INTRODUCTION

Incorporating research experiences into the undergraduate curriculum is a major emphasis of national educational reform (1, 2) and the American Society for Microbiology (ASM) (3). The educational field proposes integration of research experiences into traditional lab courses in the form of course-based undergraduate research experiences (CUREs) (4). CUREs enable students to experience research first-hand, providing a more accurate understanding of how scientific research is conducted. Authentic research experiences lead to student-reported gains in general skills (e.g., oral, visual, and written communication) and more specific research-associated skills (e.g., research design, hypothesis formation, data analysis) (5–8). In addition, students in CURE courses develop scientific reasoning skills, begin to identify themselves as scientists, are more inclined to pursue graduate education or careers in science (9–11), and have increased graduation rates (12).

To maximize student engagement in research and in the classroom, CURE curricula should focus on relevant research topics and questions. One of the fastest growing research areas in the last 10 to 15 years has been the relationship between human health and the human microbiome, or the consortia of commensal microorganisms living in and on our bodies. The gut microbiome alone encompasses more than 1,000 resident microorganisms, including bacteria, viruses, fungi, and protozoa (13). The majority of these microorganisms inhabit the colon, where they contribute to human health through the biosynthesis of vitamins and essential amino acids and the generation of metabolic products. These microorganisms also play a role in human health by regulating host immune responses and preventing the growth of pathogenic microorganisms (14).

Course-based undergraduate research experiences (CUREs) are an effective way to introduce students to contemporary scientific research. Research experiences have been shown to promote critical thinking, improve understanding and proper use of the scientific method, and help students learn practical skills including writing and oral communication. We aimed to improve scientific training by engaging students enrolled in an upper division elective course in a human microbiome CURE. The “Fiber Force” course is aimed at studying the effect of a wholesome high-fiber diet (40 to 50 g/day for two weeks) on the students’ gut microbiomes. Enrolled students participated in a noninvasive diet intervention, designed health surveys, tested hypotheses on the effect of a diet intervention on the gut microbiome, and analyzed their own samples (as anonymized aggregates). The course involved learning laboratory techniques (e.g., DNA extraction, PCR, and 16S sequencing) and the incorporation of computational techniques to analyze microbiome data with QIIME2 and within the R software environment. In addition, the learning objectives focused on effective student performance in writing, data analysis, and oral communication. Enrolled students showed high performance grades on writing, data analysis and oral communication assignments. Pre- and post-course surveys indicate that the students found the experience favorable, increased their interest in science, and heightened awareness of their diet habits. Fiber Force constitutes a validated case of a research experience on microbiology with the capacity to improve research training and promote healthy dietary habits.
byproducts through fermentation of low- or non-digestible dietary fiber (14–19). This type and proportion of fiber that reaches the colon is an important factor that can drive alterations of gut microbial composition (20–22). Diets low in fiber reduce total bacte-
rrial abundance in the gut microbiome (23), while diets high in fiber increase microbiome richness (24, 25). Interest in the role of dietary fiber in regulating the gut microbiome has led to diet interventions, which suggest that a high-fiber diet can alter metabolic parameters (21, 26) and ameliorate clinically relevant colon cancer biomarkers (25). Given the importance of fiber for a healthy gut, future dietary studies are still needed. Especially in healthy indi-
cividuals, there is a need to understand not only the stability and resilience of the “normal” microbiota, but also the amount and type of fiber that can result in positive microbial changes. Therefore, we developed a research-based learning laboratory course at University of California (UCI) to study the effect of a high-fiber diet on the gut microbiome of students. The Microbiome laboratory course at UCI, or Fiber Force, aimed to engage students in research activities by actively participating in a safe diet intervention. Students manipulated their own gut microbiomes through a safe high-fiber diet intervention and actively participated in the sample processing and data analysis. Students analyzed their own samples, gained molecular experience in the labora-
tory, and were instructed on computational tools to analyze the data. Similar to other microbiology modules described recently (27–36), a goal of Fiber Force was for students to develop critical reasoning and problem-solving skills related to microbiology and microbiome research.

Intended audience

The microbiome activity described here uses molecular biology and next-generation sequencing and computational skills. The course is intended as a microbiology or molecular biology laboratory. The course is most effective as a small enrollment course as consented students are able to undergo a diet intervention. The exercise was piloted in an upper-division elective course called Advanced Molecular Biology techniques (M130L) at the UCI (spring 2018) with enrollment of 18 students (all seniors). The class comprised 10 female and 8 male students and included 8 first-generation students. The students’ performance of the Micro-
biome course was compared with a previous version of the course (M130L, 2017) in which students were exposed to an inquiry module aimed at studying promoters using pClone described by Campbell et al. (37). The 2017 course had an enrollment of 20 students (all seniors): 8 female and 12 male, with 8 first-generation college students. The CURE study was approved by UC Irvine IRB # 2018-4297 (Microbiome intervention) # 2018-4211 (educational effectiveness), and was approved by UC Irvine IRB # 2018-4297 (Microbiome with 8 first-generation college students. The CURE study described by Campbell

course (M130L, 2017) in which students were exposed to an

Biology techniques (M130L) at the UCI (spring 2018) with

upper-division elective course called Advanced Molecular

biology, as well as metabolic and phylogenetic diversity. Many students also had experience in pipetting, PCR, DNA extraction, and DNA gel electrophoresis. However, this experience was not assumed, and we covered basic laboratory principles and practices in the course. Advanced analyses, such as phylogenetics, were covered with active lectures and discussions (Appendix 6).

Learning objectives

Upon completion of this activity, students will be able to:
- Design and execute a dietary intervention plan to study the gut microbiome, with proper sample collection and storage.
- Become proficient in microbiome laboratory and computational techniques and skills.
- Apply basic microbiome principles and concepts to solve experimental problems.
- Apply the scientific method in different ways, including writing hypotheses, analyzing results, reporting data, and proposing further experiments.
- Report hypothesis, proposed research, results, and conclusions both orally and in writing to an audience of scientists and peers.
- Integrate and evaluate results from lab experiments and primary research articles.
- Critically analyze scientific publications, research proposals, and results.
tants are in charge of facilitating discussions, teaching active
lessons, supervising group work, answering questions, and
demonstrating techniques (when needed). The weekly dis-
cussion (active lecture) handouts are provided in Appendix
6. To ensure students properly practice research and oral
communication skills, we recommend adding “laboratory or
group meetings” to the schedule to discuss research ques-
tions, hypotheses, research plans, preliminary results, and
troubleshooting. At the end of the course, students share
their findings as a poster presentation, to which instructors,
teaching assistants, students, and research laboratories are
invited. The protocols (Appendix 8) and the respective
required laboratory preparation, including materials and kits
(Appendix 9) are described in the appendices.

A significant prerequisite to implementing the Fiber
Force course is getting Institutional Review Board (IRB)
approval in advance, a process that can take up to six
months. UCI IRB reviewed the educational (educational
research) and diet intervention (clinical study) components
separately. To ensure timely approval of IRB requests, we
recommend 1) providing a detailed description of how the
data will be anonymized for privacy protection, 2) writing a
detailed consent form for students that includes a protocol
for opting out of the study without affecting course perfor-
ance (see the consent form in Appendix 15), and 3) using
a third-party (other than the instructor) as holder of the
key that connects student’s names with sample codes. The
IRB background cites previous studies performed in the
context of classrooms (see, for example, 46–48) or the
present manuscript (UCI IRB # 2018-4297) as precedent.

Suggestions for determining student learning

An essential component of research involves the ability
to write a research proposal, conduct experiments in a rig-
orous and reproducible manner, and communicate scientific
findings in oral and written forms. Accordingly, the assess-
ment task for Fiber Force involved 1) a step-by-step proposal
writing activity (Appendix 3) to evaluate ability to design and
propose new research; 2) weekly discussion handouts and
lab notebook evaluations to assess laboratory performance;
3) data meeting reports and oral poster presentations to
evaluate science communication. The assessments are
described in full in the course syllabus (Appendix 5). The
data meeting reports and poster format followed structural
conventions of a scientific publication. The activities required
students to outline the background of the field, provide the
aims and hypotheses of the study, present results in both
text and graphical forms with descriptive legends, and discuss
the validity and significance of their findings. The integration
of this assessment task with learning activities in this project
directly align with our learning objectives (Table 1). The
marking rubric for the proposal writing spanned numerous
criteria including quality of aims, literature support, effective
introduction of project aims, validity of research questions
and aims, and validity of proposed research. These rubrics
are part of a manuscript that is currently under prepara-
tion (contact the corresponding author). The rubrics used
to evaluate lab notebooks, lab meeting presentations and
poster presentations are included in Appendix 13.

Sample data

Students were required to read the literature on the
effects of diet on the gut microbiome. This led to predic-
tions of and/or hypotheses on the impact of fiber before
and after the diet intervention.

After the samples were sequenced, students were
expected to interpret OTU tables, use qiime2/r to visu-
alize data, and compare samples to validate (or not) their
predictions. Students then presented their results during a
poster symposium (samples in Appendix 19). One example
predicted that the intervention would lead to an increase in
fiber-degrading bacteria (for student-led literature review
see Appendix 19) as these bacteria should possess a spe-
cialized ability to degrade complex carbohydrates. After
analysis, the students found that the > 40 g fiber interven-
tion caused no significant change in diversity or abundance
of microbes at the genus or phylum levels, but registered
increases in some relevant bacterial genera. A second
example hypothesized that a 40- to 50-g fiber intervention
would exhibit increases in short-chain-fatty-acid-producing
bacteria known to be responsible for gastrointestinal fer-
mentation of fiber. However, the students concluded that
there was no significant difference in the relative abundance
of short-chain-fatty-acid-producing bacteria before versus
after the diet intervention. This shows that the same dataset
can be used by different groups of students to study different
predictions or hypotheses.

In congruence with the quality of posters shown in
Appendix 19, students of the Fiber Force course registered
high scores on writing, data analysis, and presentation, with
median scores of 81%, 83% and 90%, respectively (Fig. 1).

Safety issues

The Fiber Force course involves collection of fecal
samples from healthy individuals (according to answers from
the health survey, Appendix 16), but potentially pathogenic
bacteria can be present in fecal samples. As part of the course,
the instructors and teaching assistants receive BSL2
safety training to instruct students on the necessary personal
protective equipment (PPE), the safe handling of samples,
and the proper disposal of biological waste in accordance
with BSL2 regulations. Aliquoting of fecal samples, as well
as bead-beating (the first step in DNA extraction) should
be handled inside a biosafety cabinet, and DNA extraction
should be conducted in a BSL2 laboratory. The subse-
quent steps (PCR, electrophoresis) can be performed in
a BSL1 laboratory. Students with health conditions such
as pregnancy, allergies, or immune-compromised status
should not directly handle or come into contact with fecal
samples. Laboratory bench surfaces and notebooks were
decontaminated with 70% ethanol before and after each
session and all students washed their hands with antibac-
terial detergent. Electronic devices were used (if needed)
inside sealed plastic bags that were wiped before and after
each use. All waste was disposed of in accordance with
BSL2 regulations and decontaminated by autoclaving. The
biosafety rules and policies for the laboratory are included
in the syllabus (Appendix 5).

FIGURE 1. Course performance between 2017 and 2018 courses were compared using the following grade scores: A) grade on a step-by-step proposal-writing activity (outlined in Appendix 3) to evaluate ability to design and propose new research; B) weekly discussion handouts and lab notebook evaluations to assess laboratory performance; C) data meeting reports and oral poster presentation to evaluate science communication.

FIGURE 2. Experimental design for the high-fiber study intervention and collection of fecal samples.
During class, sharing ideas and recipes with each other, and budgeting. Students frequently discussed their diet choices to 15 g of fiber per cup) and are economical for students’ diets rich in wholesome fiber for two weeks, each participant was provided with 10 meals per week from a food delivery company called Thistle. These lunch and dinner meals had an average of 40 g of fiber per day (highest intervention, suggesting that the intervention does not dramatically increase time commitment outside the classroom.

Evidence of student learning
To determine whether students in the Fiber Force course mastered important research-based skills, we measured course grade on important skill-based assignments. We also compared performance in the Fiber Force course (2018) with control (quire module, studying promoters using pClone by 37) 2017 course. In 2017, each group picked a guided inquiry project module and collected data. Students studied their own promoters but did not participate in experimental design. In the 2018 course, the class as a whole volunteered as participants in interventions, designed surveys, and discussed data. They also worked in small groups for presentation and discussion. Panel A compares the students’ GPA in biology-related core courses (Biochemistry, Molecular Biology) followed before the 2017 and 2018 courses, as a way to compare incoming level. Panel B compares the average final course grade in the 2017 and 2018 courses. Panel C compares the grade average in the 2017/2018 courses with grades in other courses that students followed simultaneously that quarter. Grade anomaly is the average GPA on other courses that quarter minus M130L course grade.

FIGURE 4. Performance of students in the Advanced Molecular Biology course M130L in Fiber Force (2018) compared with control (inquire module, studying promoters using pClone by 37) 2017 course. In 2017, each group picked a guided inquiry project module and collected data. Students studied their own promoters but did not participate in experimental design. In the 2018 course, the class as a whole volunteered as participants in interventions, designed surveys, and discussed data. They also worked in small groups for presentation and discussion. Panel A compares the students’ GPA in biology-related core courses (Biochemistry, Molecular Biology) followed before the 2017 and 2018 courses, as a way to compare incoming level. Panel B compares the average final course grade in the 2017 and 2018 courses. Panel C compares the grade average in the 2017/2018 courses with grades in other courses that students followed simultaneously that quarter. Grade anomaly is the average GPA on other courses that quarter minus M130L course grade.
in other classes taken simultaneously that quarter, compared with the 2017 cohort (Fig. 4C). Students from both cohorts (2017 and 2018) scored similarly in writing, data analysis, and communication assessments (Fig. 1), with median scores between 82.67 and 90.29, indicating high levels of mastery. To gather feedback, we used a published CURE survey (https://www.grinnell.edu/academics/resources/ctl/assessment/curseurvey/cure-survey, 49), for self-reported estimates on the course experience. The (post-CURE) survey responses on the course experience were very positive, and students estimated the gains in research-based aspects of the experience (e.g., on small group work, writing proposal, data collection, and analysis, etc.) as “large” or “very large” gains (49, not shown).

In our post-course open-ended survey, we asked students to comment on particular aspects of their experience in the Fiber Force course (see questions asked in Appendix 17 and answers in Appendix 18, n = 16). The qualitative responses were thematically classified and tallied. About a third (35%) of the students listed research exposure, 25% being part of an intervention, and 25% teamwork as their favorite aspect of the course. When asked about what skills students showed highest gains in the course, 37% of students listed writing, 31% research skills, 20% oral presentation, 20% computer work, and 20% computer/data analysis skills. These answers suggest that after following the Fiber Force course, students perceive themselves as possessing increased competence in these skills, and their achieved gains align with our intended learning outcomes.

All in all, we show the Fiber Force course promoted student development of fundamental research skills, meeting our learning outcomes. The positive impact on student development of research skills is consistent with results published for other CURE courses (9, 10, 32, 36, 47). It has been shown that integrating personal microbiome studies in the classroom promotes students interest and engagement in sciences courses (47). Our manuscript presents an option for a research experience on fiber microbiome intervention suitable for undergraduate classes in which the students can participate as study subjects. Additional research would be needed to validate this CURE course on educational effectiveness, motivation, and student experience.

In addition to our learning outcomes, we highlight the benefit the diet intervention had on student awareness on healthy food choices. When asked if the intervention changed any of their food habits, 63% of students indicated that now check food labels for fiber content, while 20% indicated that they are trying to eat more fiber or choose food based on fiber content. In addition, students were more likely to communicate the health benefits of a high-fiber diet to others in their lives, which inspired the name of our course: Fiber Force, as a force for awareness.

High-fiber diet to others in their lives, which inspired the name of our course: Fiber Force, as a force for awareness. We thank the UCI Microbiome Initiative for making the UCI CMEi possible, for providing research funds, and the UCI Institutional Review Board (IRB) for granting IRB approval for the study. We thank Dr. G. F. Kopp, Division of Gastroenterology, University of California, Irvine who made this study possible. The authors have no conflicts of interest to declare.

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**SUPPLEMENTAL MATERIALS**

Appendix 1: R workshop material
Appendix 2: Qiime2 workshop
Appendix 3: Grant proposal writing timeline
Appendix 4: 10-week course schedule
Appendix 5: Fiber Force course syllabus
Appendix 6: Discussion handouts
Appendix 7: Stool collection instructions
Appendix 8: Fiber Force protocols
Appendix 9: Laboratory preparation instructions
Appendix 10: Guide to laboratory notebooks
Appendix 11: Lab meeting guidelines
Appendix 12: Poster presentation guidelines
Appendix 13: Grading rubrics
Appendix 14: Diet definitions and resources
Appendix 15: UCI IRB consent form

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