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Development of an At-home Metal Corrosion Laboratory Experiment for STEM Outreach in Biomaterials During the Covid-19 Pandemic

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Abstract

Due to the coronavirus disease 2019 (COVID-19) pandemic, many universities and outreach programs have switched to online learning platforms, which inhibits students from completing formative hands-on experiments. To address this, we developed a series of at-home experiments for undergraduate engineering students and adapted one of these experiments for outreach purposes. This experiment was well received by middle school students in the Young Eisner Scholars (YES) Program and resulted in significant learning gains by pre/post-test assessment. Additionally, students showed enhanced attitudes toward science after completing their at-home experiments, as measured by pre/post-surveys. These results motivate the use of similar at-home experiments with virtual instruction to remotely teach engineering concepts to diverse, underserved communities during the COVID-19 pandemic and beyond.

Introduction

Biomaterials are substances that can treat, augment or replace any tissue, organ or function of the body [1]. At the inception of the modern biomaterials field in the 1940's, this mostly included bioinert medical devices and prostheses for cardiovascular and orthopaedic applications [2]. Since this time, biomaterials have evolved with the field of tissue engineering, which aims to develop functional substitutes for damaged tissues [3]. Today, scientists, engineers, and clinicians collaborate to develop a wide range of novel biomaterials that can diagnose and treat numerous diseases in previously unimaginable ways [4]. Additionally, this strong interest in biomaterials is reflected economically. In 2019, the global market for biomaterials was estimated to be worth $106.5 billion, and revenues from biomaterials are projected to increase to $348.4 billion by 2027 [5]. To ensure these societal and economic demands for novel biomaterials are met, we must prioritize educating diverse students about designing, engineering, and testing biomaterials [6], [7].

One way to meet this goal is through K-12 outreach. Outreach is an important activity for increasing the number of students studying science, technology, engineering, and mathematics (STEM) at the university level [8], [9]. This is especially important for increasing the representation of individuals who are traditionally underrepresented in STEM based on race, ethnicity, gender, sexual orientation, socioeconomic status, etc. [10]–[12]. Effective outreach strategies for biomaterials education should involve hands-on experiments because they are crucial for solidifying engineering concepts and connecting theoretical content to practical applications [13]. Therefore, designing inexpensive, hands-on biomaterials activities for STEM outreach purposes is an effective way to promote STEM in diverse, underserved communities.

Educators have designed numerous engaging activities to teach the principles of biomaterials in a laboratory setting [14]–[16]. Unfortunately, these experiments cannot be completed in the online learning environment brought about by the coronavirus disease 2019 (COVID-19) pandemic [17]. Virtual experiments are an interesting alternative; however, it would be difficult to implement currently published virtual experiments in underserved communities because they are entirely computational and may require remote access to expensive testing equipment [18]–[21]. At-home experiments with virtual instruction have the capacity to overcome these challenges. Mechanical, electrical [22], and chemical engineering [23]–[25] educators have embraced at-home experiments as low-cost strategies to teach relevant topics, but there is a dearth of at-home experiments teaching principles of biomaterials. To the authors' knowledge, Lee et al. were the only group to publish an at-home biomaterials experiment [21]. To address this deficit and the challenges it poses to biomaterials education during the COVID-19 pandemic, there is a need to develop new, at-home experiments capable of effectively teaching principles of biomaterials.

Previously, we described the integration of three inexpensive, at-home biomaterials experiments into a multidisciplinary elective undergraduate engineering course called Biomaterials taught by faculty from the Chemical Engineering Department of the Cooper Union for the Advancement of Science and Art [26]. Each student received an at-home experiment kit containing all the necessary materials to complete three experiments about three major classes of materials prevalent in biomaterials (i.e., ceramics, metals, and polymers), and costs less than $100. These inquiry-based learning experiments were well received by students and resulted in positive learning gains by pre/post-test assessment. Having demonstrated the success of these at-home experiments with virtual instruction at the undergraduate level, we hypothesized that they could be adapted for STEM outreach purposes because they are inexpensive, scalable, and can easily reach diverse communities throughout the world. The objective of this study is to describe and evaluate how we adapted the Metal Corrosion Experiment from our undergraduate Biomaterials course for STEM outreach. To do so, we leveraged existing partnerships between the Icahn School of Medicine at Mount Sinai, the Cooper Union for the Advancement of Science and Art, and the Young Eisner Scholar (YES) Program to have middle school students in multiple time zones throughout the United States, simultaneously complete an activity on metal corrosion.

Activity Overview

This activity was conducted in two sessions with middle school students in the YES Program over the course of 5 weeks. In the first session, instructors administered pre-tests/surveys (**Table 1 & 2**), defined biomaterials, introduced topics of metal biomaterials, and set up the Metal Corrosion Experiment. During the second session, students qualitatively described the corrosion on their metal paperclips, devised a quantitative way to measure the effects of metal corrosion on fatigue failure, analyzed their data, and completed post-tests/surveys. The Icahn School of Medicine at Mount Sinai, the Cooper Union for the Advancement of Science and Art, and YES facilitated this virtual activity using Zoom (San Jose, CA).

To assess baseline knowledge of biomaterials, we first asked students to provide definitions of biomaterials in their own words. Using these definitions as a branching point, we provided a more formal definition with common examples of biomaterials (e.g., contact lenses, pacemakers, hip implants, and prosthetic teeth). Next, we categorized these common biomaterials into three major categories of biomaterials: ceramics, metals, and polymers. Since our activity was on metal corrosion, we focused the remainder of our virtual interaction on metal biomaterials. Specifically, we discussed the fabrication of metal biomaterials, structure-function relationships of metals, and how these properties make them valuable components of numerous medical devices [1]. To help solidify these concepts, we showed students titanium and cobalt chromium molybdenum hip implants and explained concepts in the context of metal hip implants. After introducing metal biomaterials, we explored the concept of metal corrosion with the students. Our goal was to ensure that students understood metal corrosion broadly and why it is relevant to the development of metal biomaterials. We described how the human body contains salts and proteins at a physiological temperature of 37°C and pH 7.3, all of which can promote metal corrosion. Moreover, we emphasized how corroded metals are biomechanically inferior and corrosion can release toxic byproducts. Lastly, we discussed surface modifications as a means of overcoming challenges associated with metal corrosion [27].

Once the concepts of biomaterials, metals, and metal corrosion were accessible to students, we moved into our experiment. This experiment was a new adaptation of the classic paperclip fatigue bending experiment [28]. In the traditional version of this experiment, students fatigued paperclips at different bend angles to measure the effect of bend angle on failure limit. For our modified experiment, students were asked to explore the effects of salinity on the corrosion of metal paperclips. Students incubated paperclips in water, low salt, and saturated salt solutions for 5 weeks to allow corrosion to occur. Furthermore, the concept of metal passivation was explained as an analogue to the galvanization layer on the paperclips. Students were required to sand the paperclips to remove the corrosion-resistant coating. After paperclips were incubated for 5 weeks in the various solutions, students were challenged to devise a quantifiable method of fatigue testing their paperclips. The goal was to semi-quantitatively compare the effects of the environment in which the metals corroded on biomaterial fatigue limit. After completing their experiments, students recorded their results in a shared document and instructors guided the students through data analysis in real-time.

Materials Preparation and Software

Materials were purchased from Amazon (Seattle, WA), shipped in bulk to YES activity leaders in New York City, Los Angeles, Chicago, and the Appalachian region of North Carolina, which were then distributed to students in the form of at-home kits. Each item is listed by name and Amazon Standard Identification Number (ASIN). The choice of material, brand, and quantity was selected based on economical constraints and the choice of free shipping. The materials cost approximately $1 per student. It was assumed that all students had access to tap water, salt, and a permanent marker. The following materials were purchased:

- Synrroe Nitrile Gloves (x2 sets per student) [**ASIN:** B08616G8F5]
- Officemate No.1 Smooth Paperclips (x30 per student) [**ASIN:** B008GVZEOW]
- 3M 9019 General Purpose Sandpaper Sheets, Assorted Grit [**ASIN:** B00004Z47W]
- Plasticpro 9 oz Disposable Plastic Medium Weight Clear Drinking Cups (x3 per student) [**ASIN:** B082BGLS9R]

In addition to physical materials, students were given access to a shared Google Sheet (Google, Mountainview, CA) to record their fatigue testing data. This allowed instructors to track student progress in the activity and conduct real-time data analysis with students.

Activity Execution

Prior to starting the first session, middle school students were given a pre-test to assess their baseline knowledge of biomaterials and metal corrosion. Additionally, students were given a pre-survey to assess their baseline attitudes towards STEM before the first session of the activity began.

After completing preliminary survey assessments, instructors guided students through a presentation that introduced students to metal biomaterials, structure-function relationships of metal biomaterials, and metal corrosion. Using an inquiry-based learning approach [29], [30], instructors then facilitated a student-led discussion to design an experiment that could determine how salt concentration affects the rate of metal corrosion and subsequently the rate of metal failure. At the end of the discussion, instructors summarized key pieces of the experiment, asked students to sand the galvanization layer off 30 paperclips, and instructed each student to place 10 paperclips into each of the following three environments: (1) tap water, (2) low salt, and (3) saturated salt. Students created the low salt solution by filling cups about halfway with water, then adding approximately 1 tablespoon of salt. To create the saturated solution, students filled cups about halfway with water, then added salt until there was visible precipitation. After labeling their conditions, students were instructed to store their experiment in a safe place for the next 5 weeks. To ensure salt concentrations remained approximately constant over the 5-week experiment, students marked the water line with a permanent marker and refilled evaporated water in their cups to this line weekly.

At the follow-up session 5 weeks later, students were reminded of the experiment they designed, then guided through a discussion of how the different salt environments influenced metal corrosion. Students were encouraged to take pictures of their corroded paperclips and describe qualitative differences in metal corrosion between their groups (**Figure 1A**). Next, students were introduced to the concept of fatigue failure testing and how it is useful for testing the safety and efficacy of metal biomaterials. With this knowledge, instructors guided students through an inquiry-based discussion to devise a quantifiable method of fatigue testing their paperclips. This enabled students to semi-quantitatively compare the effects of salt on metal corrosion and biomaterial fatigue limit. A special emphasis was placed on having students hypothesize which group they expected to fail more quickly based on their qualitative corrosion data. After the experimental design discussion, instructors summarized the proposed method and led students through their paperclip fatigue failure testing scheme. While there are numerous reproducible ways to fatigue test paperclips, the method we used had students open the outermost portion of the paperclip to 180°, then bend back to 90° from the starting location. Each time students bent the paperclip to 90° or 180° from the starting point counted as a bend (**Figure 1B**). Students recorded the number of bends it took to break paperclips in each group on a shared Google Sheet. After students broke a sufficient number of paperclips in each group (~5 per group), instructors showed the students how to graph and analyze the data (**Figure 1C**) and discussed the results in the context of established metal corrosion mechanisms. The discussion emphasized that ions present in the low salt condition would increase the rate of metal corrosion and the lack of dissolved oxygen in the saturated salt condition would decrease the rate of metal corrosion [31]. To conclude, students completed a post-test and post-survey to assess how their knowledge of biomaterials and attitudes towards STEM changed as a result of the experiment, respectively (**Appendices A & B**).

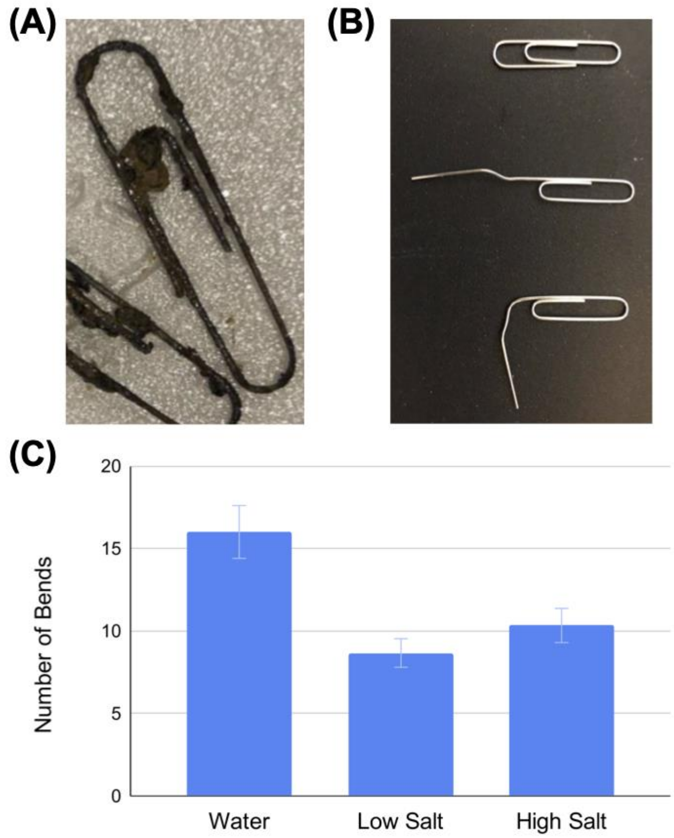

Figure 1: Representative data demonstrating successful paperclip corrosion and quantitative fatigue bending tests. (A) *Example of a corroded paperclip after incubation in salt water.* ***(B)*** *Schematic representation of paperclip fatigue bending test.* ***(C)*** *Graph of average number of bends of paperclips to fail after incubation in various salt solutions. Graph was created live during the activity using student-generated data.*

Student Outcomes

YES has multiple chapters in cities located in multiple time zones throughout the United State. Nationally, YES has 140 middle school students ranging in age from 11 to 13 years old. 56% of these students identify as female and 82% identify as black/African American or Latino/Hispanic. Approximately 45 students participated in our STEM outreach activity and eleven students (n = 11) participated in the pre/post-test assessments and pre/post-surveys. Free response questions on pre/post-test assessment questions were scored with partial credit. The average pre/post-test scores were compared using a paired Student's t-test ($\alpha = 0.05$). Survey data was first assessed qualitatively using descriptive statistics. For quantitative analysis, Likert Scale responses were converted to numerical values (i.e., Always/Strongly Agree = 5, Never/Strongly Disagree = 1) and compared using a Wilcoxon matched-pairs signed rank test ($\alpha = 0.05$). GraphPad Prism software Version 9 (Prism9, San Diego, CA) was used to conduct all statistical analysis. This study was approved by the Icahn School of Medicine at Mount Sinai and the Cooper Union for the Advancement of Science and Art Institutional Review Boards (IRB). Only tests/surveys submitted by students with completed Parental Permission Forms were used in the presented analysis.

Test questions were written to test students' understanding of biomaterials, how metals are used as biomaterials, metal corrosion, how metal corrosion affects fatigue failure rate, and how salt concentration affects metal fatigue failure rate. The complete list of questions can be found in **Table 1**. The results of our assessment showed that the average scores significantly increased from 30% on the pre-test to 75% on the post-test assessment (**Figure 2A**). In addition to significant overall score increases, we found that the percentage of students who correctly answered every question was greater in the post-test than the pre-test (**Figure 2B**). This was particularly striking for test question 2 (TQ2), which asked students to explain how metals are used as biomaterials. Only 18.2% of students answered TQ2 correctly in the pre-test and 100% of students answered correctly in the post-test. This highly significant increase in pre/post-test scoring indicates that the at-home experiment effectively taught the desired learning outcomes.

Table 1. *Pre/post-test assessment questions.*

Question Number	Question	Answer
TQ1	What is a biomaterial? Please name one in the space provided.	**Biomaterials are substances that treat, augment or replace any tissue, organ or function of the body. Some examples are contact lenses, pacemakers, hip implants and prosthetic teeth.**
TQ2	How are metals used as biomaterials?	**Metals have excellent mechanical properties and can be used as load-bearing implants (e.g., hip implant). Metals are also highly conductive, so they can be used as components for medical devices (e.g., pacemaker)**
TQ3	What is corrosion?	**Metal corrosion is the removal of metal by chemical or electrochemical reactions at the metal surface.**
TQ4	How does corrosion affect the rate metals fail?	**Corroded metals have inferior mechanical properties and fail more quickly than non-corroded metals.**
TQ5	Which will break faster?	a) Paperclip in tap water for 5 weeks **b) Paperclip in dilute salt water for 5 weeks** c) Paperclip in concentrated salt water for 5 weeks

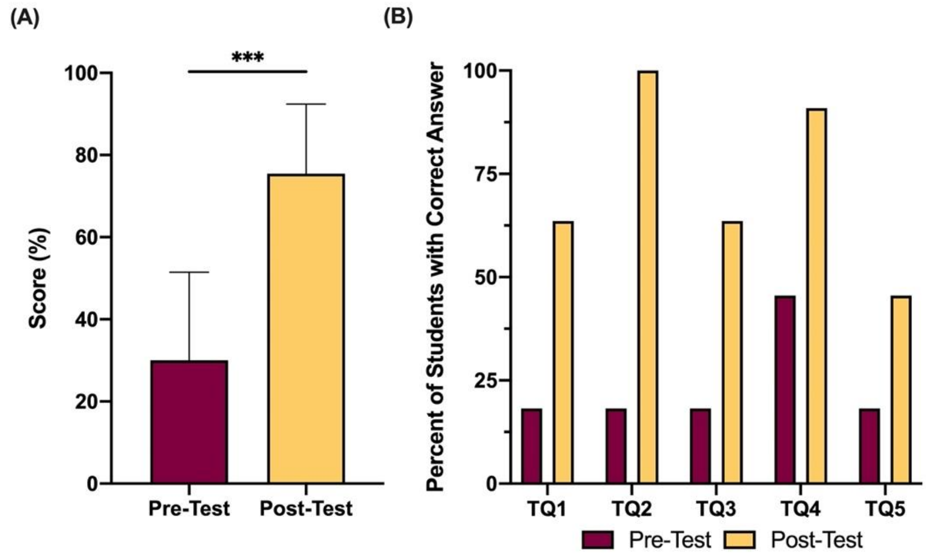

Figure 2. Students scored higher on post-test evaluation, demonstrating significant learning gains. (A) *Average student pre/post-test scores. *** = p < 0.001.* ***(B)*** *Percentage of students who answered individual questions correctly on pre/post-test assessments.*

Survey questions were written to understand how the students' attitudes towards math, science, and careers in STEM may have changed as a result of completing the at-home experiment. The complete list of questions can be found in **Table 2**. Survey question 1 (SQ1) and SQ2 ascertained whether students felt they used science and math in their everyday lives, respectively. At baseline, approximately 45% of students felt they used science always or often, and approximately 75% of students felt they used math always or often (**Figure 3**). There was little change in these percentages in the post-survey. SQ3 assessed whether students would continue to use science and math after graduation. We found that approximately 45% of students felt they would use science and math always or often after graduation. Strikingly, after completing this at-home biomaterials experiment, approximately 80% of students felt they would use science and math always or often after graduation. SQ4 asked students whether they would be interested in a career in science or math. There was no difference in the total number of students who answered “Strongly Agree” and “Agree” to SQ4, but there was a slight increase in the number of students who answered “Strongly Agree,” as opposed to “Agree”. Conversion of Likert Scale responses to numerical values (i.e., Always/Strongly Agree = 5, Never/Strongly Disagree = 1) showed no statistically significant differences in pre/post-survey answers for any questions.

Table 2. *Pre/post-survey questions.*

Question Number	Question
SQ1	I use science in everyday life.
SQ2	I use math in everyday life.
SQ3	I will use science and math in everyday life after I finish school.
SQ4	I would be interested in a career in science or math.

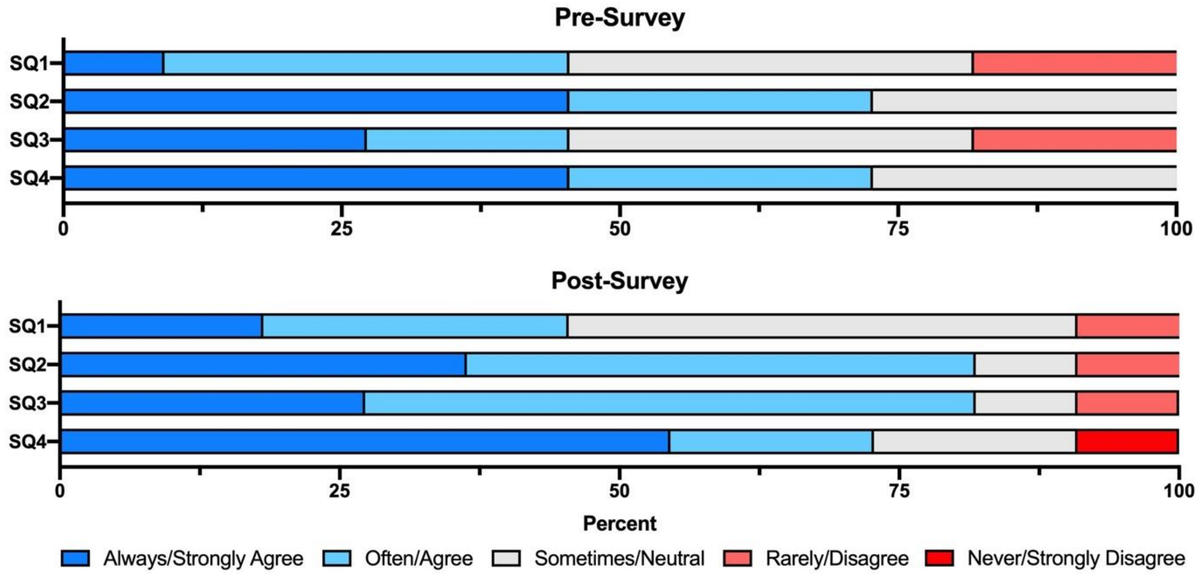

Figure 3. Student post-survey data shows increased positivity towards science after completing at-home experiment.

Discussion and Conclusion

Biomaterials is a promising field of study that offers solutions to heal individuals suffering from a host of diseases and ailments [2]. Thus, there is a pressing need to educate engineering students about biomaterials to meet this demand [6], [7]. Previously, educators designed engaging experiments to teach principles of biomaterials in a laboratory setting [14]–[16]; however, the outbreak of COVID-19 has made these in-person experiments impossible for most institutions and outreach programs. Some universities and outreach programs had existing virtual learning infrastructure to transition to remote learning [32]. However, the remote learning activities conducted were limited to computational simulations or live experiments streamed virtually to students for at-home analysis [18]–[21]. Furthermore, the extension of this remote learning infrastructure for outreach to underserved communities generally was not a priority. Only recently have institutions of higher learning worked to remotely include students from underrepresented communities, and these activities were not STEM-focused [33]. As an alternative, we developed a series of at-home biomaterials experiments, which used inexpensive materials and virtual instruction [26]. These experiments were successful at the undergraduate level; therefore, we adapted the Metal Corrosion Experiment for STEM outreach purposes. We hypothesized that this activity would effectively teach middle school students from underserved communities the principles of biomaterials, by enabling them to complete formative hands-on experiments, in their homes, with readily available materials.

Based on our pre/post-test assessments, we found that middle school students who completed at-home, inquiry-based learning experiments had significant learning gains of approximately 45 points (**Figure 2A**). Moreover, the percentage of students who answered each question correctly increased by upwards of 25%, indicating strong learning gains across all tested topics (**Figure 2B**). As a point of comparison, freshman engineering students experienced learning gains of approximately 50 points in pre/post-test assessments after completing traditional published laboratory experiments [34], [35]. The learning gains quantified from our at-home experiments were approximately equal. This indicated that the at-home experiment is a comparable alternative to traditional laboratory experiments in the learning constraints brought about by the COVID-19 pandemic for a first introduction to a topic.

Pre/post-survey analysis showed that after completing our at-home experiment, more students felt they would use science always or often in their everyday lives after graduation (**Figure 3**). This change brought the post-survey results of SQ3 to the pre/post-survey results of SQ2, which assessed whether students felt they currently use math in their everyday lives. Practical applications of math in everyday life are generally accessible to students (e.g., shopping, traveling, etc.), but practical applications of science are more abstract. Thus, the results of our pre/post-survey analysis for SQ3 and SQ2 are very interesting because they may indicate that our at-home science experiments, which used simple household materials, allowed students to more broadly understand how scientific principles can be applied to their everyday lives. Minor changes were found in the pre/post-survey answer distributions for SQ1 and SQ4, which assessed current feelings towards science and long-term feelings towards careers in math and science. This result was not surprising because the partnership between the Icahn School of Medicine at Mount Sinai, the Cooper Union for the Advancement of Science and Art, and YES allows students to be regularly exposed to STEM activities. Therefore, it is unlikely that this particular activity would enhance their long-term feelings towards STEM, since their baseline scientific exposure was already so high.

There were some challenges associated with the virtual instruction of students through at-home experiments. First, it was difficult to secure signed Parental Permission Forms from participating students virtually, as demonstrated by our low yield of students whose pre/post-test and survey data we could analyze. In an attempt to enhance our yield, we included information on educational research and how it can benefit underrepresented students, like the ones in the YES program. To further increase yield in the future, we would recommend that educators give similar information to both students and parents. Also, it was difficult to measure student engagement with the activity because not all students had their video cameras on. We did encourage students to turn their cameras on and created spaces for students to visually share pieces of their experiment (e.g., corroded paperclip pictures) with the group on Zoom and via social media (e.g., Twitter and Instagram). Additionally, there was high engagement in the Zoom chat after encouraging students to share their thoughts through that platform. We recommend incorporating visual activities (e.g., student sharing of pictures) and Zoom features (e.g., annotate, chat, polls, etc.) when educators facilitate similar activities. For example, before defining biomaterials, we asked students to annotate a blank slide with words they associated with biomaterials. This engaged students in the activity and provided instructors with an initial framework to build upon when teaching new material.

Overall, we've demonstrated that the described at-home Metal Corrosion Experiment was used as an effective STEM outreach tool for teaching principles of biomaterials to middle school students. Biomaterials educators could use this activity, as described, or modify the experiment to highlight other variables that impact the rate at which metals corrode (e.g., pH). In doing so, educators have the freedom to create engaging exercises that allow students to discover how different environmental conditions in the human body impact metal corrosion. In modifying the activity, educators should adhere to Next Generation Science Standards (NGSS) for middle school students. In line with middle school NGSS, our activity emphasized basic statistical techniques to determine differences between groups, using logical causal explanations to explain differences, and communicating information in evidence-based arguments [36]. If working with elementary school or high school students, educators should modify the activity to align with developmentally appropriate NGSS. For example, an elementary school-level activity would ask a simpler question with less conditions (i.e., tap water vs. salt water) and focus on collaboratively completing the activity [37]. Conversely, a high-school level activity would give students the freedom to explore multiple variables of interest, use more rigorous statistical analysis and discuss findings in the context of designing metal biomaterials for real-world applications [38].

More broadly, the success of this experiment justifies the use of at-home experiments with virtual instruction as a model for teaching various engineering principles beyond the COVID-19 pandemic. This model of hands-on outreach is very exciting for educators because it allows global experts to virtually teach diverse students from around the world, without being constrained by their geographic location. Additionally, this model is likely to be especially useful for engaging underrepresented students who don't live near universities and are at a large disadvantage for advancing in STEM [39]. Using the outreach model presented in this paper, underrepresented students in remote areas can have access to enthusiastic educators from institutions of higher learning, which could enhance their opportunities in STEM. As a future direction for this work in the field of biomaterials, we plan to adapt our undergraduate at-home experiments for ceramic toughness and polymer stiffness for STEM outreach purposes. This would involve simplifying the broad list of potential variables undergraduate engineering students explored in their inquiry-based approach (e.g., ceramic porosity, polymer solution concentration) and target specific learning gains about ceramic toughness and polymer stiffness. Our long-term goal is to implement these lessons in more remote areas of the country to better serve a wider range of underrepresented students.

Safety and Hazards

Instructors should ensure that students take appropriate safety precautions while conducting at-home experiments. Students should be advised to check on their experiment weekly to ensure there is no leaking or unwanted water damage. Students should wear laboratory gloves and goggles/glasses when handling corroded paperclips for qualitative analysis and fatigue testing. Broken paperclips will produce sharp edges, so students should be warned to take care during fatigue testing as not to injure themselves or others. After completing the experiment, students should wrap broken paperclips in a paper towel prior to throwing them in the garbage. This precaution, or similar precautions, will ensure garbage bags don't break and family members aren't injured when throwing away garbage. After cleaning up, students should wash their hands thoroughly.

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