Integration of
BIOLOGICAL APPLICATIONS INTO THE CORE UNDERGRADUATE CURRICULUM:
A Practical Strategy

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Our era has seen a shift in how educators and researchers approach biological sciences from surveillance to unraveling a deeper, mechanistic understanding.[1] What was once purely empirical is now modeled and controlled. Chemical engineers have kept pace with and contributed to the advances in technology that have enabled this quantifiable understanding of biological systems. Beginning in the 1970s – '80s, areas such as pharmacokinetics, tissue engineering, protein engineering, metabolic engineering, and more recently, biological systems engineering emerged within ChE departments, resulting in positive and significant impacts on a variety of industries. At the top of the list of technology markets was medical technology, due to opportunities with high profit margins. Moreover, as the technologies matured, we have seen a radical transformation even in the bulk chemical industry.[2,3] The motivation to develop bio-based products includes lower cost, reduced dependency on petroleum resources, and environmental benefits. Indeed, it is estimated that the market for bio-based chemicals is approximately 10% of the total chemicals market.[4]

At the same time that chemical engineers were playing a leadership role in biotechnology research, the undergraduate curriculum for ChE students remained essentially stagnant. Applications in petroleum processing have dominated the core curriculum, as presented in the enduring textbooks

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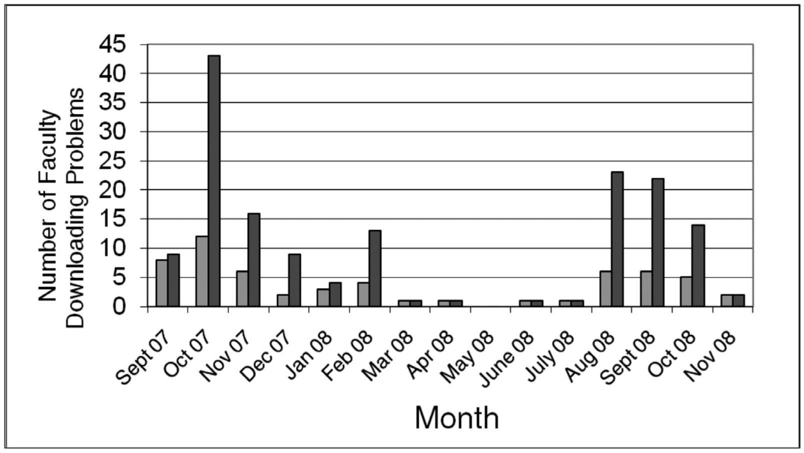
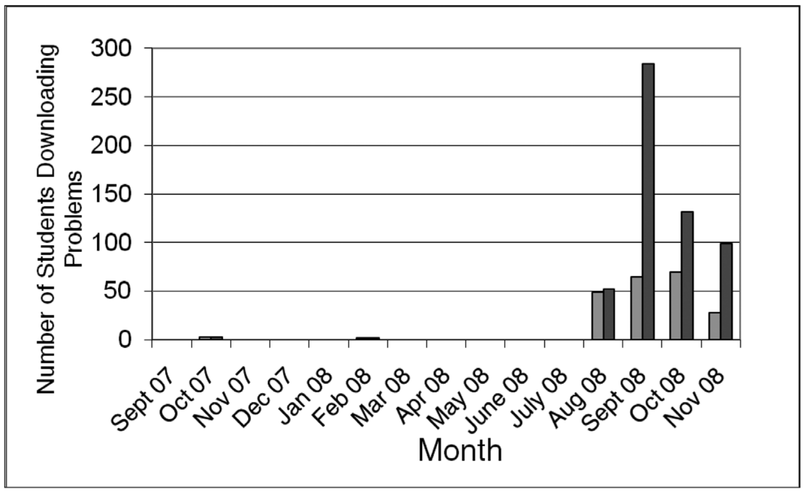
***Figure 1a** (top right). Number of faculty downloading problems during the grant period, as well as the total number of problems downloaded. Light gray = # of faculty; dark gray = # of problems.*

***Figure 1b** (lower right). Number of students downloading problems during the grant period, as well as the total number of problems downloaded. Light gray = # of students; dark gray = # of problems.*





of our discipline. Modification to the core curriculum would require updated or altogether new textbooks with the same ability to apply the fundamental principles to current application areas. These changes have been occurring at a slow pace.[5-8] A number of textbooks on biochemical engineering were developed that served as excellent resources for elective courses.[9-15] These texts present essential biology and biochemistry as well as applications of chemical engineering principles in bioprocessing, which was typically the target employment opportunity of graduates at the bachelor level. Elective courses on biochemical engineering have generally been taught by faculty appropriately trained at the Ph.D. level.

Both ChE faculty and the National Science Foundation (NSF) have recognized the need to address "bioX," namely, the broad range of bioengineering topical areas, including biochemical, biomolecular, biomedical, and all engineering life science subject matter, in the undergraduate curricula.[16] Many grass-roots efforts have begun and are under way across the United States. To reflect the trend of incorporating biological applications, many academic departments have changed their names to Chemical and Biological Engineering, or Chemical and Biomolecular Engineering, or similar, resulting in enrollment stabilization or gains. Some ChE programs now require biochemistry and/or biology courses, at times instead of some traditional chemistry courses.[17] The NSF recently supported a grant though the Division of Engineering Education to Tufts University for the "Integration of Chemical and Biological Engineering in the Undergraduate Curriculum: A Seamless Approach."[18] Three workshops were held to "facilitate the incorporation of biological engineering into the entire [ChE] curriculum." NSF also sponsored workshops to discuss the modernization of ChE education[19] with a particular emphasis on the integration of biology, molecular transformation, and other frontier areas into the ChE curriculum. A significant outcome of such projects has been an increased awareness among ChE faculty of the need to enrich and revitalize ChE education to address the needs of industry and the interests of students.

Perhaps the most significant obstacle to incorporating such interdisciplinary content into the undergraduate curriculum, as urged by the National Academy of Engineering,[20] is that faculty without formal training in bioX need preparation in order to effectively incorporate biological applications into their curricula. In many cases, undergraduate chemical engineers have more, or at least more recent, biology training than their professors. Faculty developing relevant problems for new science applications, such as biotechnology or nanotechnology, must have some appropriate expertise. Many such educational problems have been created, but have remained in file cabinets for use by their authors.

BIOENGINEERING EDUCATIONAL MATERIALS BANK WEBSITE DEVELOPMENT

To address the need for an organized, accessible educational resource for faculty interested in integrating bioX concepts into the core ChE curriculum,[2] a web-based repository of solved bioX problems relevant to the undergraduate core courses has been created.[21] The website, Bioengineering Educational Materials Bank or BioEMB, is a MySQL[1] secure

1 *MySQL is open source database software that is now owned by Oracle.*

database that enables students, faculty, and others access to problems in biological engineering (<http://www.bioemb.net>). The problem bank is organized by web pages for each core chemical engineering course. On each course page a set of commonly used textbooks is posted. Clicking on a book title will open a page with that book's table of contents and links to problems that can be assigned according to the topics in those chapters. This organization allows faculty to easily select a problem that can be assigned with other problems from the textbook for a given chapter or section. Only the faculty are granted a level of access that displays the solutions to the problems. Some security features are built into the website to identify if hackers have been able to access the solutions. Each problem shows a title, keywords, an abstract that describes the context of the problem, the problem statement, and, in the case of faculty access, the problem solution. Some of the words in the problem statement are highlighted and are linked to a popup dictionary to help readers who may be unfamiliar with the technical terms used. For the initial phase of the project, the table of contents of two of the most commonly used textbooks for the material and energy balance course[22, 23] were posted on the website listing appropriate BioEMB problems to be assigned with other problems from textbook.

The website was launched in 2007 and usage statistics are shown in Figures 1a –b. Figure 1a shows both the number of faculty downloading problems by month and the total number of problems downloaded each month. All problems posted were for material and energy balances. These data are not necessarily a direct measure of how many problems were assigned in courses. Figure 1b shows similar information for student downloads. The rise in student downloads towards the end of the project reflects the requirement by intervention site faculty for their students to register on the website and download their own problems.

WORKSHOP FOR FACULTY

In addition to the website development, a workshop was held to prepare faculty without formal training in bioX to utilize biological applications in their MEB courses. Faculty from 19 institutions participated. The workshop included two half-days of lectures that covered basic biology presented from a chemical engineer. During the final portion of the workshop, faculty were assigned to teams and challenged to solve 16 problems posted on the website. The goal of the problem-solving session was to facilitate that the faculty return to their institutions completely prepared to incorporate the problems in their course once the semester began.

MATERIALS AND METHODS

Project Assessment Overview

The goal of the project has been to enable faculty to incorporate biological applications in their core ChE courses, and through their exposure to these applications, to enable students to apply their ChE principles to these interdisciplinary problems. Clearly, the overall goal of the project is the development of the resource for faculty and faculty training. As seasoned biochemical engineers with significant industrial exposure, the project faculty have a sense of what types of problems students need to be able to solve. Hence the majority of the project resources have been committed to the resource development, but assessment of student learning is nonetheless essential to show the effectiveness of the project. Consequently, the assessment of the project has included probing student performance on simple questions addressing bioX and non-bioX learning objectives. The testing presented in this paper is the second attempt at demonstrating student performance. The first year of the project, beta testing included typical textbook material and energy balance problems. The students overall performed very poorly on the tests (average scores across institutions ranged from 0.13 + 0.03 to 0.36 + 0.04 as the lowest and highest average scores out of 1.0). A second round of beta testing was performed that included a set of simple concept and calculation questions and, in addition, two measures of "familiarity" were explored, namely student speed to answer the questions and student perception of their confidence to answer the questions correctly. The outcome of this second testing is presented in this paper. Additional questions were included on a survey to see if any associations could be found relating student demographics to student performance. The survey also probed student satisfaction associated with the inclusion of bioX applications in their course. The following sections present the purpose and type of analysis performed.

Demographics of Participating Students

Three intervention and three non-intervention sites, for comparison, participated in the project with 99 and 196 students enrolled, respectively. With the exception of one non-intervention site (with 22 students; survey not completed) all of the universities participating were public (state) universities. Exemption status for carrying out a human subjects research project was obtained from all participating institutions. Students were enrolled who were taking the material and energy balance course. No prior course in biology was required of the students. Of the students who completed the survey, about 60% were male, over 75% were in their sophomore year in school, 10% were Hispanic, and the average estimated (self-reported) GPA of participants was about 3.3.

Instructional Objectives

The ability of undergraduates to apply their ChE principles to biological applications was assessed relevant to learning objectives normally included in the material and energy balance course. An evaluation tool was developed that asked focused, multiple-choice questions to address relevant student-learning objectives. The questions included simple calculations and one terminology question. The specific learning objectives

TABLE 1 Learning Objectives (LO) Addressed in MEB Bio Test		
Test question number in parentheses		
LO#	Bio learning objective	Traditional ChE learning objective
1	Work with common biological units (1)	Work with common units for achieving a desired expression (2)
2	Identify typical products of respiration and metabolism for a whole cell bioprocess (3)	Identify typical products of a combustion process (4)
3	Learn and use basic bioprocess terminology (5)	Learn and use basic chemical process terminology (6)
4	Use chemical formulas to represent cellular composition and cellular transformations (7)	Use chemical formulas to represent molecular composition and transformations (8)

probed are listed in Table 1. These questions attempted to make a head-to-head comparison of students' abilities to answer bioX and non-bioX questions addressing analogous learning objectives.

Description of Intervention

To teach the bioX learning objectives, 11 problems were assigned at each of the intervention sites together with the traditional ChE problems. The intention of the project team was that the 11 problems should make up 15% to 20% of the total problems assigned in the course. Intervention-site faculty could incorporate them as they saw fit, whether as in-class problems, homework, or exam problems. Intervention faculty were asked to have their students register on the website and download their own problems so that they would more readily access the BioEMB dictionary that is linked to specific words in the problem statements.

Evaluation of Outcomes —Knowledge, Speed, and Confidence

The test consisted of the eight brief technical questions, each followed by one question assessing speed in answering the question and also one question asking the student to rate their level of confidence in answering the question. The six testing sites administered the tests between late November and December. Paper tests were given together with a survey (one non-intervention site did not administer the survey). The test questions were identical, but the follow-up questions were slightly different on the positive and negative site surveys as appropriate.

To capture an estimation of how long each problem took for the students to complete, a multiple-choice question with different time-range options was used. Thus the students were not expected to time themselves for the solution of the problems very accurately. For the data analysis, the midpoint of the time range requested was assigned to the selected response.

For the students to rate their own level of confidence in answering each question, again a multiple-choice approach was taken on the test. Their choice of confidence level could fall under "I don't know how to do this problem," "Low level of confidence – enough to try," "Reasonably confident," and "Absolutely confident," and the numerical values were assigned as 1, 2, 3, and 4, respectively. By assigning a numerical value to the scale, an average could be calculated. One problem (number 5) had a slightly different scale, which does not impair the effectiveness of comparing between intervention sites and comparison sites. This difference, however, should be taken into account when comparing the bioX vs. non-bioX questions for learning objective 3, as there is a slight difference in the confidence scales.

DATA ANALYSIS

The University of Virginia Center for Survey Research assessed overall frequencies on all survey and assessment variables and on the three created variables of SURVEY (eight different questions), UNIVERSITY (six different universities), and SITE (two: intervention and comparison). Questions 1 through 5 on the student survey were reversed-coded and overall means were provided for those variables. The percent correct for each assessment answer was calculated and broken down by each of the three created variables with t-tests to make comparisons across the intervention and comparison sites.

The students' self-reported times to complete each assessment item were collected on the assessment form and the answers were recoded into numbers of minutes. The mean times were broken down with t-tests to make comparisons across the intervention and comparison sites (data not shown here because there were no statistical differences between times for intervention vs. comparison sites).

Likewise, the students' self-reported confidence levels for their answers were assigned numerical values (1-4) and were analyzed by t-tests to make comparisons across the intervention and comparison sites.

To determine the effect of the inclusion of BioEMB problems in the course on student career interest, a three-way crosstabulation calculation was performed on the two questions at (1) intervention vs. (2) comparison sites:

1. *Prior to taking this course, I was interested in a career in biotechnology (two answers—interested, not interested)*
2. *How did the "course" or "biotech content" change your interest in pursuing a biotech career, if at all? (three answers—increased interest, made no difference, decreased interest)*

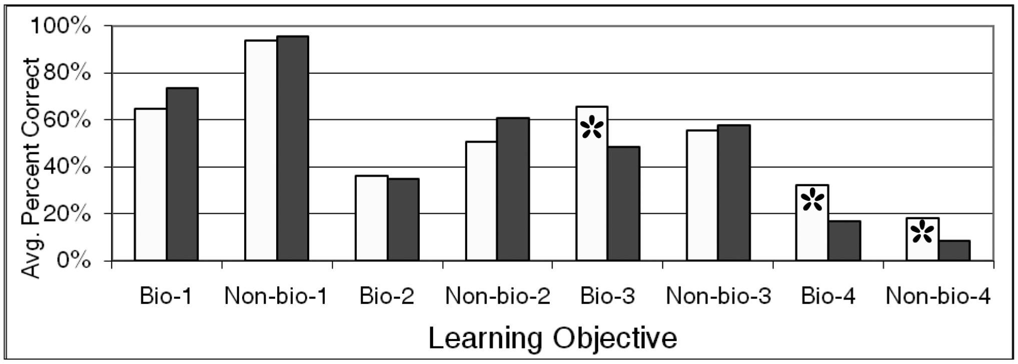


Figure 2. *Average student Performance Across Intervention and Comparison Sites. Light gray = Intervention Site; dark gray = Comparison Site; asterisks on the figure indicate that the difference between the intervention and comparison site performance is statistically higher at the 95% confidence level.*

Pearson Chi-square tests were performed to determine the relationship between the two answers of question 1 and the three answers of question 2.

RESULTS AND DISCUSSION

The averages for each of the eight problems addressing each of the eight learning objectives in Table 1 across intervention and comparison sites are shown in Figure 2. Asterisks on the figure indicate that the intervention site performance is statistically higher than the comparison site at the 95% confidence level. Thus, it should be noted that the difference between the intervention and comparison sites is significant for the bioX question of Learning Objective 3 and for both the bio and non-bio problems of Learning Objective 4.

Upon reviewing the data, some considerations can help explain results. The bioX concept tested by problem 1 (Bio-1) is simply to convert g/l of fructose into mM. In principle this does not require any special training, and the question was asked to see if students who had more exposure to bioX problems during the course would be more comfortable with units associated with small volumes. Most of the problems in the material and energy balance course use mass fractions and mole fractions, so the use of moles or grams per volume may have been less familiar to the non-bio students. Based on the test results, however, it can be said that students who had the bioX problems in their course showed no significant advantage in terms of solving that simple problem. As one could expect, there is no significant difference in the test results on the non-bio mass fraction calculation in problem 2 (Non-bio-1). Likewise, there was no significant difference in the students' abilities to solve the problems for learning objective 2 – [problems 3 (Bio-2) and 4 (Non-bio-2)]. Problem 3 clearly requires more familiarity with biological systems, involving the gaseous and liquid-phase products of a bioreactor. While it would be reasonable to expect that students who have solved problems such as "Calculation of oxygen uptake rate in a fermentor" and "Fermentor water balance" would have had some exposure to fermentation processes, it apparently was not enough to enable them to answer the question correctly more frequently than at the comparison site. The results for the non-bio problem regarding the products of a combustion process are also not significantly different between the intervention and comparison sites.

Learning objective 3 addresses terminology. The bioX term probed was "respiratory quotient" [question 5 (Bio-3)] and the non-bio term was "theoretical oxygen" [question 6 (Non-bio-3)]. Familiarity with terminology would be an example of Bloom's level one learning,[24] or "knowledge." Two of the comparison sites answered this question correctly with a much higher incidence than merely guessing, so it could be presumed that they had seen the term somewhere in a separate course. Even so, the intervention sites did perform better than the comparison sites to a significant degree. While terminology is not the most important tool that an engineer must learn, it could be inferred that knowledge of terminology is a necessary first step for interdisciplinary learning, which is an important aspect of this project. For students to learn to apply engineering concepts in different technical fields, mastery of different terminology enables communication and recognition of concepts.

The questions addressing learning objective 4 are clearly the most challenging of the set [problems 7 (Bio-4) and 8 (Non-bio-4)]. Students are required to perform elemental balances for both the bio and non-bio question, including solving a simple set of linear equations, in order to find the required product stream amounts. Overall the students performed poorly on these two problems, however, the students at the intervention sites performed significantly better than the comparison sites on both the bio and non-bio problems. That the students at the intervention sites performed better on both the bio and non-bio questions might suggest that the students at the intervention sites were somehow stronger students overall, but other data collected support that the students at all the sites had similar capabilities. For example, the self-reported GPAs of the students at both the comparison and intervention sites were similar. The average self-reported GPA at the intervention sites was 3.28 (100% reporting) while that at the comparison sites was 3.33 (42% reporting). With the exception of one of the smaller comparison sites, all schools are state universities and attract a broad range of students.

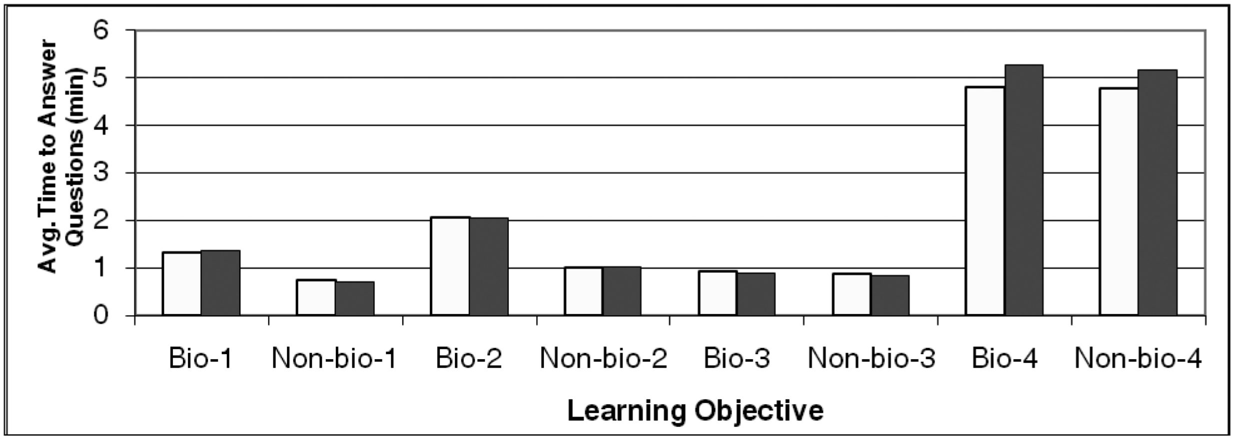


Figure 3. *Student average self-reported times to answer questions at intervention and comparison sites. Light gray = Intervention Site; dark gray = Comparison Site; no asterisks on the diagram indicates that there were no statistical differences between the times to answer questions between the intervention and comparison sites.*

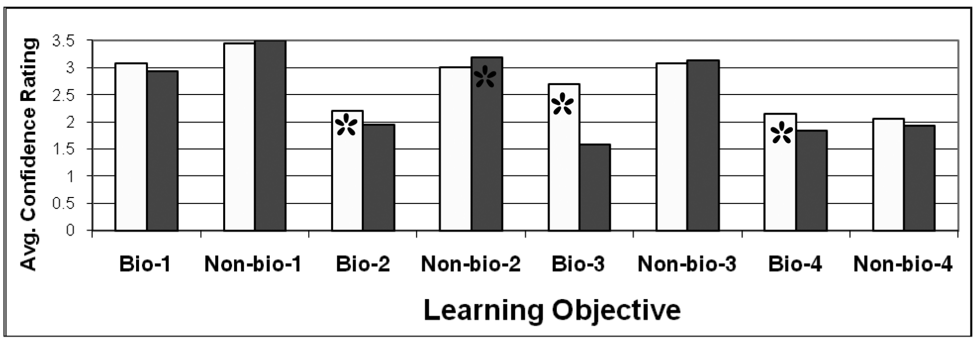


Figure 4. *Student self-evaluation of the level of confidence in answering questions for each of the four learning objectives probed. Light gray = Intervention Site; dark gray = Comparison Site; asterisks on the figure indicate the difference between the intervention and comparison site performance is statistically different at the 95% confidence level.*

Students' self-reported times (Figure 3) to answer each of the questions were very similar at both the intervention and comparison sites. The similarity in timing could be accounted for by comparable preparation to answer the questions across the different sites, but this cannot be confirmed without an extensive analysis. The higher amount of time to answer questions from learning objective 4 corresponds to the relative difficulty of those questions in contrast to the first six questions.

Comparing the students' self-evaluation of their level of confidence was performed as a way to quantify the students' "familiarity" with the bio and non-bio questions. The data are shown in Figure 4. For learning objectives 2, 3, and 4, there is a statistically significant difference in the reported confidence level to answer the bio questions between the intervention and comparison sites. Regarding the non-bio problems, there is only a statistically significantly higher (6.3% higher rating) reported confidence level for the non-bio sites to answer the question for learning objective 2.

There is a clear trend that having had the bio problems in the course resulted in a higher level of self-reported confidence to answer bio questions. With the exception of question 3 (Bio-2) the higher level of confidence was coupled to a statistically higher performance on the bio problems.

SURVEY RESULTS

The survey addressed questions about student demographics, including gender, race, year in school, and overall estimated GPA. The goal of these questions was to determine if the inclusion of BioEMB problems had an impact on a particular group of people. While there were some statistical differences between various groups, in all cases the numerical differences were too small to draw any relevant conclusions. There were a few notable conclusions when comparing the intervention and non-intervention sites as aggregates. For example, students agreed that their professor made an effort to bring biotechnology topics into their course at the intervention sites whereas they disagreed with the statement at the non-intervention sites.

Students were surveyed about their interest in the BioEMB problems as well as their interest in biotechnology in general. Based on the data, student interest in the BioEMB problems varied from school to school. Of interest, within the intervention sites, those who were interested in a career in biotechnology before the BioEMB intervention were more interested afterwards, while those who were not interested in a biotech career before the course were less interested after the course (χ^2=7.563, p=.023). At the comparison sites there was no statistically significant affirmation of the students' original career interests (χ^2=1.422, p=.491), The faculty at the comparison sites did include some bioX problems, as described in the student surveys; however, the problems did not come from the BioEMB website.

In terms of the number and difficulty of the problems, the students also reported variable impressions. Again, these differences may depend on how the problems were included in the course. For one of the intervention sites, the problems were reported to be just about the right level of difficulty and even some of the students would have been happy to have more of them. At the other two institutions, the problems were reported to be somewhat too difficult and, on average, students would have been happy to have fewer of them. On the other hand, at the comparison sites, the response to the question regarding the number of problems in the course fell between "too few" and "just about right." Thus, the students, on average, would have wanted more biological problems included in their course.

FACULTY WORKSHOP

The results of the survey evaluation at the end of the workshop suggested that the attendees viewed the workshop as helpful to them in adding problems addressing biological applications into their material and energy balance courses. Participants were challenged with a set of 16 material and energy balance problems with varying degrees of difficulty and biological content. The problem-solving sessions facilitated the crafting of clearer problem statements, taking into account the needs of the non-bio users, and helped to identify aspects of the problems that were more challenging for those without bioX backgrounds.

In the end-of-workshop survey, 85% of the faculty responding agreed that the bioX lectures addressed their concerns about lack of familiarity with bioX concepts, 100% agreed that the bio lectures were effectively presented, 90% agreed or strongly agreed that the BioEMB website appeared to be user friendly and effective, and 95% agreed or strongly agreed that they would recommend the workshop to a colleague. 75% of the attendees agreed that the problem-solving session was useful. Finally, several faculty who participated in the workshop offered to beta test the problems in their material and energy balance courses.

CONCLUSIONS AND FUTURE WORK

A website has been developed for hosting solved problems addressing biological applications for undergraduate chemical engineering curricula. The number of U.S. institutions that have downloaded problems as of December 2008 was 32 chemical engineering departments, representing more than 20% of the total number of departments. In addition, faculty from Turkey, Mexico, the UK, Spain, Brazil, Norway, and Colombia have also downloaded problems for their courses. Students at intervention sites scored significantly higher on two out of four bio-related learning outcomes and even one non-bio-related outcome. Students at the comparison sites did not perform statistically better on any of the non-bio questions, suggesting that the intervention did not detract from students' abilities to apply chemical engineering principles to traditional problems. The intervention did not have an impact on the speed with which students answered the questions but students at intervention sites had significantly more self-reported confidence to answer the questions addressing biological applications than at the comparison sites. Within the intervention sites, students who were interested in a career in biotechnology before the BioEMB intervention were more interested afterwards, while those who were not interested in a biotech career before the course were less interested after the course. At the comparison sites there was no statistically significant affirmation of the students' original career interests. A Phase II project has been funded to include the addition of solved problems for ChE courses for the remainder of the core undergraduate curriculum beyond material and energy balances: Transport Phenomena (Fluids, Heat and Mass Transfer), Thermodynamics, Process Dynamics and Control, and Reactor Design and Kinetics.

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