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An Inquiry-Based Learning STEM Outreach Module to Teach Principles of Bioadhesives and Tissue Repair

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An Inquiry-Based Learning Tissue Repair Module for STEM Outreach

Abstract

Bioadhesives are an important subset of biomaterials, which aid wound healing, hemostasis, and tissue repair. In order to advance the field of bioadhesives to promote more regenerative healing, there is a societal need to teach diverse trainees about their design, engineering, and testing. To address this, we deployed a hands-on, inquiry-based learning (IBL) bioadhesives module to middle school students from underserved communities in the Young Eisner Scholars (YES) program**.** The module, which lasted approximately 3 hr, was designed to teach students about applications of bioadhesives, engineering bioadhesives for various biomedical applications, and mechanically testing their adhesive strength using standard practices. Students who participated in our IBL bioadhesives module displayed significant learning gains by pre/post-test assessment, demonstrating that the module was effective for middle school outreach. Pre/post-survey assessments showed no significant differences in attitudes towards STEM, which was likely due to the fact that students in YES had a strong predisposition for STEM. Overall, results motivate the use of this module, or similar hands-on IBL modules, for outreach with K-12 students who are underrepresented in STEM.

Introduction

Biomaterials is an interdisciplinary field that employs knowledge from biology, chemistry, materials science, and engineering to create materials that improve human health [1]. To date, biomaterials have been used as medical implants, methods to promote tissue healing, molecular probes and biosensors, drug delivery systems, and scaffolds to regenerate human tissues [2]. Based on these important benefits to human health, biomaterials are projected to have global revenues of $348.4 billion by 2027 [3] and the employment of bioengineers is projected to increase by 6% by 2030 [4]. To satisfy these increasing societal and economic demands for biomaterials, we must engage students at a young age to join the field of biomaterials.

Bioadhesives are an important class of biomaterials, designed to adhere biological components together for tissue repair [5]. In a clinical setting, bioadhesives are used to stop internal fluid leaks [6] and aid in healing surgical wounds [7]. Additionally, scientists and engineers have designed experimental bioadhesives to seal soft tissue defects and repair orthopaedic tissues [8,9]. Furthermore, bioadhesives have been developed as delivery vehicles for cells [10,11] and other bioactive factors [12,13], which may promote more regenerative healing. The current state of bioadhesives focuses on sealing tissue defects; however, the aim for next-generation bioadhesives is to promote complete healing, or regeneration [14]. Achieving this goal will require diverse scientific teams, which produce higher impact work [15–17].

Outreach with K-12 students is an effective way to engage younger students to study science, technology, engineering, and mathematics (STEM) at the university level [18,19]. Focusing these efforts on individuals who are traditionally underrepresented in STEM based on race, ethnicity, gender, sexual orientation, socioeconomic status, etc., is especially important for diversifying STEM fields [20–22]. Also, it is important to consider the types of outreach activities that educators use to engage students. The physicality of hands-on activities has proven to be effective for teaching engineering concepts because it connects theoretical content to practical applications [23]. Thus, designing hands-on, low-cost modules about biomaterials and deploying them to students who are considered underrepresented in STEM may be an effective way to engage diverse trainees in STEM fields.

There are many published educational modules to provide students with hands-on experience with biomaterials; however, there is a dearth of modules about bioadhesives. For example, modules have been designed to teach students about films [24], fiber-reinforced ceramic composites [25], the mechanical properties of hydrogels [26,27], and the corrosion of metals [28]. These modules, and many others, have provided students with informative hands-on experiences to teach principles of biomaterials. Unfortunately, there are no published modules that can provide similar hands-on experiences for the field of bioadhesives at the K-12 level. This represents a significant gap in the field of bioadhesives, which can limit early exposure of diverse trainees to the discipline and impede advances in bioadhesives for tissue repair.

Previously, we described an inquiry-based learning (IBL) bioadhesives module to teach undergraduate, master's and PhD/postdoctoral trainees how to design, engineer and test bioadhesives [29]. Trainees tested the adhesive strength of two different bioadhesives (*i.e.*, glutaraldehyde-crosslinked gelatin and cyanoacrylate) with two different substrates (*i.e.,* chamois strips and polylactic acid strips) using American Society for Testing and Materials (ASTM) standards. This IBL bioadhesives module resulted in significant learning gains and significant improvements in scientific literacy for trainees at multiple education levels. Having demonstrated this activity was successful for undergraduate, graduate, and postgraduate trainees, we hypothesized that we could use Next Generation Science Standards (NGSS) to adapt the module for middle school outreach [30]. The objective of this study is to describe and evaluate how we adapted our IBL bioadhesives module for STEM outreach with middle school students from underserved communities. Leveraging an existing partnership between the Icahn School of Medicine at Mount Sinai and the Cooper Union for the Advancement of Science and Art, we deployed a modified version of our IBL bioadhesives module on a cohort of middle school students from YES, which empowers students from underserved communities to succeed in high school, college, and future careers.

Activity Overview

We were interested in adapting our IBL bioadhesives module for middle school students from underserved communities because early exposure to STEM can help galvanize future participation in STEM [18,19]. Our module could be divided into three stages: (1) Pre-activity exercises, (2) IBL activity, and (3) Post-activity exercises.

During the pre-activity exercises, we evaluated baseline technical knowledge and baseline attitudes towards STEM, then provided students with an interactive background on bioadhesives. A pre-test and a pre-survey were used to measure baseline technical knowledge of bioadhesives and baseline attitudes towards STEM, respectively. The pre-test and pre-survey were created by the authors. Following pre-test/survey assessment, instructors provided an interactive, 30-minute introduction to bioadhesives. Active learning tools (*e.g.*, brainstorming, polling) were used throughout the pre-activity introduction because numerous studies have demonstrated that active learning both engages students and enhances comprehension [31–33]. Moreover, active learning strategies are especially effective when working with students from disadvantaged backgrounds [34]. Instructors specifically highlighted the definition of a bioadhesive, the different mechanisms of adhesion [35], how bioadhesives can be modified for biosensor and tissue engineering applications [2], and how to use standard mechanical testing methods from the American Society for Testing and Materials (ASTM) to test bioadhesives [36]. These learning objectives were highlighted since they would cumulatively give students the necessary tools to engineer bioadhesives for diverse applications.

In the second stage, students planned and executed the IBL bioadhesives activity. The activity was modified from a previously published module for undergraduate, graduate, and postgraduate trainees [29]. While adapting the activity, we emphasized the following scientific literacy categories from Next Generation Science Standards (NGSS) for middle school students [30]: (1) asking a scientific question, (2) developing an experiment to answer the question, and (3) analyzing results with basic statistical techniques. To do so, instructors started the activity by facilitating a student-led discussion about the goals of the activity, independent variables of interest, and quantifiable output measurements. Students were then divided into teams of 3-4 students to complete the hands-on activity. Each team was provided with the materials listed below (**Materials Preparation and Software**) to test how the drying time of a bioadhesive will affect its adhesive strength. Under the supervision of instructors, students adhered leather chamois strips together with multiple bioadhesives (*i.e.*, gelatin and cyanoacrylate), then used a lap-shear testing configuration, modified from ASTM 2255-05, to quantify adhesive strength. Teams reported their results in real-time using a Microsoft Excel spreadsheet and worked with instructors to analyze their data with basic statistical techniques.

The final stage of the module included team summaries of their results, an open discussion of bioadhesives, and post-test/survey assessments. To start the discussion, each team was asked to give a brief summary of their findings and describe how their conclusions may be applied to real-world engineering challenges with bioadhesives. Team-based discussions were included in the activity as an equitable and inclusive way to promote student learning [37,38]. After these summaries, instructors prompted the entire group with questions relating directly to the results of their activity (*e.g.*, Which adhesive was stronger? Why?) and more open-ended questions that challenged students to think about real-world applications of bioadhesives. After the guided discussion, students were encouraged to ask any questions they had about the activity, bioadhesives, and careers in STEM. To conclude the module, students were given a post-test and post-survey to assess learning gains and changes in attitudes towards STEM, respectively.

Materials Preparation and Software

Instructors provided students with metal spatulas and a heat gun or hair dryer, which were brought from their home institutions, to complete the module. It was assumed that all students had access to a ruler and a pen. We did not assume that all students had access to a device with a video camera (*e.g.*, smartphone), so instructors provided their smartphones to groups who didn't have access to a device with a video camera. Module-specific materials were purchased from Amazon (Seattle, WA) based on those previously used by instructors at Cooper Union for engineering education modules [29]. Each item is listed below by name and Amazon Standard Identification Number (ASIN):

- Synrroe Nitrile Gloves (x2 sets per student) [**ASIN:** B08616G8F5]
- Knox Unflavored Gelatin [**ASIN:** B001UOW7D80]
- Gorilla Gel Super Glue [**ASIN:** B08FXWWMCM]
- Car Nature Chamois Real Leather Washing Cloth Cleaning Towel Wipes Clean Cham H88 [**ASIN:** B06XNPFDK3]
- Plastic Tag Fastener Snap Lock 3” Pin [**ASIN:** B074W3V1KD]
- Dr. Meter Backlit LCD Display Electronic Balance Digital Hanging Scale with Rubber Paint Handle [**ASIN:** B07FR6M7M9]

Gelatin and Gorilla Glue (*i.e.*, cyanoacrylate) were chosen as bioadhesives for this module because they can adhere through distinct mechanisms [35]. Cyanoacrylate, an FDA-approved bioadhesive for surgical wound closure [39], adheres through mechanical interlocking. Gelatin is an easily tunable and biocompatible bioadhesive [40], whose mechanism of adhesion can vary based on the presence of a crosslinking agent. If a crosslinking agent is present, the crosslinked gelatin can adhere to protein-rich surfaces (*i.e.*, leather chamois) through chemical interactions. Without a crosslinking agent, gelatin adheres via mechanical interlocking. Bioadhesives were adhered to chamois. Students used a lap-shear configuration that mimics the American Society for Testing and Materials (ASTM) 2255-05 testing protocol to quantitatively test the adhesive strength of these bioadhesives [36].

Instructors prepared several materials prior to the module. Gelatin was prepared as a 5% (w/v) solution at Cooper Union and transported as a solidified cube in a plastic bottle. Chamois were cut into 2x3 cm rectangles and half of the chamois were strung with safety ties. Lastly, a Microsoft Excel spreadsheet (Microsoft, Redmon, WA) was prepared so students could record their lap-shear testing data in real-time and analyze the data as a group. Data was recorded and analyzed on a laptop provided by the instructors.

Activity Execution

For the first stage of the module, students completed a pre-test/survey then participated in a pre-activity exercise. The pre-test was used to measure preliminary technical knowledge about bioadhesives (**Table 1**) and the pre-survey was used to measure attitudes towards STEM (**Table 2**). Instructors then introduced students to fundamentals of bioadhesives and their real-world applications in a pre-activity exercise. At the end of the session, instructors facilitated a discussion about independent variables that could impact the strength of a bioadhesive, including chemical composition, drying time, etc. Finally, instructors worked with students to choose which independent variable of interest would be tested in their activity and how students could test the impacts of these variables on adhesive strength. Due to time constraints, groups decided to use bioadhesive drying time as an independent variable and develop hypotheses.

For the second stage, students were divided into teams of 3-4 students to carry out the hands-on IBL activity. Each team tested two types of bioadhesives: gelatin and cyanoacrylate. Gelatin was prepared by instructors at a concentration of 5% (w/v) and cyanoacrylate was used at the manufacturer concentration. Students used these two bioadhesives to adhere leather chamois strips. Leather chamois strips were chosen because they have a rough, protein-rich surface, which could allow for adhesion through chemical interactions or mechanical interlocking. Since we did not conduct the activity in a laboratory space, we did not include a crosslinking agent with our gelatin bioadhesive; thus, gelatin and cyanoacrylate adhered through a mechanism of mechanical interlocking. Prior to distributing chamois, instructors threaded them with a plastic safety tie for mechanical testing. Students then marked the chamois with a horizontal line 0.5 cm from the bottom of the strip, on the opposite side as the safety tie. This line marked the lap joint area for bioadhesive testing (**Figure 1A**). Students applied a constant volume of either of the bioadhesives to the lap joint area, then adhered two chamois together at the lap joint. To vary the drying time, students briefly applied heat using a hairdryer, then let samples dry at room temperature for up to 30 min.

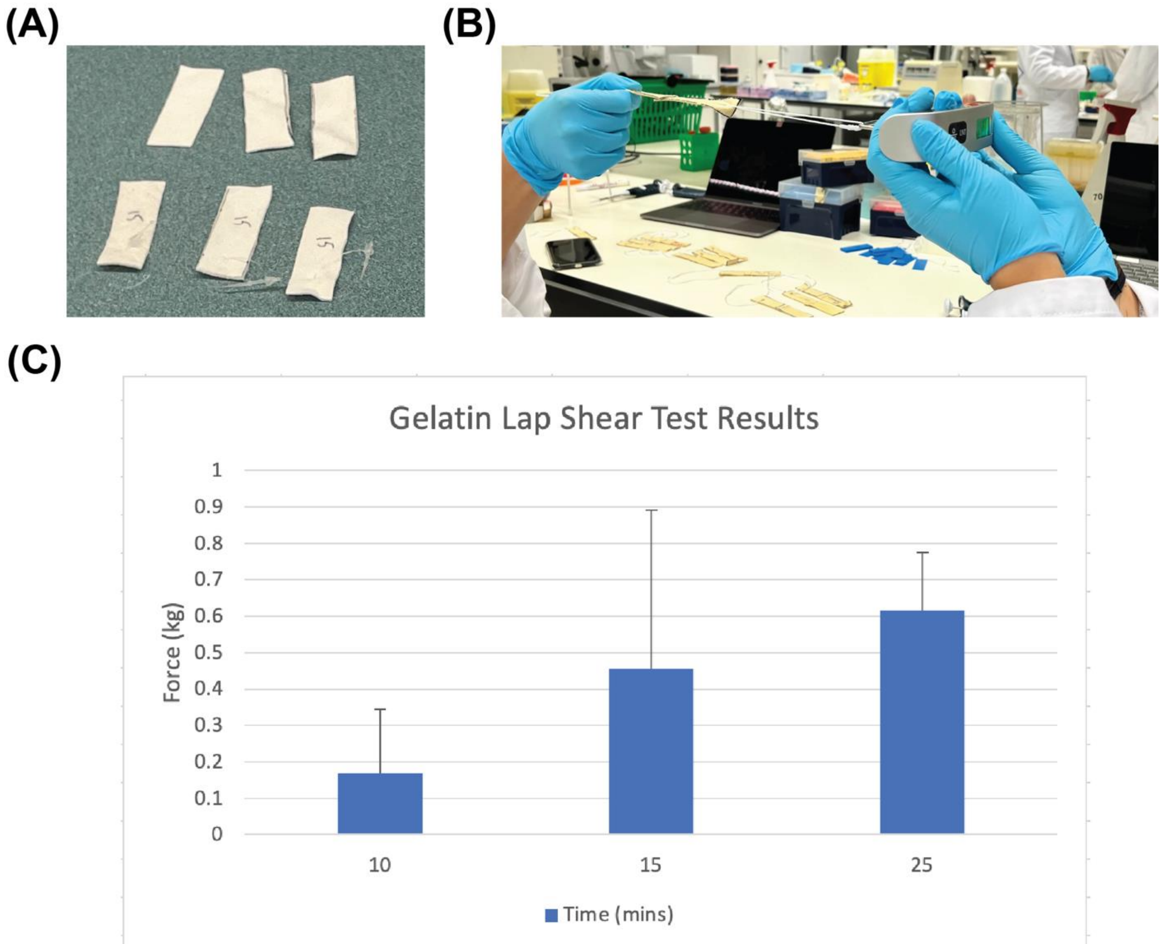

***Figure 1. Representative bioadhesive testing procedure and student data demonstrating successful adhesion of chamois leather strips and lap-shear mechanical testing. (A)** Leather chamois strips with plastic safety ties. **(B)** Example of lap-shear mechanical testing procedure using a luggage scale to measure force. **(C)** Graph of average force to failure for gelatin bioadhesives over different drying times. Graphs were created live during the activity using student-generated data.*

Table 1. Pre/post-test questions to assess technical knowledge.

Question Number	Question	Answer
TQ1	What is a bioadhesive?	**Keywords: tissue, sealant, wound healing, glue**
TQ2	How does a bioadhesive work?	A. Mechanical interlocking B. Chemical bonding **C. Both A and B** D. None of these
TQ3	Name a bioadhesive glue that can be used for tissue repair.	**Keywords: cyanoacrylate, gelatin, chitosan, bovine serum albumin**
TQ4	What is one application for a bioadhesive?	**Keywords: wound dressing, joining tissue, sealing leakage, healing tissue, fixing tissue, drug cell delivery**
TQ5	How do you test the strength of a bioadhesive?	**Keywords: pulling, pushing, bending, breaking, tearing, breaking force**

As samples completed their experimental drying times, students tested their samples using a lap-shear setup that mimicked ASTM 2255-05 [36]. For the setup, one team member manually held a digital luggage scale and connected the top chamois to the luggage scale via the plastic safety tie. To quantifiably test the samples, another team member was instructed to pull the bottom chamois until failure in a constant, steady fashion, while a third team member recorded the force reading using a device with a video camera (*e.g.*, smartphone) (**Figure 1B**). To teach students about reproducibility and to allow for statistical analysis, teams tested each condition in triplicate. Teams collected data on a Microsoft Excel spreadsheet, then worked with instructors to analyze results, generate graphs, conduct basic statistical analyses, and draw conclusions (**Figure 1C**).

In the third stage of the module, students participated in a group post-activity exercise, then completed a post-test/survey. To start the discussion, teams presented their experimental design, results, and contextualized their results in real-world applications of bioadhesives. After all groups had presented, instructors guided the entire group through a broader discussion of bioadhesives and answered any questions. At the end of the discussion, students completed a post-test and post-survey to evaluate how the activity affected their understanding of bioadhesives and attitudes towards STEM, respectively.

Student Outcomes

There are 50 middle school students in the New York City chapter of YES, and 98% of the students in this program identify as Black/African American or Latino/Hispanic. Thus, our cohort consisted almost entirely of individuals who are underrepresented in STEM by race/ethnicity. This choice was made purposefully, since focusing outreach efforts on individuals who are traditionally underrepresented in STEM based on race, ethnicity, gender, sexual orientation, socioeconomic

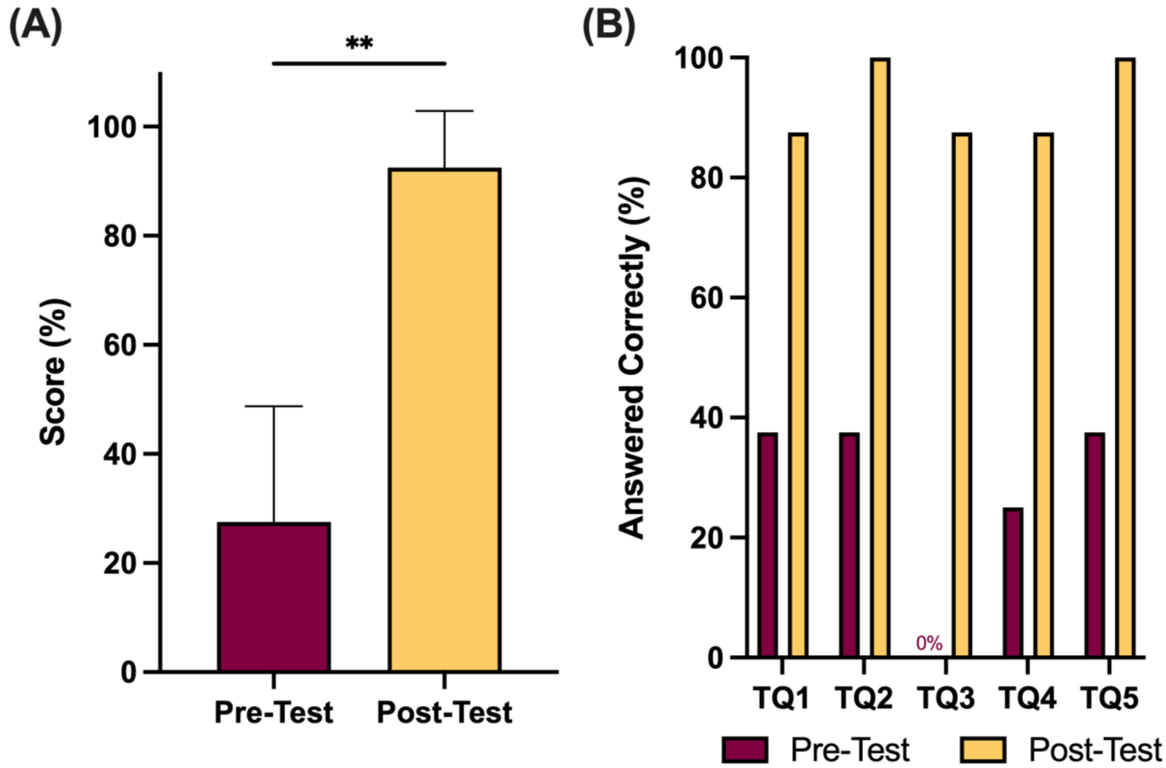

Figure 2. Students demonstrated significant learning gains after completing the IBL bioadhesives outreach module. (A) *Average student pre/post-test scores. ** = p < 0.01.* ***(B)*** *Percentage of students who answered individual questions correctly on pre/post-test assessments.*

status, etc., is especially important for diversifying STEM fields [20–22]. Approximately 12 of these students participated in our STEM outreach module and all were asked to provide a completed Parental Permission Form. Only paired tests/surveys submitted by students with completed Parental Permissions Forms were used in the presented analysis. This study was approved by the Cooper Union Institutional Review Boards (IRB).

Students in the cohort were given pre- and post-tests to evaluate learning gains resulting from participating in the IBL bioadhesives outreach module. Eight students (n=8) participated in the pre/post-test assessment. The pre/post-test consisted of five questions, composed by the authors, to test student understanding of bioadhesives, their applications, and how to mechanically test them (**Table 1**). Free response questions were scored using keywords. The average pre/post-test scores were compared using a Wilcoxon signed-rank test (α=0.05). All statistical analyses were conducted using GraphPad Prism software Version 9 (GraphPad, San Diego, CA).

Pre/post-test results showed significant score increases from 27.5% on the pre-test to 92.5% on the post-test **(Figure 2A)**. Additionally, the percentage of students who correctly answered each question was greater in the post-test than the pre-test **(Figure 2B)**. This was particularly striking for TQ3, which asked students to name a bioadhesive glue that can be used for tissue repair. No students answered this question correctly on the pre-test, yet 87.5% answered correctly on the post-

Table 2. Pre/post-survey questions to assess attitudes towards STEM.

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.

test. These increased post-test scores demonstrate that our IBL bioadhesives outreach module effectively taught students the desired learning outcomes.

Students in the cohort were also given pre- and post-surveys to evaluate changes in their attitudes towards STEM resulting from participating in the IBL bioadhesives outreach module. Seven students (n=7) participated in the pre/post-survey assessment. The pre/post-survey consisted of four questions, composed by the authors, to assess whether students believed they currently use science and math, and whether they will use science and math in the future (**Table 2**). Questions were answered on a Likert scale of "Strongly Agree" to "Strongly Disagree". Numerical values were assigned to each response (i.e., 0 = "Strongly Disagree", 1 = "Disagree", 2 = "Neutral", 3 = "Agree", and 4 = "Strongly Agree"), and pre/post-survey responses were compared using a Wilcoxon signed-rank test (α=0.05).

Students in YES already had a strong inclination towards STEM, which was not significantly altered by participating in our IBL bioadhesives outreach module. At baseline, 42.7% of students agreed that they use science in everyday life (SQ1), 71.3% of students agreed that they used math in everyday life (SQ2), 42.7% of students agreed that they would use science and math in everyday life after finishing school (SQ3), and 71.3% of students were interested in a career in science or math (SQ4) (**Figure 3**). The percentage of students agreeing to each post-survey question differed slightly from the pre-test; however, none of these changes were statistically significant. Of note, one student who indicated that they would not be interested in a career in science or math in the pre-test answered in the post-test that they would be interested in career in science of math.

Discussion and Conclusion

Bioadhesives are a promising solution to wound healing, hemostasis, and tissue repair [5]; however, diverse teams of scientists are required to advance this field from repairing tissues to regeneratively healing tissues [15–17]. To the authors' knowledge, there are no published modules to teach principles of bioadhesives to K-12 students. The failure to introduce diverse, young students to bioadhesives represents a significant gap in the field of bioadhesives because it may limit the advances made to this field. To address this gap, we previously developed and validated an inquiry-based learning (IBL) bioadhesives module to teach undergraduate, graduate, and postgraduate trainees about how to design, engineer, and test bioadhesives [29]. This module promoted significant learning gains and significant improvements in scientific literacy for all

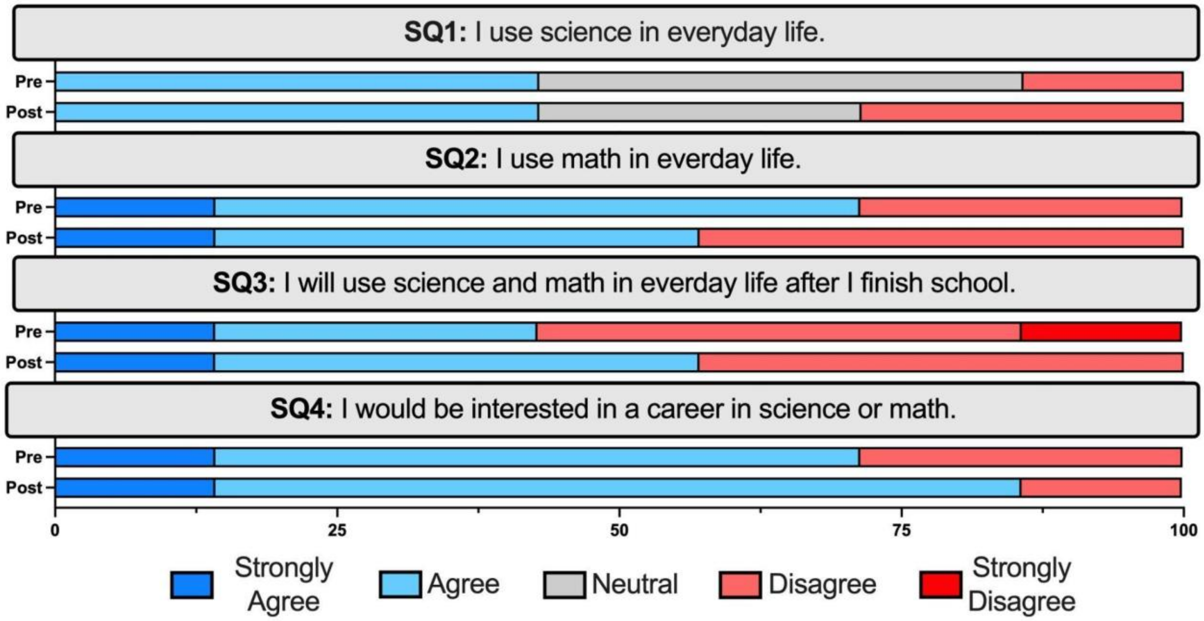

Figure 3. Students had high baseline interest in STEM, which did not significantly change after completing the IBL bioadhesives outreach module.

trainees; therefore, the goal of this study was to adapt and deploy this module for K-12 outreach. We hypothesized that this IBL bioadhesives module could effectively teach middle school students in YES principles of bioadhesives. Introducing students from underserved communities to new areas of STEM may help keep them excited about STEM and encourage them to pursue careers in STEM fields.

Pre/post-test assessments demonstrated that students experienced significant learning gains of 65 points from participating in our IBL bioadhesives outreach module. Moreover, the percentage of students who answered each question correctly increased by at least 50% from the pre-test to the post-test, indicating strong learning gains across all tested topics. These learning gains surpassed those experienced by undergraduate, master's and PhD/postdoctoral trainees completing our more complex IBL bioadhesives module [29], which was expected since middle school students would likely have never been exposed to bioadhesives before. Moreover, these learning gains were comparable to those experienced by freshman engineering students [41,42] and middle school students [28] completing IBL laboratory modules. These significant learning gains demonstrate that this IBL bioadhesives outreach module effectively teaches students principles of bioadhesives.

Pre/post-surveys demonstrated that students did not experience significant improvements in their attitudes towards STEM from participating in our IBL bioadhesives outreach module. These results were not surprising because the students selected to participate in YES are high-achieving and have preexisting STEM interest, as demonstrated by our pre-survey results. Also, there has been a longstanding partnership between the Icahn School of Medicine at Mount Sinai**,** Cooper Union**,** and YES, which has allowed these students to regularly participate in a variety of STEM activities. Lastly, the number of students participating in our study was small (n=8), so the study was likely underpowered to detect small differences in attitudes towards STEM. One noteworthy observation from SQ4 was that one additional student indicated that they would be interested in a career in science or math after completing our module, which suggests that this module can spark student interest in STEM. However, future studies with larger cohorts of students who have less STEM exposure will be required to determine if this IBL bioadhesives module can effectively enhance student attitudes towards STEM.

One limitation of this study is that we do not compare the learning gains from our IBL bioadhesives module to the learning gains from a traditional lecture on bioadhesives. There are numerous critiques of traditional learning, in which teachers provide instruction through lecture [43], such as creating power imbalances, limiting student engagement, and promoting superficial learning [44,45]. IBL, in which students collaboratively construct knowledge during their learning [46], is one pedagogical model to overcome these challenges. The efficacy of IBL in STEM was rigorously demonstrated with the Promoting Inquiry in Mathematics and Science Education Across Europe (PRIMAS) Project [47]. This study, conducted at 14 institutions in 12 European countries, showed that IBL fostered superior outcomes than traditional learning for students at the primary and secondary education levels. Given this strong evidence on behalf of IBL in STEM, this study did not aim to demonstrate that our IBL module was superior to traditional learning. Rather, the aim of our study was to evaluate an IBL bioadhesives module and disseminate the methods for educators to employ with local outreach organizations.

Developing simple, effective, and inexpensive STEM modules is a way that educators can help combat some diversity, equity, and inclusion (DEI) challenges facing STEM fields. K-12 outreach has been considered an important activity for enhancing student participation in STEM [18,19]. Hands-on outreach modules are effective for teaching principles of biomaterials because they connect theoretical concepts to practical applications [23]. When developing hands-on outreach modules, it is important to recognize that communities of individuals who are underrepresented in STEM based on socioeconomic status likely have limited access to the resources necessary to complete STEM modules [21]. Thus, our module, which effectively taught STEM principles with inexpensive materials, allowed for easy deployment to underserved communities. Teaching these students about principles of STEM at a young age may spark their interest in STEM and encourage them to pursue careers in STEM fields. We recognize that one module cannot be the panacea for resolving systemic DEI issues in STEM; however, the IBL outreach module presented is one example of an inexpensive activity with appropriate technical rigor to teach students about STEM.

Safety and Hazards

Instructors should uphold appropriate laboratory safety throughout the activity. Students participating in our IBL bioadhesives outreach module were provided with gloves to wear when handling bioadhesives. Cyanoacrylate dries quickly and can be difficult to remove from surfaces; therefore, students were advised to take care when applying this bioadhesive. During biomechanical testing, the chamois strips will abruptly detach as the bioadhesives reach their limits, so students were warned about this prior to mechanical testing. After completing the module, students discarded the tested chamois strips into the garbage and washed their hands thoroughly.

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