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Incorporating Diversity, Equity, and Inclusion Content Into Bioengineering Curricula: A Program-Level Approach

Diversity, equity, and inclusion (DEI) are interconnected with bioengineering, yet have historically been absent from accreditation standards and curricula. Toward educating DEI-competent bioengineers and meeting evolving accreditation requirements, we took a program-level approach to incorporate, catalog, and assess DEI content through the bioengineering undergraduate program. To support instructors in adding DEI content and inclusive pedagogy, our team developed a DEI planning worksheet and surveyed instructors pre- and post-course. Over the academic year, 74% of instructors provided a pre-term and/or post-term response. Of responding instructors, 91% described at least one DEI curricular content improvement, and 88% incorporated at least one new inclusive pedagogical approach. Based on the curricular adjustments reported by instructors, we grouped the bioengineering-related DEI content into five DEI competency categories: bioethics, inclusive design, inclusive scholarship, inclusive professionalism, and systemic inequality. To assess the DEI content incorporation, we employed direct assessment via course assignments, end-of-module student surveys, end-of-term course evaluations, and an end-of-year program review. When asked how much their experience in the program helped them develop specific DEI competencies, students reported a relatively high average of 3.79 (scale of 1 = "not at all" to 5 = "very much"). Additionally, based on student performance in course assignments and other student feedback, we found that instructors were able to effectively incorporate DEI content into a wide variety of courses. We offer this framework and lessons learned to be adopted by programs similarly motivated to train DEI-competent engineering professionals and provide an equitable, inclusive engineering education for all students. [DOI: 10.1115/1.4063819]

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Introduction

Bioengineering and biomedical engineering are interdisciplinary technical fields that apply engineering principles toward the betterment of human health. Bioengineering intersects principles of diversity, equity, and inclusion (DEI) through technical and interpersonal content topics such as inclusive design, bioethics, and inclusive professionalism.

While DEI topics have historically been absent from engineering curricula and accreditation standards, recent changes in the ABET accreditation criteria reflect the importance of educating students on these topics. In 2019, ABET added DEI-relevant student learning outcomes, including the ability to create inclusive environments and recognize ethical and professional responsibilities while taking global, economic, environmental, and social contexts into consideration [1]. Pilot criteria established by ABET in 2023 expand on these requirements by including a curricular professional educational component that "promotes diversity, equity, and inclusion awareness for career success". Additionally, the pilot criteria call for faculty to "demonstrate awareness and abilities appropriate to providing an equitable and inclusive environment for its students, and knowledge of appropriate institutional policies on diversity, equity, and inclusion [2]."

A variety of approaches could be used to address these new ABET criteria [3], but incorporating DEI into curricula can be difficult for a variety of reasons, such as instructors' lack of adequate pedagogical training and prior exposure to DEI topics during their education [4] as well as an ongoing need for instructor training and support [5]. This work aimed to educate DEI-competent bioengineers and meet evolving ABET requirements by improving DEI content included in departmental curricula. Toward meeting these goals and addressing established challenges in adding DEI content, we supported and collaborated with instructors, cataloged DEI content in departmental curricula, and assessed student feedback and effectiveness of curricular DEI content. Unique from previously published studies that examine an individual course or a small subset of courses to teach DEI content [6–12], this work presents a framework and lessons learned on a program-scale.

Methods

Overview. Throughout the 2020–2021 academic year, instructors were provided with a "DEI planning worksheet" that contained wide-ranging examples of DEI curricular incorporation and were offered individualized assistance in creating and/or implementing DEI content. The worksheet also contained strategies for additional ways to address DEI in courses, including inclusive pedagogical approaches. Departmental curricular DEI content was cataloged by surveying instructors pre- and post-term. At the end of the academic year, undergraduate juniors and seniors were surveyed about their program experience, including perceptions of departmental inclusiveness and development of DEI skills and/or knowledge. During the academic year, a subset of DEI curricular interventions was additionally assessed by measuring student DEI knowledge demonstrated in assignments and exams.

Development of the Planning Worksheet.

Initiation and Implementation. The DEI planning worksheet (See Supplemental Materials on the ASME Digital Collection, S1) was first created by the departmental committee chairs of the Justice, Equity, Diversity, and Inclusion (JEDI) Committee and the Curriculum Committee. Disseminated as a planning tool, the overall goal of the worksheet was to encourage instructors to consider how they would intentionally build an inclusive learning environment, especially in light of the COVID-19 pandemic and online learning. The worksheet aimed to encourage instructors to critically assess their own course content, pedagogy, and classroom practices to improve student outcomes and experiences, with a focus on students' perceptions of inclusivity. Designed to be multifaceted, the worksheet encouraged instructors to incorporate: (1) instructor leadership on inclusivity, (2) inclusive pedagogy, including for online learning environments, (3) student feedback on classroom inclusivity, (4) student training in professional development skills, and (5) modifications to course materials to include work from historically excluded and underrepresented scientists, clinicians, and scholars [13,14] and/or clinical or design considerations in biomedical engineering to address health inequity and/or global health. Instructors were not required to incorporate all five components but were asked to provide information for each of these areas.

Iterative Modifications on Worksheet. Toward continual improvement of the worksheet tool, an expanded team was formed, which included representatives from the departmental Accreditation and Continuous Improvement (ACI) Committee, Curriculum Committee, and JEDI Committee and a consultant from the University of Washington Office for the Advancement of Engineering Teaching and Learning (ET&L). Based on instructor feedback on the DEI planning worksheet, the team met weekly to improve on the DEI worksheet. The collaborative work between the three committees fostered integration of considerations regarding curriculum, inclusive pedagogy, intentional reflection of course content in relation to DEI content, and identifying areas of continuous improvement. In subsequent iterations, the team added more resources for instructors, updated examples, and improved organization and readability of the worksheet. Toward decreasing the perceived time burden for instructors to engage in this work, subsequent worksheet versions included links to easily adaptable lessons, slides, and course content, as well as a matrix with ideas for potential JEDI-related topics, themes, history, ethics, and context for each course. Instructors were also offered 1:1 consultations to support their efforts, collaborate on curriculum development and assessment, and answer questions.

Post-Term Surveys of Faculty Instructors. In our undergraduate program, one key component of the continual improvement process is asking instructors to complete a "Course Improvement Memo" at the end of the term (full survey included in the Supplemental Materials on the ASME Digital Collection, S2). In this memo, instructors discuss which aspects went well in the course and which need improvement. Instructors document any changes made in response to departmental committee input or student feedback and discuss improvement plans for the next offering. In this work, we incorporated questions into the existing Course Improvement Memo to collect data on DEI content and inclusive pedagogy. We also used the post-course surveys to obtain instructor feedback on the usefulness of the worksheet planning tool and any suggestions for improvement.

From pre- and post-term instructor responses, DEI content was grouped into key competencies and categorized per course for the entire undergraduate bioengineering core curricula. Notably, any voluntary, ungraded, supplemental activities or content (e.g., a suggested reading or video) was not considered DEI content for cataloging purposes because we characterize this content as co-curricular (but not curricular).

Student Assessment Via Annual Program Review Feedback Sessions. Each spring, a consultant from our institution's Office for the Advancement of Engineering Teaching and Learning (ET&L) conducts separate program assessments with bioengineering junior and senior cohorts. Students identify program strengths and make suggestions for improvement. Program review questions evolve each year and are designed around current issues, with input from multiple departmental stakeholders.

The program feedback session for the juniors and seniors was held near the end of the academic year, specifically at the end of a core junior class meeting and a Capstone seminar class meeting, respectively. Facilitated by our ET&L consultant, feedback was gathered via an online individually-based anonymous survey (full survey included in the Supplemental Materials, S3). Students unable to attend the synchronous feedback session were given multiple additional opportunities to complete the survey. Of the junior cohort, 60% provided responses (44/74 students). Of the senior cohort, 55% provided responses (40/73). The survey asked for input on teaching practices to continue upon return to in-person instruction, feedback on student perception of the inclusiveness of our department, and their development of skills/knowledge related to DEI.

Toward our interest in establishing an inclusive and welcoming environment for all students, we wanted to investigate if our students' experiences in our department were different depending on various demographic factors and personal identities. Open-ended, optional demographic questions were therefore included as part of the survey (Supplemental Materials, S3). Students were considered historically excluded and underrepresented (HEU) based on racial and/or ethnic identity if their responses indicated that they were Black, African American, Latino, Chicano, Pacific Islander, and/or multiracial while including one of the aforementioned races/ethnicities. Students were considered non-HEU if their responses indicated that they were white, Caucasian, Asian American, and/or mentioned specific countries of origin in Europe or Asia (e.g., "Chinese").

Student Assessment Via Course Assignments and End-of-Quarter Surveys. In addition to program-level assessment, this work also involved assessment of student experience and/or performance in individual courses after DEI content intervention. These assessments were in the form of an anonymous end-of-module voluntary survey, comparative assessment of lecture-presented content at different stages of the course (short-form homework question, then exam question), and long-form paper assessment of a self-directed investigation related to the students' research topic. We deliberately selected a wide variety of courses (lab and lecture, undergrad and graduate), DEI topics (inclusive design, systemic racism, bioethics), learning mechanisms (hands-on, didactic presentation, individualized feedback, self-directed), and assessment mechanisms (survey, short-form homework question, exam questions, long-form paper assignment) for inclusion in this work to demonstrate numerous paths for implementation and assessment of DEI content in bioengineering curricula.

Human Subjects. Assessment of this work involved results from student assignments, anonymous program reviews, and end-of-course surveys. The University of Washington Human Subjects Division determined that the activity of human subjects research described in this paper qualifies for exempt status (IRB ID: STUDY00013973).

Results

Adoption of Worksheet Tools, Curricular Modifications, and Inclusive Pedagogy by Instructors. Over the 61 total courses offered in the academic year, 74% of instructors provided a pre-term response and/or a post-term response. Specifically, 44% of instructors (27 courses) provided both pre- and post-term responses, 30% (18 courses) provided either pre-term or post-term, and 26% (16 courses) did not respond.

Incorporation of Diversity, Equity, and Inclusion Content. Of responding instructors, 91% described at least one specific, substantial improvement to the DEI curricular content in their pre- and/or post-term responses. Some representative instructor responses on pre- or post-term responses include:

> "Every year, the students are assigned presentations of a paper by teams. In their presentations, they start by presenting a cancer type to frame the relevance of the paper. This year, they were asked to research ALL the demographics of the cancer incidence and treatments, i.e., by gender, race, and country… I believe that this exercise raised a lot of awareness among students about cancer treatment inequalities across various demographics and what solutions they, as bioengineers, can provide in the future."

> "I have added a module to learn about and discuss biases in grant awarding and biases in funding of grants addressing health inequity."

> "I will both highlight research inputs from female and BIPOC scholars as I present work. Also, I will talk about the importance of input from communities in design (e.g., understanding needs and desires of people with disabilities when designing technologies aimed to alter human abilities)."

> "I added a new lesson on implicit bias to the second week of the quarter and short reflection assignments on their team working performance, including efforts towards inclusivity."

Of the 9% of responding instructors who did not indicate any specific, substantial improvements to the DEI curricular content, we obtained a wide range of responses indicating varying perspectives and apparent buy-in on adding DEI content to bioengineering courses. For example, a subset of instructors indicated that they made minor course modifications to provide DEI content that students can investigate on their own time, but that the content did not use class time or contribute to the course grade. Additionally, a subset of instructors indicated no interest/availability in adding DEI content to their courses. Our work ultimately focused on supporting and assisting instructors who were interested in improving the DEI content in their curricula, and thus we chose not to engage with the

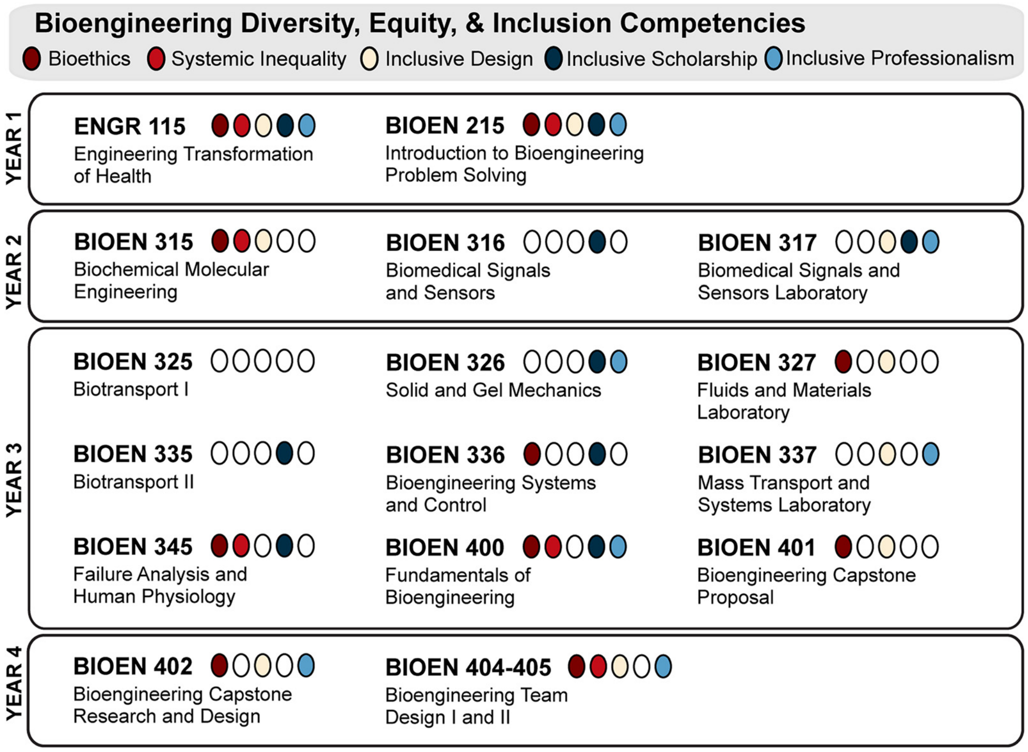

Fig. 1 Diversity, equity, and inclusion curricular incorporation in undergraduate bioengineering courses. The DEI-related content in each course was cataloged among the five DEI competencies identified (bioethics, systemic inequality, inclusive design, inclusive scholarship, and inclusive professionalism). Bioengineering undergraduate degree requirements include an introductory class in year one (choice of either ENGR 115 or BIOEN 215), bioengineering technical core in years two and three, and capstone design (choice of either BIOEN 401-402 or BIOEN 404-405). Senior electives and courses not taught by bioengineering faculty are not depicted.

subset of instructors who were uninterested in adding this content to their course.

Incorporation of Inclusive Pedagogy. Of responding instructors, 88% mentioned incorporation of at least one specific, substantial change toward inclusive course pedagogy. Of the instructors who submitted responses, 72% indicated that they included an updated inclusivity statement in their syllabus, 63% were self-educating on DEI topics using the recommended materials, 54% added recommended inclusivity questions (questions included in Supplemental Materials on the ASME Digital Collection, S1) to their course evaluations, and 44% devoted time to discussing inclusivity on the first day of class. For courses that were offered remotely, 58% used polling and/or breakout rooms, 44% used a mechanism for voluntary online discussion, 47% used modules to help students navigate content, 26% pre-recorded lecture videos to free up synchronous class time, and 57% uploaded recorded lectures for asynchronous learning.

Instructor Feedback on the Planning Worksheet. Instructors were asked for feedback on the DEI worksheet. The majority of instructor feedback (82%) was positive. One common theme was that the worksheet initiated thinking about ways to enhance their course's DEI content and/or inclusive pedagogy. For example, some representative instructors said,

> "[The] best part is that it gets us to think about these topics intentionally when we are laying out the course… Getting started in the right way (first day of class) by addressing these topics is key, it sets the stage."

> "You put it front and center in my mind. Even though this stuff is already very much on my radar, it made me even more mindful of that."

> "It was good to think about it ahead of the quarter and make changes before the course began."

Another theme of positive instructor feedback was that the form's examples helped them brainstorm what content might be appropriate in their course. Representative comments include,

> "The form allowed me to think about different options available and give me some good ideas of what to include."

> "It helped me to see what I could do given the type of course I run."

While the majority of instructor feedback was positive, some instructors (18%) did not find the worksheet helpful, either because they used other resources or did not find it as applicable for their non-lecture (lab or seminar) course. For example, representative comments include,

> "I looked up resources myself to augment my class."

> "Great information, for sure! Just not the most relevant to a seminar class."

Diversity, Equity, and Inclusion Curricular Changes. From the responding instructors who described at least one specific curricular incorporation of diversity, equity, and inclusion content, we grouped the bioengineering-related DEI content into five DEI competency categories:

- Bioethics—Addressing topics of health disparities, global health, human subjects, environmental ethics, or access to healthcare technologies.
- Inclusive Design—Application of universal and inclusive design principles to engineering problems.
- Inclusive Scholarship—Incorporating authors/scholars from historically marginalized and underrepresented groups.

- Inclusive Professionalism—Development of professional inclusive skills such as recognizing bias, interrupting microaggressions, or demonstrating inclusion in teamwork.
- Systemic Inequality—Explaining the connection between bioengineering and systemic racism, sexism, ableism, or other forms of oppression (e.g., health inequities).

Based on curricular improvements reported by instructors pre- and/or post-term, the DEI content was categorized per course and cataloged for the bioengineering undergraduate curricula (Fig. 1; for a more detailed catalog, See Fig. 1 available in the Supplemental Materials on the ASME Digital Collection.). Courses incorporated content that included on average approximately 2.5 DEI competencies. Notably, some courses found a way to incorporate all five DEI competencies (e.g., Introduction to Bioengineering Problem Solving), while others (e.g., Biotransport I) incorporated zero or one competency. Interestingly, the introductory and upper-division design classes tended to have the most DEI incorporation compared to the programs' intermediate core courses.

In this section, we provide examples and assessments of different DEI competency content incorporated into courses of varying size, topic, level, and format.

Systemic Inequality Content Incorporated Into Undergraduate Lecture- and Lab-Based Core Course. Bioengineering 345 "Failure Analysis and Human Physiology" is a 4-credit lecture- and lab-based core undergraduate course taken by third-year bioengineering undergraduates. In spring quarter 2022, the enrollment in this course was 65 students. In the lecture portion of the course, a single slide on disparities in heart failure was added to the introductory lecture on cardiac pump function. This single slide contained two graphics: one showing that African Americans have an increased cardiovascular disease-related mortality rate compared to other races [15] and one describing the pathways between structural racism and healthcare disparities in heart failure including seventeen examples related to unequal healthcare, residential segregation, state-sanctioned violence, and unequal employment [16].

To assess student learning on this topic, the following prompt was added to an assignment on cardiac anatomy and pathology,

> "Race, unlike sex, age, and ancestry, is not a biological variable that affects health outcomes. However, racial disparities in outcomes and burden exist for heart failure (among other diseases) in the United States, with Black Americans disproportionately affected due to structural racism. List 3 social inequities that lead to racial disparities in heart failure outcomes/burden, and for each, describe in ~40–60 words how the inequity leads to these disparities (at least ~120 words total). For more information on why race is not a biological variable: Teaching Diversity: The Science You Need to Know to Explain Why Race Is Not Biological [17]".

Complete, full-credit answers required: (1) correctly identifying a specific social inequity, (2) explaining the connection between structural racism and the social inequity, and (3) describing the connection between the social inequity and a specific racial disparity in heart failure burden or outcomes. Students correctly identified a wide range of social inequities caused by structural racism, including interpersonal racism by medical professionals, food deserts, and inequitable access to health insurance.

The most common mistake (51 out of 64 students) involved students missing the key connection between structural racism and a specific social inequity. For example, one student wrote,

> "Black Americans tend to live in lower-income areas in the U.S. which have worse access to healthy foods and fewer safe places to play outside or exercise,"

but did not explain how structural racism causes Black Americans to live in lower-income areas (e.g., racism in redlining and food access [18,19]). Ultimately, after reviewing the added lecture slide on structural racism and healthcare, students were able to provide substantive, partial answers, but only 20.3% of students (13 out of 64) provided a complete example without missing a key component. If the connection between the described social inequity and structural racism was not clearly described, the student was given personalized, descriptive feedback from the graduate teaching assistant.

Students were subsequently assessed on their understanding of this content in their midterm exam, where they were asked two questions. First,

> "In a few sentences, describe one example of how structural racism leads to racial disparities in heart failure burden/outcomes."

In their exam, 42 out of 65 students (64.6%) were able to describe a specific example of how structural racism leads to racial disparities in heart failure burden/outcomes without missing any key components. Notably, there was improvement in student performance between the homework assignment and the midterm exam; on the homework assignment, 20.3% of students described a clear connection between a specific aspect of structural racism and a specific social inequity whereas 64.6% were able to do so on the subsequent midterm exam.

In addition to questions with open-ended responses that were evaluated on a rubric, we added a closed-ended question that assessed a wide-spread and harmful misconception about race [20–22]. Students were asked a true/false question, "Race is a biological variable, and racial disparities in heart failure are caused by biological differences between races". Of the 65 enrolled students, 64 (98.5%) correctly answered "false", indicating that students understand that race is not a biological variable. While we do not have a quantification of students' understanding of this concept pre-intervention, we note that 98.5% of students demonstrating an accurate understanding that race is not biological is in stark contrast to other studies; for example, over 1 in 3 medical students believing that "Blacks' skin is thicker than whites'" [20].

These demonstrated competencies and improvement show promise that minor curricular changes (in this case, one lecture slide and one homework question) paired with formative feedback can be effective and impactful. In particular, as this course was lecture-based, enrolled 65 students, and had pre-existing technical curricular requirements that made it challenging to add additional content, we propose this intervention model may be translatable to many engineering courses with similar formats and constraints.

Inclusive Design Content Incorporated Into Undergraduate Core Lab Course. Bioengineering 337 "Mass Transport and Systems Laboratory" is a 2-credit laboratory course taken by third-year bioengineering undergraduates. In winter quarter 2022, enrollment was 65 students. New in 2022, the instructor added a module in which students utilized their engineering skills to support accessible play for children with disabilities via toy adaptation [23,24]. This module built on universal design and accessibility curriculum covered in the introductory bioengineering course BIOEN 215 (Introduction to Bioengineering Problem Solving) [25] and represented a partnership with HuskyADAPT, a student-driven community at the University of Washington which supports the development of accessible design and play technology [26,27]. Students were challenged to modify battery-powered toys to make them accessible to individuals with disabilities by installing a universal jack, so the toy could be activated by many different types of switches depending on users' needs. Before the lab, students were required to review background material, including the developmental importance of toys, an introduction to adapted toys as an example of inclusive design, a refresher on basic circuitry principles and electrical components, and tips on soldering. The lab was executed in one class session (2.5 h) and more details on the methodology, including the curriculum used, are described in Taylor & Mollica 2023 [28].

Working in teams of three, all students were able to successfully adapt their toys and install a universal jack in parallel with the existing activator switch. These toys were given to HuskyADAPT, who subsequently donated them to families, schools, and clinics. Beyond the social good of creating accessible play technology, students reported overwhelmingly positive feedback with this new module. At the end of the module, students were asked to participate in a voluntary survey about their experiences, and 82% of students submitted responses. Through 5-point Likert scale ratings, students reported that the toy adaptation module was an enjoyable experience (average = 4.8, standard deviation (SD) = 0.41) and helped them appreciate how engineering can have a direct, positive impact on people (average = 4.7, SD = 0.54) [28].

Bioethics (Health Disparities) Content Incorporated Into Graduate Cardiovascular Engineering Elective Course. Bioengineering 582/482 "Cardiac Bioengineering" is a 3-credit graduate-level elective course also available as a technical elective to senior undergraduates. The course is designed to present cardiovascular engineering content through didactic lectures and critical analysis of recent literature. To support development of self-directed inquiry skills in cardiovascular engineering, 60% of the total course grade is assessed from two papers on cardiovascular disease: the first on the current standard of care for the pathology and the second on current and emerging bioengineering approaches to study and treat the disease. The course instructor added a graded DEI-related component wherein students were instructed with the following prompt:

> "In each review, please include a discussion relevant to diversity and inclusion as it affects your topic. Perhaps your chosen cardiac pathology unequally affects people of different demographics. Or maybe there is inequity in access to adequate care. We also invite you to examine the academic labs contributing to research in the field; who makes up these research teams? We present this as an opportunity to explore the issues of diversity and inclusion within this field, from the medical as well as the academic perspective."

Of the 21 students enrolled in the course in autumn of 2021, the average score on the newly added DEI-component was 88.8% (3.55 out of 4, SD = 0.65) on paper 1 and 93.5% on paper 2 (3.74 out of 4, SD = 0.71). Papers contained a wide variety of discussion topics: (1) description of inequities in the disease incidence and/or outcomes by race, sex, ancestry, etc., (2) analysis of the contributors to health inequities such as systemic inequalities, genetics, lifestyle/environmental factors, etc., (3) discussion of access (or lack thereof) to bioengineered technologies, (4) analysis of the scientific and medical contributors/researchers to the disease of interest, (5) representation (or lack thereof) in clinical trials, and (6) inclusive design (or lack thereof) of computational frameworks, medical devices, and other medical solutions. The graduate teaching assistant provided individualized feedback on this section in each paper. Representative examples of instructional comments on papers receiving full credit include,

> "The analysis included in this section is manifold and brings together numerous sources to discuss the disproportionate impact of malaria on individuals in the Global South, both directly and indirectly. Information from these sources as well as the author's own thoughts and analysis are synthesized in a very compelling and eye-opening way."

> "Thorough analysis of the gaps still present between racial groups and its impact on the currently stated prevalence of atrial fibrillation. Could have included a discussion of disparities between available diagnostics/treatments, etc. in other geographical areas outside of the United States."

> "Thoroughly discusses considerations pertaining to access to care if bioengineered approaches, currently only studied in laboratories, were made available in the clinic, both with respect to multiple age groups and genders. A discussion of ethics related to bioprinting organ replacements is nicely weaved into this section supporting the arguments made."

In the first paper covering the disease of interest, papers receiving less than full credit on the DEI component commonly lacked discussion of the connection between the health disparity and systemic inequality. For example, the grader comment for a paper receiving a score of 1.5/4 was,

> "While there is a mention of disparities in prevalence between RCM (restrictive cardiomyopathy) between Caucasians and African Americans in the U.S., there is no designated discussion and analysis of diversity (ethnicity, income, gender, geographic region, etc.) and its impacts on RCM."

In the second paper on bioengineering approaches to study/treat the disease of interest, papers receiving less than full credit commonly included disease-related health disparities but lacked discussion of inequities in engineering, research, and design for bioengineered treatments. For example, the grader comment for a paper receiving a score of 3/4 was,

> "A thorough discussion [of health disparities] in terms of gender and race is included in the paper, however, this discussion was again more relevant for the first paper. Given the topic of this second paper being on currently studied bioengineering approaches, this second paper should have included a discussion about diversity and potentially ethical considerations focused on the research/clinical trial aspects of myocardial infarction."

Unique from the previous two example undergraduate courses, this graduate-level course involves substantial self-directed inquiry. In line with other course expectations, the emphasis of the DEI content addition was on student-directed analysis and direction rather than didactic delivery. Students were able to identify and describe an impressive breadth of DEI-related considerations on their topic of interest, including content that fit within bioethics, systemic inequality, inclusive design, and inclusive scholarship. We found that graduate and senior undergraduates in this course required minimal guidance from graders/teachers to self-investigate health disparities and inequities related to their disease of interest, ultimately earning 91.1% on average.

Student Experience and Feedback

Context for Annual Program Review Feedback Sessions. We designed the program review survey in light of our year-long work with facilitating instructors addressing DEI content in their courses. Besides asking for feedback on program-level initiatives and experiences, one main goal was to obtain feedback on student perceptions of inclusivity in the department and their development of a multitude of skills/knowledge related to DEI in our undergraduate program.

Teaching Practices. To obtain feedback on student perceptions of which inclusive teaching approaches were useful and should be

Table 1 Student recommendations for teaching practices to be maintained upon return to in-person instruction

Practices to continue	Instances, out of 44 respondents
Provide recorded lectures as a resource to review course content	23
Accessible office hours (using multiple modalities including Zoom and in-person)	23
Flexible due dates	8
Piazza online discussion boards (anonymous questions)	4
Video tutorials to supplement lectures	4
Poll everywhere	4
Flexibility in attending class synchronously	3
Open-note exams	2
Have a 24-hour window to take the exam	1
Have slides available before lectures	1

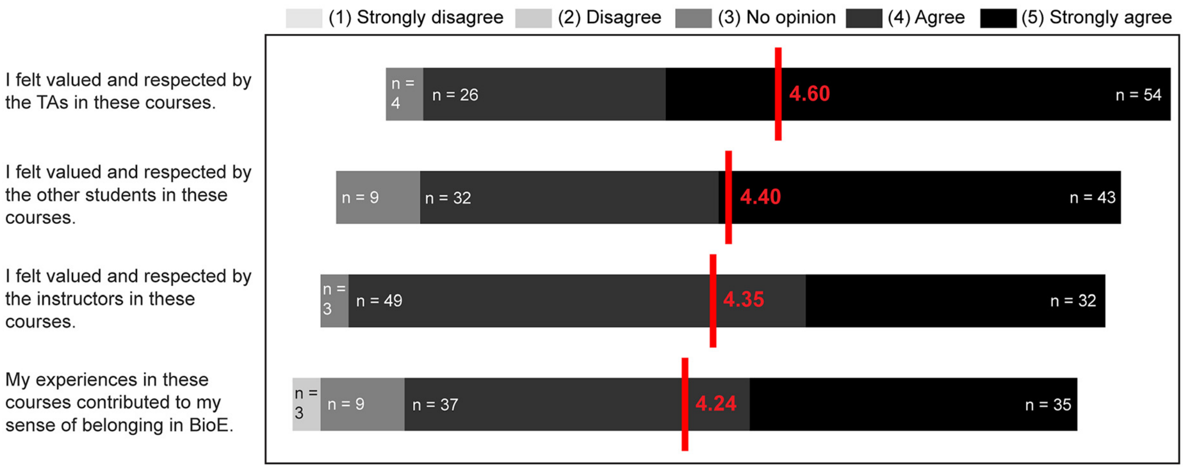

Fig. 2 Program review results from bioengineering juniors and seniors regarding course inclusivity, interactions with classmates and teaching teams, and sense of belonging. Participants (n = 84) responded on a Likert scale: 1 = strongly disagree (light gray) to 5 = strongly agree (black). Responses were plotted as a floating bar graph centered around their mean (vertical line and number). Questions were placed in the order of their average rating.

prioritized, we asked the students: "What teaching practices and tools would you suggest that bioengineering courses continue to use when returning to in-person instruction?" The major themes cited by students were (1) access to recorded lectures and (2) flexible and virtual office hours. All student recommendations are included in Table 1.

Inclusiveness and Climate. Students overall expressed feeling valued and respected in the bioengineering courses, with their course experiences helping to foster a sense of belonging in the program (Fig. 2). Students highly scored questions stating that they felt valued and respected by the teaching assistants (TAs) (average = 4.60, SD = 0.58), other students in the courses (average = 4.40, SD = 0.68), and instructors (average = 4.35, SD = 0.55). These responses suggest that overall, an inclusive environment was fostered by both the teaching team and fellow students. Although the majority of students (n = 72 out of 84) either agreed or strongly agreed that their experiences in the bioengineering courses contributed to their sense of belonging in the program (average = 4.24, SD = 0.79), nine students cited 'no opinion', and notably and concernedly, three students disagreed with this statement. Open-ended responses from students who disagreed did not provide insight into their experiences beyond mentioning disengagement due to online learning.

Diversity, Equity, and Inclusion Skills and Knowledge. Based on junior and senior responses in the annual program review, students noticed and appreciated the DEI content added to courses, including indicating to what extent their experience in the bioengineering program has helped them develop specific DEI knowledge and skills (Fig. 3). Out of the six DEI skill/knowledge areas, average student ratings were between "quite a bit" (rating: 4) and "very much"

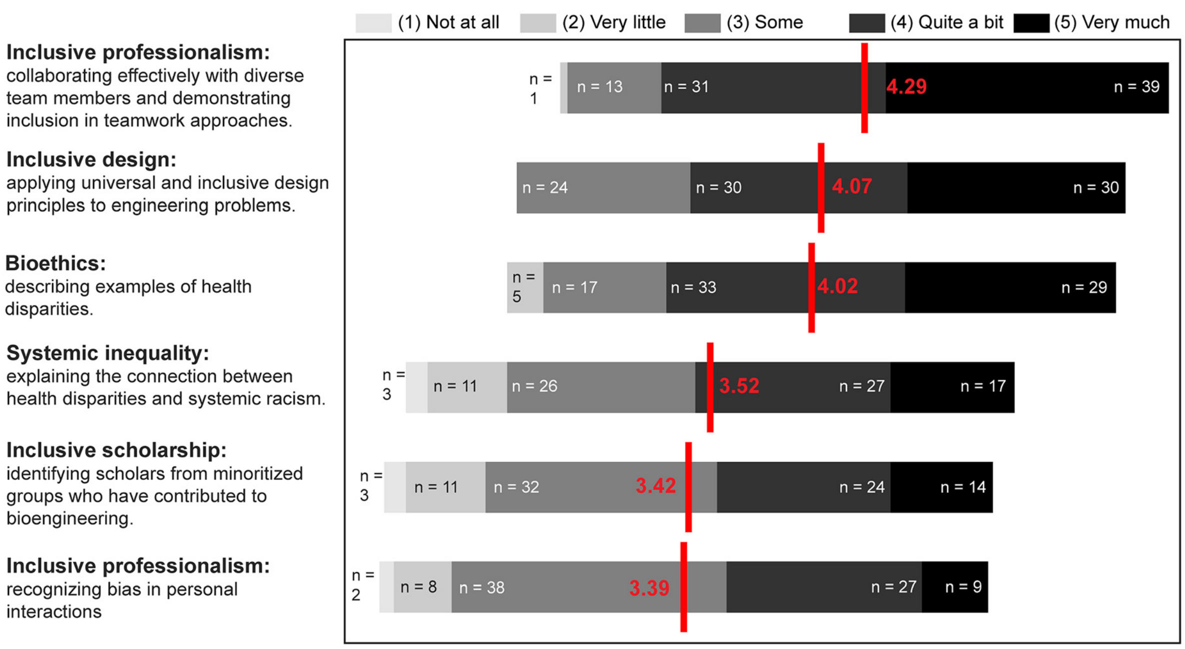

Fig. 3 Responses from juniors and seniors to "how much has your experience in the bioengineering program helped you develop each of these DEI skills/knowledge?" Participants (n = 84) responded on a Likert scale: 1 = Not at all (light gray) to 5 = Very much (black). Responses were plotted as a floating bar graph centered around their mean (vertical line and number). Questions were placed in the order of their average rating.

(rating: 5) for three areas. In response to how much the program helped them develop skills in "collaborating effectively with diverse team members and demonstrating inclusion in teamwork approaches", students responded with the highest rating (average = 4.29, SD = 0.77). The next highest-rated areas included "applying universal and inclusive design principles to engineering problems" and "describing examples of health disparities" (average = 4.07 and 4.02, SD = 0.80 and 0.89, respectively). In addition to relatively high average ratings for these knowledge/skills, only 2% of responses (6 out of 252) were "very little" and none were "not at all", indicating that all respondents experienced some knowledge/skill development in these areas.

For the remaining three DEI skills/knowledge areas, students responded less positively, with average ratings between "some" (rating: 3) and "quite a bit" (rating: 4). In response to how much the program helped them develop skills in "explaining the connection between health disparities and systemic racism", the average rating was 3.52 (SD = 1.07). The lowest-rated areas included "identifying scholars from minoritized groups who have contributed to bioengineering (average = 3.42, SD = 1.03) and "recognizing bias in personal interactions" (average = 3.39, SD = 0.89). Notably, in addition to ratings trending lower for these three knowledge/skills areas, some students (n = 2 or 3) responded with "not at all" (rating: 1) regarding how much the program helped them develop these knowledge/skills.

Relationship Between Diversity, Equity, and Inclusion Skills/Knowledge, Departmental Inclusiveness, and Student Identity. We next investigated how the student response about DEI skills/knowledge developed in the program varied by (1) perception of

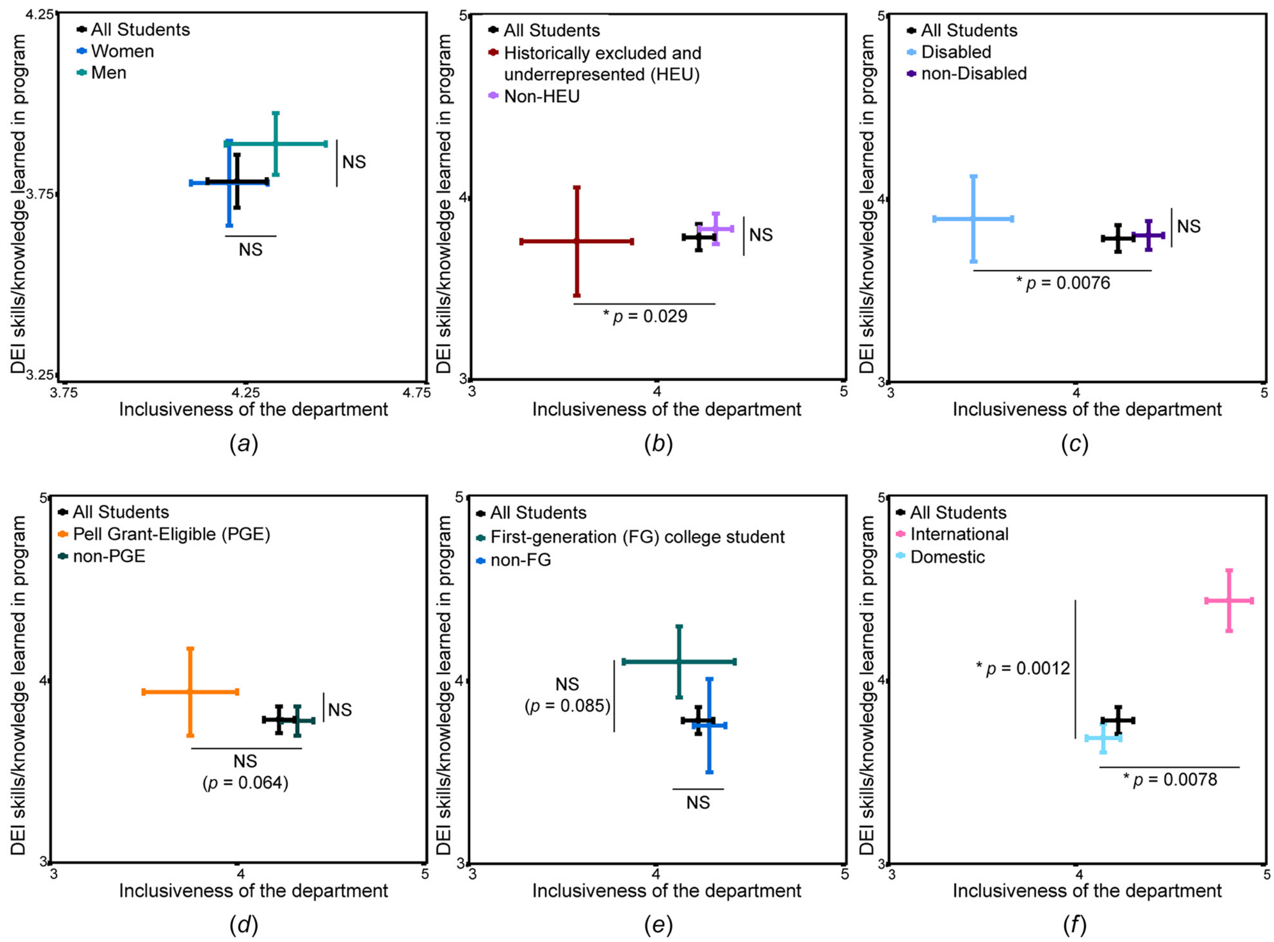

Fig. 4 Relationship between student-rated inclusivity of the department versus DEI skills/knowledge learned in the program by identity. 2-D error plot depicting the student responses to the inclusiveness of the department (x-axis) and the DEI skills/knowledge (y-axis) learned in the program. The center of each cross represents the mean and the error bars represent standard error of the mean. The black cross shown in (*a*)–(*f*) averages responses from all students (n = 84) while the other crosses (colors indicated in legends) depict a subset of responses grouped by student-reported identities. (*a*) Men (n = 30) and women (n = 44) did not significantly differ in how they rated the inclusiveness of the department or the DEI knowledge/skills learned in the program. (*b*) Students of races and/or ethnicities that have been historically excluded and underrepresented (HEU) in STEM (n = 7) found the department significantly less inclusive than non-HEU students (n = 63), but reported a similar rating of DEI knowledge/skills learned. (*c*) Students with a disability (n = 11) also reported that the department was significantly less inclusive and did not report a difference in DEI knowledge/skills learned compared to students who did not have a disability (n = 67). ((*d*)–(*e*)) While not statistically significant at the $p < 0.05$ level, responses from Pell grant-eligible (PGE) students (n = 8) trended lower in inclusivity than their non-PGE peers (n = 69) ($p = 0.064$) while responses from first-generation (FG) (n = 8) college students trended higher in DEI knowledge/skills learned compared to their non-FG peers (n = 70) ($p = 0.085$). Of the n = 8 respondents in the PGE and FG groups, n = 3 students were both PGE and FG while the other n = 5 were unique respondents. (*f*) International students (n = 11) reported significantly higher inclusiveness of the department and the DEI skills/knowledge learned in the program compared to domestic students (n = 68). Statistical significance is indicated by the asterisk (*) and defined as $p < 0.05$ after a Mann–Whitney U test. NS indicates "not significant". X- and y-axes ranges vary by panel to best represent the data, but each panel shows an x- and y-axis with an equal range. Values of students per group do not always add to the total respondents (n = 84) because responses to the demographic/identity questions were optional and some respondents chose not to answer some or all questions.

inclusiveness of the department and (2) student identity and demographics (Fig. 4). Students were asked "Please indicate your perception of the inclusiveness of our department" on a scale from none (rating: 0) to very high (rating: 5). The average response was 4.23 (SD = 0.75) and, notably, all responses were greater than or equal to 3. Additionally, the rating of programs' development of the six DEI skills/knowledge presented in Fig. 3 was averaged into a single rating per respondent. Average student response to inclusiveness of the department was plotted versus average DEI knowledge/skills learned in the program for all students and by student identity (Fig. 4).

When examining responses by self-reported student identity, men and women did not significantly differ in how they rated the inclusiveness of the department or the DEI knowledge/skills learned in the program (Fig. 4(*a*)). Given that women often report that engineering spaces are unwelcoming [29,30], our finding was surprising and promising. Near-gender parity in our departmental faculty (40% women in the University of Washington (UW) Department of Bioengineering versus 26.7% nationally in biomedical engineering departments [31], 26.3% in the UW College of Engineering [32], 19.2% in engineering departments nationally [31]), gender parity in the junior and senior cohorts (56% and 55% women, respectively, versus 30% in the UW College of Engineering [32] and 51.5% in biomedical engineering nationally [31]), and/or women in departmental leadership roles (including chairs of the department and the committee on Justice, Equity, Diversity, and Inclusion) could support this similar inclusiveness reported by men and women students in our department.

Students of races and/or ethnicities that have been historically excluded and underrepresented (HEU) in STEM found the department significantly less inclusive (average = 3.57) than non-HEU students (average = 4.32) but reported a similar rating of DEI knowledge/skills learned (Fig. 4(*b*)). Due to an abundance of prior work demonstrating that engineering environments are less inclusive to people of races and/or ethnicities historically excluded from STEM [14,33–36], this difference in inclusiveness was expected, yet further illustrates the great deal of work needed to provide an equitable and inclusive experience to HEU students. While we must address differences in departmental inclusiveness, we were encouraged that HEU and non-HEU students reported similarly high DEI knowledge/skills learned in the program, suggesting that the DEI content in courses provided an equally effective educational experience. Toward avoiding disparate learning experiences, assessing whether the DEI knowledge/skills learned varied by identity was essential to this study.

Similar to responses from HEU students, students with a disability also reported that the department was significantly less inclusive (average = 3.45) compared to students who did not have a disability (average = 4.39) but did not report a difference in DEI knowledge/skills learned (Fig. 4(*c*)). The less inclusive experience aligns with the literature that reports social exclusion from faculty and peers, as well as a failure to adequately accommodate students with disabilities [37,38].

For both Pell Grant-eligible (PGE) and first-generation college students (FG), there were no significant differences in inclusiveness of the department or DEI knowledge/skills learned in the program compared to their non-PGE and non-FG peers, respectively (Figs. 4(*d*)–4(*e*)). However, while not statistically significant at the $p < 0.05$ level, responses from PGE students trended lower in inclusivity than their non-PGE peers ($p = 0.064$, Fig. 4(*d*)) and responses from FG students trended higher in DEI knowledge/skills learned compared to their non-FG peers ($p = 0.085$, Fig. 4(*e*)). The lower ratings regarding inclusiveness of the department from PGE students aligns with prior work on the multifaceted challenges PGE students can experience in engineering, such as feeling excluded amongst the more privileged students [39]. While not statistically significant at the $p < 0.05$ level, FG students reporting higher DEI knowledge/skills learned could be due to differences in prior exposure and/or expectations between FG and non-FG students.

Finally, international students reported that the department was significantly more inclusive and reported significantly more DEI knowledge/skills learned compared to their U.S. domestic student peers (Fig. 4(*f*)). The positive result from international students regarding inclusiveness of the department was surprising given prior findings identifying the instances of exclusion often experienced by international engineering students, particularly the language barrier and social isolation [40,41]. Given that project-based learning, teamwork, and active learning are recommended toward supporting international students' belonging in engineering [40], our program's emphasis on these approaches may have contributed to the high ratings from international students. Inclusion of international students could also have been supported by our relatively small program size (∼70 students per cohort), a dedicated international student resource office, and proactive departmental advising. Finally, differences could also be due to relative prior exposure and/or expectations for coverage of DEI skills in the engineering curriculum.

Discussion

In this work, we took a program-level approach to develop and assess diversity, equity, and inclusion content in bioengineering curricula. To support instructors in incorporating DEI content and inclusive pedagogical practices, we created and provided instructors with a pre-course planning worksheet and offered one-on-one consultations. We surveyed instructors pre- and post-term to catalog DEI content and worked with instructors to assess the effectiveness of DEI content additions. Over the courses in the academic year, 74% of instructors provided a pre-term and/or post-term response. Of responding instructors, 91% described at least one DEI curricular content improvement, and 88% incorporated at least one new inclusive pedagogical approach. From the responding instructors describing DEI content incorporation, we grouped the bioengineering-related DEI into five competency categories: bioethics, inclusive design, inclusive scholarship, inclusive professionalism, and systemic inequality. These content areas were cataloged over the bioengineering undergraduate program and we found that, on average, courses included approximately 2.5 DEI competencies. We found that DEI content within different competencies can be effectively incorporated into bioengineering courses that vary in size, topic, level, and format. For example, we describe systemic inequality content in a lecture-based undergraduate physiology course, inclusive design content in an undergraduate lab, and bioethics content in a graduate cardiovascular engineering course. In addition to illustrating DEI content incorporation into a variety of classes, we demonstrated a variety of assessment mechanisms including direct assessment via course assignments, end-of-module student surveys, end-of-term course evaluations, and an end-of-year program review. These assessments provided promising results about the effectiveness of these DEI content additions, including positive student feedback, highly rated self-assessment of DEI knowledge/skills learned in the program, and improvement in direct measures of DEI competency.

We also assessed student perception of the inclusiveness of our department and found that on a 0 to 5 scale (with rating 5 = very high inclusiveness), the average rating was 3.57. The inclusiveness rating varied by student-reported identities, including both students historically excluded and underrepresented (HEU) in engineering based on their race and/or ethnicity and students with a disability finding the department less inclusive than their non-HEU and nondisabled peers, respectively. While these results indicate concerning differences in departmental inclusiveness which must be addressed, we were encouraged that these groups reported a comparable amount of DEI knowledge/skills learned in the program, indicating a similarly educative experience among the students. Interestingly, international students reported a unique trend, rating the department as significantly more inclusive and reporting the DEI knowledge/skills learned in the program as significantly higher, in comparison to their U.S. domestic peers.

Overall, this work provides a program-level approach to adding DEI-related content and pedagogy into bioengineering curricula, with translatable instructional tools and assessment mechanisms we hope will be useful for other educational programs wishing to engage in similar efforts.

The effective incorporation of DEI into engineering courses is nontrivial and can present challenges for a variety of reasons, including a need for formal faculty training and support [4] and a systematic, multifaceted review of course materials [42]. Prior work has also demonstrated variability in the amount of importance instructors attach to incorporating diversity issues into their courses [5]. In this work, we experienced similar variability in instructor response and participation in these efforts, with 26% of our faculty instructors not responding to the reporting requests of our team and 9% of responding instructors not reporting any significant improvements to their course's DEI content. Due to the wide range of instructor buy-in, there was likely variability in inclusivity and DEI content among courses that contribute to students' overall perception of inclusivity (Figs. 2, 3, and 4). To move our DEI initiative forward and avoid the potential harms of compulsory engagement in DEI work [43], we chose to focus on the vast majority of our instructors who engaged in the process and made substantive updates to their engineering courses to incorporate DEI content. Future work could include investigation of how specific course content, instructor approach, peer interactions, and/or other curricular and intradepartmental factors impact learning outcomes and student perceptions of inclusivity, especially for students from groups historically excluded from STEM. Additionally, future work could leverage the DEI content catalog (See Fig. 1 available in the Supplemental Materials on the ASME Digital Collection) to achieve continuity among courses by building upon DEI content covered in prerequisites. Also, expansion of the DEI content catalog to include elective courses could empower students to enroll in electives that build their DEI knowledge/skills.

An additional emerging barrier to the incorporation of DEI content in engineering programs is political opposition in a subset of states. Recently passed legislation has banned public colleges and universities from spending federal or state funds on DEI initiatives in Florida [44]. In addition, effective January 2024, DEI offices at public colleges and universities in Texas will be banned [45]. Considering the current climate in some states surrounding these topics, engaging in DEI-related curricular efforts may present added complexity. However, we assert that these diversity, equity, and inclusion topics are so intertwined with the field of bioengineering that these topics can be incorporated seamlessly into fundamental engineering courses without dedicated funding sources and/or specific labeling as "DEI topics." For example, many engineering courses have historically addressed engineering ethics via case studies of bridge collapses and other engineering failures due to conflicts of interest, oversight, or negligence. Additionally, bioengineering course content often covers ethical topics such as cloning, cell sourcing, and treatment of animal subjects. Ethics topics related to racism, sexism, ableism, and other forms of oppression (e.g., contraceptive trials in Puerto Rico, Tuskegee syphilis study, HeLa cell sourcing) can be incorporated into curricula amongst the aforementioned ethics content. Additionally, the design of inclusive products is critical to engineering. It should be a priority to train students to consider the accessibility of their engineering design and recognize racial, gender, disability, socioeconomic, etc. bias in designs (e.g., gender bias in car safety, racial bias in pulse oximeter function). Further, many courses reference the work of scholars in the field. Ensuring that the highlighted work is conducted by scholars of a wide variety of identities supports student learning and sense of belonging [46]. Because these topics fit seamlessly with existing bioengineering content and we worked with instructors to add them without dedicated financial resources or DEI-specific office, we contend that this work can be conducted even in states with political opposition.

The program-level approach described here is unique, to our knowledge, and builds upon others' course-level approaches to add DEI content [6–9,12]. Another approach is to address DEI engineering education at the College of Engineering-level, which has the potential for substantial impact and educational continuity, but likely requires substantially more resources (e.g., dedicated directors, funding, and the authority to mandate faculty training) [47]. Ultimately, all of these approaches have the potential for impact, and we encourage a thoughtful reflection about which approach is feasible. For example, our team consisted of graduate students, faculty, and staff within the Department of Bioengineering who engaged in this work as service without dedicated funding. Therefore, we had the opportunity to approach this from the program-level, but we would have needed substantially more personnel, funding, and authorization to approach this from the College of Engineering-level.

While we demonstrated that this program-level approach resulted in high faculty engagement and positive student feedback, this work is only a preliminary step in a complex journey to educate the next generation of DEI-competent bioengineers. Furthermore, establishing an inclusive educational environment for all students is multifaceted, challenging work and as expected, adding DEI content to the curriculum and addressing inclusive pedagogical approaches did not eliminate inequities in student inclusion in the department. Examination into the experiences of groups who reported significantly lower inclusion is essential toward rectifying this disparity in inclusion. Moving forward, this work should also integrate iterative improvements and assessments of those improvements. Additionally, to ensure DEI updates are sustained from offering-to-offering, future efforts should involve updating the course learning objectives to reflect the goals of the DEI content additions. Further, in addition to assessing the impact of individual courses, it would be informative to assess DEI knowledge/skills via longitudinal assessment as students progress through the program. Longitudinal assessments could provide formative feedback, enabling the adaptation of course content to address deficiencies in DEI skills/knowledge. In addition to gathering information about DEI course content from instructors as described in this work, we plan to ask students about DEI coverage in the curriculum to get a more comprehensive understanding of DEI-related curricular topics being addressed, as well as which topics and approaches are effectively engaging and impacting students. In our department, we have representatives on the Accreditation and Continuous Improvement, Curriculum, and Justice, Equity, and Diversity Committees who we plan to engage in these efforts.

Overall, we are encouraged by our progress thus far and motivated to continue this work toward educating our students on important DEI-related topics and establishing an inclusive climate for learning and development. We hope that other similarly motivated programs can adopt the ideas and approaches provided in this work in order to provide engineering students with crucial DEI knowledge and skills.

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Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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