely representative of the student experience across all three courses. Therefore, caution should be exercised in interpreting our student feedback data for other contexts.

The pH sensor constructed in the module is accurate to approximately +/- 0.5 pH units, if measurements are conducted carefully. However, from our experience in the classroom, accuracy tends to be closer to approximately +/- 1.0 pH units, given the variability in and sources of error introduced during student use. Sources of error can be minimized by ensuring that the LED and light sensor are well secured in the student-built pH sensors and that careful attention is paid to sample preparation and indicator dye use directions in the *Lab Procedure* (Supplemental Materials).

Beyond the high school classroom

The current module is intended to educate a high school audience, but it is further adaptable and has also been used in additional settings aside from the implementation and evaluation described here. The module has been incorporated in professional development workshops for high school science teachers to provide training on connections between climate, chemistry and scientific instrumentation. An adaptation of the module has been used to teach upper-level oceanography undergraduates about sensor construction and function in an introductory ocean technology course, and it has the potential to be adapted for other undergraduate courses.

The module has also been used as a tool to train undergraduates in science communication and pedagogy. In an undergraduate oceanography service-learning course, the module was used as an example to teach students about creating and aligning teaching materials with NGSS standards. Most undergraduate STEM education does not include science communication training, prompting calls for increasing its inclusion for undergraduate STEM majors (Brownell et al. 2013). Engaging in such experiences has demonstrated benefits for undergraduates including skill development and increased confidence as science communicators (Dohaney et al., 2017). Our module can help serve to provide undergraduates with science communication opportunities while simultaneously engaging high school students in valuable sensor building learning experiences.

At present, the model requires visual confirmations to build and communicate with the sensor, and record and interpret data in an MS Excel spreadsheet. However, the module can be made more broadly inclusive, and could be coupled with assisted technologies to support students with visual impairments. Screen readers could be used to read out sensor values and enable interaction with the MS Excel datasheet, and braille tablets could enable students to type code, though we have not tested this. Modules like ours present diverse avenues for training educators and science communicators, and for educating future scientists and scientifically literate citizens.

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