Advances in Graduate Training for Engineering Built Environment Microbiomes

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Advances in Graduate Training in Microbiome Engineering in Built Environments

Abstract

Engineering of built-environment microbiomes is an evolving field that has gained increased attention in parallel with recognition of the key roles that built-environment microbiomes play in human health. Lack of tools to elucidate how microbial systems operate in built environments has impeded assessment of built-environment health and leveraging microbiomes to improve built-environment health. Microbiome engineers must integrate knowledge of microbial ecology, synthetic biology, genetics, bioinformatics, statistics, machine learning and related societal, ethical and policy implications. For real world impacts, microbiome engineers must learn to not only integrate across fields but also partner with industry to translate discovery and innovation to in-field application for societal benefit. Since many graduate training programs in U.S. universities are siloed, engineering research centers can provide unique opportunities for transdisciplinary training, immersive research, development of entrepreneurial skills, and interaction with industry partners. This paper describes the training model developed by the NSF funded Precision Microbiome Engineering Research Center (PreMiEr). PreMiEr's vision is to enable bioinformed design and operation of smart, healthy built environments through microbiome engineering and to train the next generation of engineers and scientists to work across disciplines as leaders in this emerging field. This model integrates training across five universities and multiple disciplines. PreMiEr first launched a comprehensive technical workshop series featuring core bioinformatics, data science, statistics and microbiology topics. Since trainees enter from different disciplines, it was essential to offer introductory workshops for those with no background in key areas. Additional technical and professional training evolved to address trainees self-reported learning gaps or those identified by program evaluation. These include: a Seminar Series with cutting edge overviews of research; a student lead Journal Club featuring literature review covering knowledge gaps linked to students' research; Center wide convergent research meetings to accelerate collaborative outputs and understanding of research linkages across projects; Industry sponsored Technical Workshops; and an Accelerator series to support students and faculty in moving technology innovations toward societal impacts. Results from rigorous program evaluation has shaped refinement of training with students' ratings now linking training elements to development of targeted knowledge and skills. Core competencies for engineering microbiomes in built environments (MoBE) were defined and assessed with significant student rated gains. Assessment will be further validated by faculty ratings of doctoral students' progress in these areas. This initiative is significant due to the lack of graduate-level training in the US in microbiome engineering in the built environment space.

1- Introduction

Americans spend over 90% of their lives indoors, in homes, schools, workplaces, and healthcare facilities[1]. Microbes in these built environments influence human health in multiple ways. While exposure to certain pathogens can increase health risks, emerging evidence suggests that microbes in the built environment may help prevent illness and support overall well-being [2], [3], [4]. However important, microbial ecosystems in the built environment remain poorly understood and are ineffectively managed [5], [6], [7]. Current strategies to manage microbial communities typically rely upon indiscriminate disinfection methods that eliminate all microbes, thereby disrupting microbial communities that may be beneficial for human health. Moreover, these "scorched earth" methods can lead to unintended consequences, including the selection for antimicrobial resistance [8]. With growing recognition that sterility is not synonymous with health, there is a need for microbiome-centered approaches to engineer healthier indoor spaces.

Recognizing the importance of microbes of the built environment (MoBE), there is growing interest in monitoring, managing, and even modifying these microbial communities to benefit human health[4]. Microbiome engineering as a field focuses on manipulating microbial populations to harness their capabilities and functions. By capitalizing on microbial functions, microbiome engineers seek to benefit human health, environmental health, and industrial application. The capacity to engineer microbiomes requires fundamental understanding of community ecology and the ability to track, control and model microbial interactions [9], [10]. To apply microbiome engineering to real world built environment systems, engineers should be able to evaluate the societal, ethical and policy implications of their innovations[11], [12], [13]. Furthermore, to translate their innovations, graduate students will need to train within and across fields along with partnerships with industry to emerge as professionals who spearhead and define this field [14], [15].

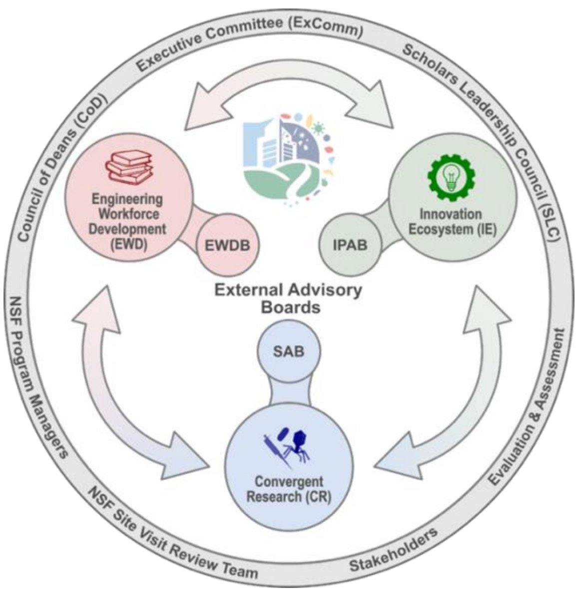
This current paper describes the graduate training model developed by the NSF funded Precision Microbiome Engineering Research Center (PreMiEr). Launched fall of 2022, the center spans five partner institutions: Duke University, North Carolina State University (NCSU), North Carolina Agricultural & Technological State University (NCAT), the University of North Carolina- Chapel Hill (UNC-CH) and the University of North Carolina- Charlotte (UNC-C). PreMiEr's vision is to enable bioinformed design and operation of smart, healthy built environments through microbiome engineering with the mission of developing innovative approaches to engineer built environment microbiomes that promote beneficial microbes while preventing the spread of pathogens. Achieving this vision requires parallel training of the next generation of engineers and scientists to work across disciplines and become leaders in this emerging field. While much of graduate training remains siloed in U.S. universities, convergent research and engineering centers provide unique opportunities for transdisciplinary training and immersive research as well as building industry connections for societal application.

2- Engineering Research Center Overview

PreMiEr aims to redefine the current paradigm of built environment (BE) microbiome management by advancing a bioinformed framework for real-time sensing, predictive risk assessment, and precision microbiome interventions that foster healthier indoor environments.

Through integrating convergent research, workforce development, and translational partnerships, PreMiEr's focus is on generating methods for managing microbial ecosystems in the BE, that move beyond pathogen elimination and support beneficial microbial communities. This shift from *indiscriminate disinfection to targeted, microbiome-centric engineering* is both a scientific frontier and a public health imperative.

Figure 1. PreMiEr Foundations Integrate Research with Training and Translation.



PreMiEr is comprised of three integrated foundations (Figure 1.): Convergent Research (CR), Engineering Workforce Development (EWD), and an Innovation Ecosystem (IE).
In the Convergent Research (CR) foundation, researchers work in interdisciplinary teams to co-develop sensing tools, risk models, and interventions related to MoBE.

Engineering Workforce Development (EWD) programming is interwoven with Convergent Research (CR) to develop a technically skilled, interdisciplinary workforce equipped for holistic BE management and innovation through microbiome engineering.

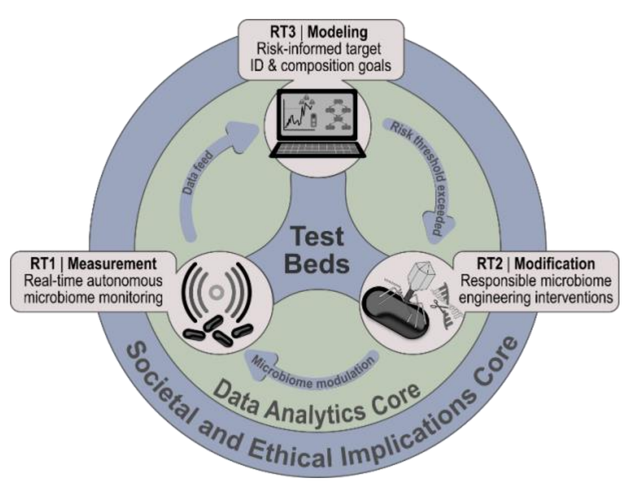
Innovation Ecosystem (IE) initiatives are aligned with training and accelerate translation by aligning research with industry, community, and policy needs: a) Industry and stakeholder input shapes research directions; b) Scholars build entrepreneurial and translational skills; and c) Industry partners leverage PreMiEr testbeds for R&D.

Each foundation is guided by reviews from their respective advisory boards as well as the comprehensive evaluation led by the evaluation team. Collectively, these foundations form a dynamic, adaptive framework connecting training with discovery and deployment.

3- Research Organization

Convergent Research (CR) is organized across three integrated Research Thrusts (RTs): Microbiome measurement, Modification, and Modeling and is supported by the Data Analytics and Societal & Ethical Implications Cores. (Figure 2).

Figure 2. PreMiEr's Research Thrusts & Cores



Achieving PreMiEr's vision depends on development of three enabling technologies mapped to research thrusts:

1. Advanced tools for real-time detection and spatial mapping of MoBE (RT1);
2. A generalized toolbox for targeted modification of microbiomes to reduce pathogen risk and encourage healthy MoBE (RT2);
3. An integrative framework to evaluate MoBE-health and guide interventions (RT3).

PreMiEr's research is focused on two main "Use Case" built environment systems. Use Case 1 focuses on *healthcare and hospital* settings, where microbiomes in the built environment play an important role in the transmission of healthcare-associated infections. Healthcare-associated infections (HAIs) affect 1 in 31 patients daily [16] with direct costs of HAIs to hospitals estimated at $28- $45 billion annually [17]. Engineering solutions for Use Case 1 should reduce pathogens in the hospital setting, without introducing selective pressures for antimicrobial resistance and virulence. Use Case 2 focuses on *residential, commercial, and occupational* settings where exposure to indoor mold can exacerbate respiratory conditions. Engineering solutions in Use Case 2 focus on prevention and mitigation of fungal growth in built environments, without disrupting potentially beneficial microbiomes or creating microbial deserts.

Center research is conducted across an array of integrated test beds (Figure 3). Test beds range from simulated and highly-controlled to real-world environments and allow researchers to develop, evaluate, and iterate design of MoBE engineering technologies under relevant conditions. Scholars gain immersive research experience across test beds as well as training in systems thinking and technical depth.

Figure 3. PreMiEr's Test Beds

The Data Analytics (DA) Core provides input on research design and data analysis across research projects to achieve harmonization, interoperability, and reproducibility of data across Center research as well as scholar training. The Societal and Ethical Implications (SEI) Core supports responsible innovation and guides ethical and societally relevant translation of scientific advances for real-world impacts.

4- Graduate Training Overview

Graduate training is a key priority of the Engineering Workforce Development (EWD) foundation. The overarching goal of EWD programs is to train the next generation of engineers and scientists to lead future advancement in engineering the microbiome for solutions at the interface of health and the built environment. Components include: a) convergent research experiences integrating microbiology, engineering, genomics, data science and social science, and b) core technical and professional training informed by c) societal and ethical implications.

Center-wide training is accessible across campuses for scholars (undergraduate, masters, doctoral students and post-doctoral associates) as well as faculty and staff. This current paper focuses primarily on *doctoral students' training in general research and MoBE specific areas* and related outcomes. Training is guided by the EWD leadership team, which includes two of the co-authors.

5- Training Design and Implementation

At startup, PreMiEr primarily focused on general research training and core technical skill development fundamental to microbiome research and engineering. As the center's research evolved, with more focused research aligned with hospital and residential applications, new MoBE engineering training elements were developed, integrating evaluation team and NSF site visit feedback to define and build competencies in microbiome research and engineering in the built environment space.

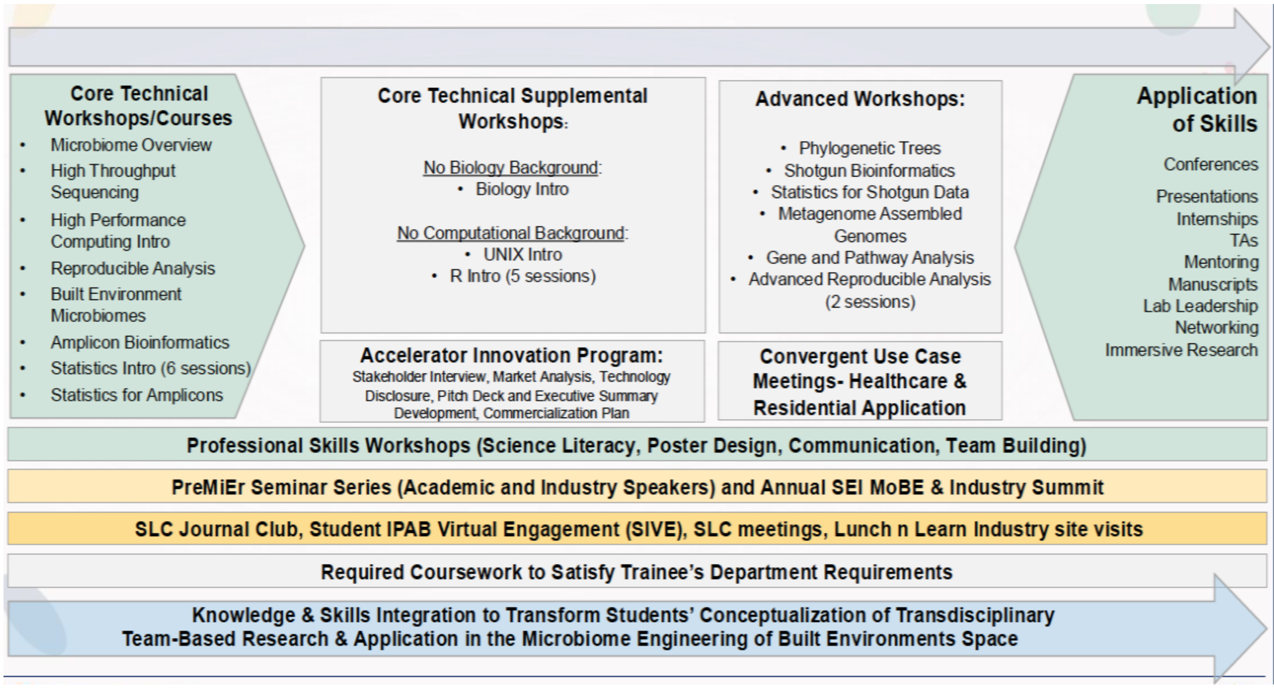
5-1 Pedagogy. To address the increasing complexity of societal problems, scientists and engineers working in complex systems, such as microbiomes in built environments, need convergent thinking and skills that enable them to integrate a broad range of disciplinary approaches and tools, critically evaluate information, and work effectively in teams [18]. Many traditional approaches to graduate training focus on disciplinary depth without integration across disciplines [19]. In contrast, the training model presented here is built on the premise that disciplinary depth combined with interdisciplinary breadth informed by stakeholder input and targeted MoBE technical training, will advance trainees development of innovative approaches that address real-world problems and provide students with a systems framework for tackling such complex problems [20].

5-2 Training Model and Components. PreMiEr's comprehensive educational structure includes an array of technical, professional and entrepreneurial elements that provide both breadth and depth and build transferable workforce skills. This model adapted features of a successful National Science Foundation Research Traineeship Program (NRT) integrating bioinformatics for microbiome research and engineering, co-led by two of the co-authors [21].

Training elements, shown in Figure 4 below, include: a) a core technical series that provides bioinformatics, statistics and data science fundamentals for MoBE engineering and research; b) skill application opportunities; c) an Accelerator series to build entrepreneurial skills; and d) Professional Skills workshops to build transferrable skills for success across sectors; and e) relevant Seminars, Journal Club, and Lunch & Learn Industry engagement events.

These training elements are supplemented by an annual Societal and Ethical Implications (SEI) conference and an Industry Summit uniting researchers and industry to build translation and career paths. Training for disciplinary depth is ongoing through required departmental courses across disciplines. Faculty also integrate PreMiEr findings into courses across sites as described in sections to follow.

Figure 4. PreMiEr's Overall Graduate Training Model. Adapted from [21].



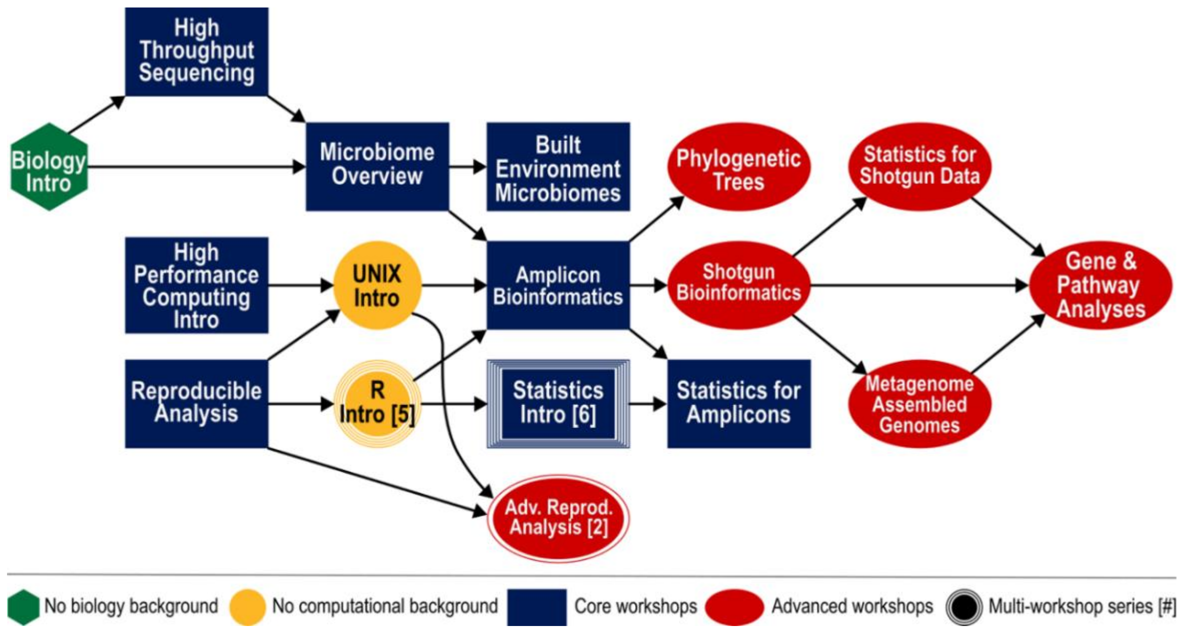
5-3 Startup Implementation- Core Technical Workshop Series. To meet the objective of developing key technical training for graduate and post-doc scholars to conduct research and engineering on BE microbiomes, a comprehensive technical curriculum was launched fall of 2022, mapped to key topics and gap areas shown in Figure 5 below.

Technical topic development included pedagogical considerations by providing entry level skills training to accommodate varying disciplinary backgrounds (introductory workshops in biology, UNIX, and R for individuals without biology and/or computational backgrounds to build foundational knowledge for students across disciplines). The overarching strategy for selecting technical topics for high impact included: topics at the intersection of what students lack from previous training but necessary to carry out MoBE research and engineering. With these criteria in mind, topics selected for this workshop series fall into four major categories below along with associated learning objective content:

1. Biology, microbiome, and metagenomic experimental methods: the biology basics necessary to understand microbiomes of the built environment and the theory underlying experimental methods common for studying microbiomes;
2. Reproducible analysis, high-performance computing, and data science: foundational computational skills needed as background for bioinformatic and statistical analysis;
3. Statistical foundations: the statistical background necessary to understand the bioinformatic and statistical analysis methods that they will use; and
4. Bioinformatic and statistical analyses: how to go from the raw data generated by common microbiome experiments to generate meaningful results.

These workshops are designed to prepare engineers and scientists to measure impacts of engineering interventions using state-of-the-art microbiome sequencing approaches. They also enable researchers to interpret and evaluate microbiome sequencing results to modify the design of engineering solutions based on observed or modeled outcomes. The addition of workshops with Industry partners to this series help develop workforce skills actually used in bioindustries. Workshops are primarily hybrid to provide access across PreMiEr's five university partner campuses which are also in driving distance of each other in North Carolina. When hands-on in person workshops are hosted, they are often hosted on more than one campus. While this series was developed as part of core doctoral student training, they are also accessible center wide for masters students, postdocs, faculty, and research staff. Workshops cross-train researchers in microbiology, engineering, and other empirical sciences to work alongside theorists, model builders, and computational scientists.

Figure 5. PreMiEr's Core Technical Workshop Series Topics

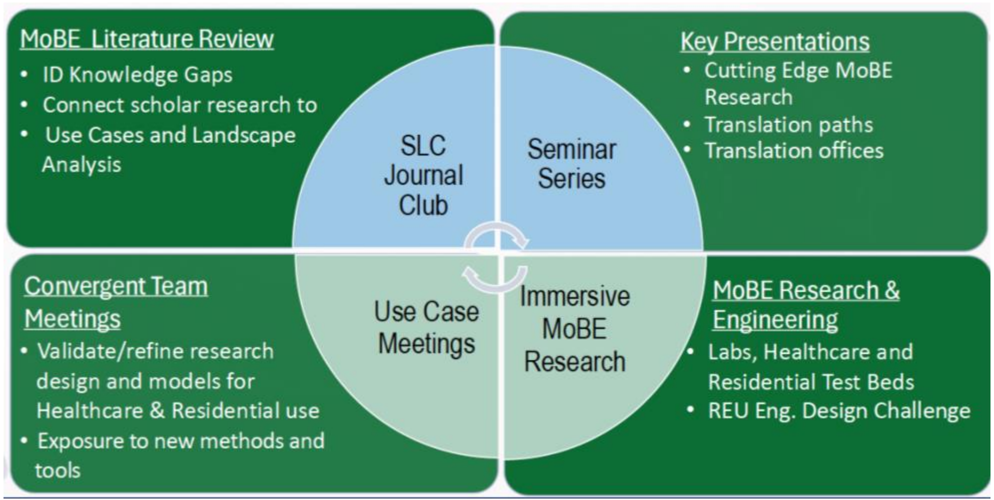


6- Refinement and Advances in Training

6-1 Progression in MoBE training. New programming was developed in response to requests from scholars and recommendations from the evaluation team that included: a) scholars needs to better understand their role in the center; and b) how their research fits into overarching goals. In addition, recommendations from the year 2 NSF Site Visit review included the need to elucidate gaps in knowledge related to landscape analysis in the MoBE space as well as the need for additional state-of- the art training in microbiome engineering in BE specific areas.

By year 3, these new or refined training experiences described below were launched to further advance MoBE skills and knowledge. These elements are now woven throughout PreMiEr's evolving programming. Elements in this series (Figure 6) represent current offerings and are an outgrowth of the progression in training described in the subsequent section.

Figure 6. MoBE Specific Engineering Training Elements



6-2 Initial Training Elements.

Fall 2023, a virtual *Lunch & Learn Seminar Series* began with combined focus on research relevant topics along with professional development workshops. Speakers were mostly PreMiEr faculty presenting center-funded projects. Based on assessment, the need for more opportunities for scholars to interact across sites was identified, and this series was replaced by the Research-in-Progress series.

Spring 2024, the *Research-in-Progress Series* was launched for scholars to discuss their own research projects. Of these, talks covered microbiome engineering areas and developing engineering tools for plumbing associated microbes. This series provided scholars opportunities to discuss common technical questions while gaining insights for collaboration across projects.

6-3 Current Revised MoBE Training Elements.

Fall 2024, the *Scholars Leadership Council (SLC) Journal Club* was formed to address knowledge gaps in current MoBE relevant literature. Scholars or invited speakers review: 1) cutting edge literature relevant to microbiome engineering and microbes of the BE; and 2) discuss connection of scholars projects with Use Cases and knowledge gaps. Scholars exercise leadership, build presentation skills, and practice cross-disciplinary communication. Importantly, students are guided in connecting their individual research to the broader aims of the MoBE field and identifying research connections with peers and broader Center goals.

Spring 2025, the revised *Seminar Series* replaced the *Research in Progress* series to bring in primarily external speakers based on their contributions to the field of MoBE engineering. Speakers, from a range of disciplines, cover highly relevant current issues in MoBE and modern approaches to microbiome engineering. Presentations have contributed to better understanding of focus on healthcare-associated infections, understudied transmission from premise plumbing, phage cocktail deployment for controlling microbiomes in premise pluming, and innovative methods and opportunities for advancement.

Fall 2024, the *Health & Residential Use Case Convergent Team Meetings* were launched and attended by researchers across all funded research project teams. Meetings serve as system wide integrators of research design and outputs across multiple projects. They provide exposure to new methods, highlight insights from inter-disciplinary colleagues, and help identify knowledge gaps while ensuring that research remains relevant to Center goals. Pre-meeting agenda and consistent structure include: a) a short "work in progress" presentation followed by a 10 minute Q&A.; and b) a 2-3 minute report out by each research group on their progress. Recent meetings have asked trainees to describe the linkages of their project outputs to other research projects. Follow-up emails summarize meeting content, topics linkages, and assign agreed upon next step tasks further consolidating and accelerating productivity. Use Case meetings have been critical integrators of interdependent research projects across campuses, thrusts and cores. Since graduate students and postdoctoral associates are the primary presenters, meetings provide an open forum for learning to discuss research design through varying disciplinary lens and connect to frontier knowledge, and methods. Faculty leads consistently attend and provide feedback for refinement and next steps.

Immersive Research Experiences have been ongoing since startup and are closely tied to PreMiEr's thrusts and test bed initiatives. Graduate students gain mentored experience in faculty labs and in Healthcare and Residential test beds.

7- The Case for MoBE Engineering Competencies to Guide Training and Assessment

Parallel with the creation of new MoBE training elements, EWD leadership focused on defining MoBE competencies. Many trainees will identify as "microbiome engineers," who lead with microbiome-focused knowledge and skill sets as they "design, test, build, and learn" [9] from biological and built environment systems. Such skills require graduate training across multiple fields, including microbiome sciences, building science, biological engineering, and environmental engineering. However, no established graduate-level framework currently exists to formally integrate these domains into a cohesive training pathway. To address this gap and ensure consistent, high-quality workforce preparation, EWD leadership developed a set of MoBE engineering competencies to guide the design, implementation, and assessment of MoBE-focused training across the Center.

In the U.S., multiple universities offer formal graduate degrees in biomedical engineering, bioengineering, and biological engineering. At present, only one institution, Colorado State University, offers a graduate certificate explicitly framed around *microbiome engineering* [22]. Despite the increasing relevance of this field for high impact societal benefits, no programs in the U.S. offer a standalone MS or PhD in microbiome engineering. Without formalized programs or curricula, students have limited pathways to become leaders in the field of microbiome engineering. The absence of curricula and standards also leaves a gap for faculty who wish to align coursework and curricula with workforce development.

In light of these curricular gaps, EWD leadership developed a set of core competencies to guide training. We adapted the learning objectives for Colorado State University's graduate certificate in Microbiome Sciences and Engineering as well as the research framework presented in [10] to develop competencies specific to MoBE engineering. These competencies were drafted with an outcome-based approach; envisioning what our graduates should be able to *do* when they join the workforce. While demonstrating the core foundational research and engineering skills included in the ASEE's engineering competencies model [23], our trainees should demonstrate additional competencies necessary for microbiome engineering. These include the ability to:

1. Understand the MoBE Landscape
   a. Describe the role of microbiomes in human, environmental, and industrial systems.
   b. Describe core problems in the field of microbes of the built environment.
   c. Explain current methods for designing and engineering microbiomes.
2. Apply MoBE and Microbiome Engineering Knowledge
   a. Apply knowledge of microbial physiology, ecology, and/or evolution to propose methods for engineering the microbiome of the built environment.
   b. Employ state-of-the-art methods for characterizing microbiomes (long-read amplicon, metagenomic sequencing) and discuss limitations of these approaches in the built environment.
   c. Design an experiment to measure the impact of engineering interventions on microbiomes of the built environment.
3. Appraise and Evaluate MoBE Research and Engineering Solutions
   a. Provide useful suggestions to advance others' research at Use Case and/or lab meetings.
   b. Predict the impact of engineering interventions on microbiomes in the built environment.
   c. Appraise MoBE engineering solutions based on their societal and ethical implications.
   d. Modify the design of engineering solutions based on observed or modeled outcomes.

8- Methods

8-1 PreMiEr's Overall Evaluation. The center has a comprehensive evaluation plan with formative and summative components to assess programming quality, delivery and alignment with goals and objectives (formative) and short/medium outcomes and longer term impacts (summative). A mixed methods approach connects data from one source with another to triangulate findings, integrating qualitative and quantitative data to minimize biases associated with single source collection. Analyses include descriptive and inferential statistics and identification of recurrent themes for summarizing interviews and open-ended survey questions.

8-2 Study Questions. The current study covers a subset of the broader evaluation to assess: a) quality and delivery of key content and training elements relevant to MoBE research and engineering; and b) impacts of revised training and processes to improve knowledge and skills among doctoral students in three key areas: 1) understanding PreMiEr's mission; 2) systems thinking and application to research; and 3) MoBE specific competencies in research and engineering.

Formative evaluation questions are listed below and map to findings in the Formative Results section.

<u>To what extent and in what ways:</u>

1. Does PreMiEr develop key technical training to equip students with expertise to conduct research and engineering on microbiomes in the built environment space?
2. Are core training elements of high quality, accessible across universities, and aligned with desired outcomes?

Summative evaluation questions listed below map to findings in the Summative Results section. In what areas and to what extent do doctoral students:

1. Gain understanding of PreMiEr's mission?
2. Demonstrate systems thinking and application to research?
3. Develop competencies needed for MoBE research and engineering in particular?

8-3 Data Sources. Data sources for this study, listed below, are a subset of data collection during PreMiEr's comprehensive year-round evaluation activities. These include:

1. PreMiEr's Annual Multi-Site Survey with new questions to assess MoBE competencies.
2. Evaluator observations of Use Case meetings, seminars, workshops and other training events.
3. Administrative data on participation levels and outputs (courses, training activities etc.).
4. Post Technical Workshops Surveys on a subset of the technical workshop series.

8-4 Participants.

Recruitment. a) The technical workshop series evaluation was conducted as part of an NIH-R25 funded Research Education Program (Grant# R25 AI140495). Participants were recruited from among the workshop attendees, and data was collected using a course-evaluation format with anonymous Post-Workshop Surveys administered after each session. Participation was voluntary. Results were shared with co-authors, one of whom was a lead instructor in the series. b) Participants in all other components for this study were recruited by emailing all participating doctoral students across five campuses for the last three years as part of PreMiEr's IRB approved Annual Evaluation. Participation in the study was voluntary. The number of doctoral students completing PreMiEr's Annual Multi-Site Survey is reported in the relevant Results sections.

Demographics. Across three years, there were 62 doctoral student respondents to PreMiEr's Annual Multi Site Survey, spanning 15 departments: Biology, Biological Sciences, Biostatistics and Bioinformatics, Bioinformatics and Genomics, Biomedical Engineering, Civil and Environmental Engineering, Computer Science Engineering, Electrical and Computer Engineering, Environmental Sciences and Engineering, Marine Sciences, Mechanical Engineering and Materials Science, Molecular Genetics and Microbiology, Population Health, Public Administration, Statistical Sciences.

9- Findings-Formative

9-1 *Development of key technical content for microbiome research training.*

Technical Workshops. To meet the objective of developing key content for graduate students to begin conducting MoBE research and engineering, EWD leadership launched a well-planned technical curriculum, mapped to core topics and gap areas described in previous section and shown in previous Figure 6. Topic development included pedagogical considerations of entry level skills by offering introductory workshops in biology for individuals without biology, and data science workshops for those without computational backgrounds. This curriculum has been successfully delivered for the last three years with hybrid and hands-on in person workshops across campuses. Below are workshops delivered Year 2 along with attendance at workshops. The 25 workshops shown below represent the Year 2 series and have been repeated each year since startup so that trainees entering PreMiEr can continue to benefit from this series.

Date	**Table 1.** PreMiEr Technical Training Series 2023-24	Attendees	Access
2023-11-6	Exploratory analysis & visualization, Part 2 *	16	Hybrid
2023-11-13	Exploratory analysis & visualization, Part 3*	16	Hybrid
2023-11-20	Bring your own Data- Hands on practice*	7	Hybrid
2024-01-15	Molecular training for digital and qPCR	6	In person
2024-01-22	Breakdown of an experiment*	8	Hybrid
2024-01-29	Probability, distributions, and confidence intervals*	8	Hybrid
2024-02-05	Hypothesis testing and power/sample Size*	7	Hybrid
2024-02-12	Linear regression, categorical predictors, interaction effect*	7	Hybrid
2024-02-19	Logistic regression and classification models*	7	Hybrid
2024-02-26	High-dimensional predictive models, cross-validation*	7	Hybrid
2024-03-04	Introduction to high-throughput sequencing*	18	Hybrid
2024-03-18	Amplicon bioinformatic and statistical analysis*	3	Hybrid
2024-03-25	Phylogeny	16	Zoom
2024-04-01	Sequence classification methods for shotgun metagenomics	15	Virtual
2024-04-08	Beyond shotgun: Hi-C metagenomics workflow	12	Virtual
2024-04-15	Statistics for shotgun metagenomics	10	Virtual
2024-08-26	Biology and Microbiomes	8	Hybrid
2024-09-09	Overview of Microbiome Lab Techniques	15	Zoom
2024-09-16	Industry - Lab-in-a-Box Workshop virtual session	24	Zoom
2024-09-23	Introduction to Unix and cluster computing*	3	Hybrid
2024-09-30	Industry Lab-in-a-Box Workshop	5	In person
2024-10-04	Industry - Lab-in-a-Box Workshop	5	In person
2024-10-07	Introduction to R*	21	Hybrid
2024-10-21	Intro to data driven research*	16	Hybrid
2024-10-28	Intro to data driven research*	16	Hybrid

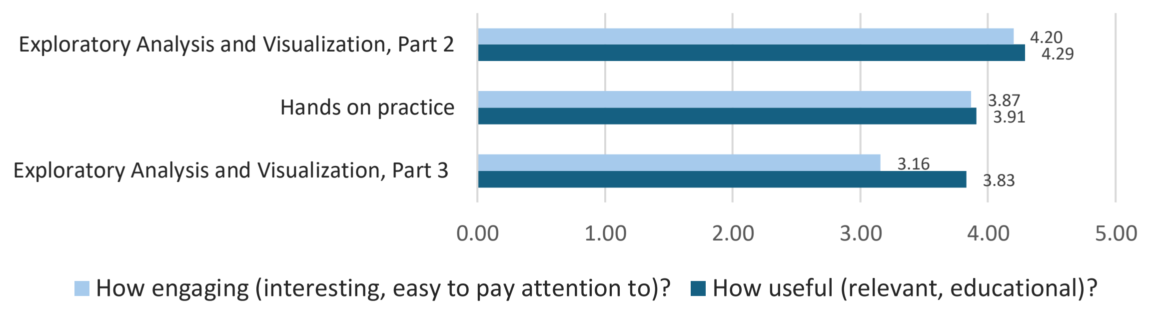
* Workshops funded by an NIH-R25 sponsored Grant# R25 AI140495 and co-led by one of the co-authors and offered in collaboration as part of PreMiEr's technical series.

9-2 ***Development of quality training linked to outcomes.***

Shared evaluation was coordinated between R25 program leadership and PreMiEr's evaluation team. Evaluation was divided into two parts on different topic areas. Data sources were Post-Workshop Surveys administered after each workshop. Data Science Workshops (highlighted in grey above), and a second subset of Statistics Workshops (highlighted in blue above) were formatively evaluated as part of the R25 shared evaluation results below.

<u>Data Science Workshops.</u> Survey links were sent immediately after each workshop with the exception of the 11/6/23 workshop which was not surveyed. The R25 team shared anonymous data with PreMiEr's evaluation team who summarized findings below. Workshops in this series were designed to: a) build knowledge from introductory level and b) provide hands on practice for application. Attendance ranged from 7 to 16 per workshop (Table 1 above). The survey response rate ranged from 50% to 100%. All workshops were offered in hybrid form. More respondents attended via zoom than in-person. Data Science sessions for both modalities were rated as: very useful (relevant, educational) and very engaging (interesting, easy to pay attention to) for 1 of 3 workshops. Two workshops were rated moderate to very for usefulness and engagement. Key results are shown in Figure 7 below.

Figure-7. Ratings of Usefulness and Engagement Data Science Workshops
(Scale: 1-not at all, 2- slightly, 3- moderately, 4- very, 5-extremely)

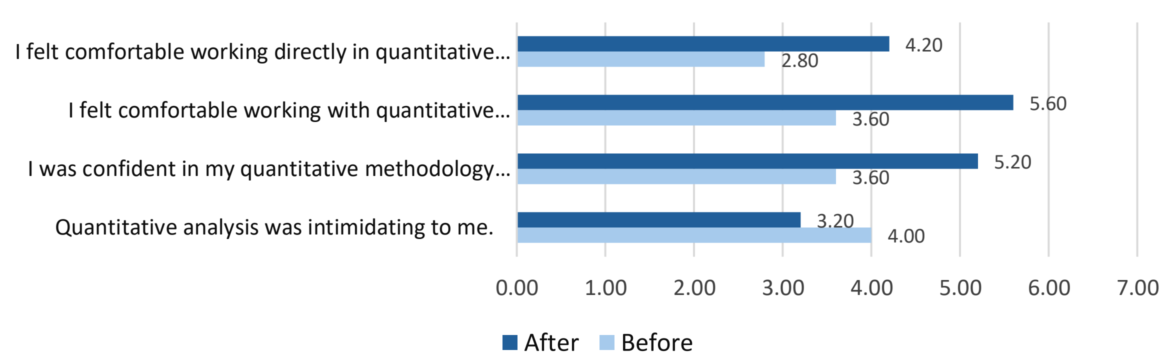


Strong appreciation was noted for hands on exercises and availability of training information online. Suggestions for improvement include**:**

- Check in with students about pace of introductory session.
- During class, ask if students need more information and or help completing examples.

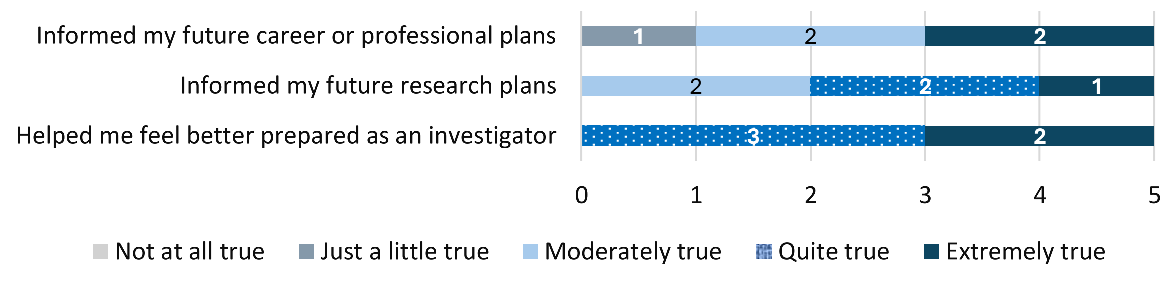
*Statistics Workshops***.** Five participants responded to the post workshops survey (1 postdoc, 2 research staff, 2 graduate students). The majority attended in-person. Respondents varied in amount of prior formal quantitative training, but all were similar in experience (somewhat frequent use, n=5). Respondents indicated sessions were appropriate length. All session components (lecture, running code, time for questions, case studies) were seen as at least moderately useful; lecture and case studies were seen as most useful. Suggestion for improvement included: provide more supplemental/additional resources (n=2), hands-on and practice time(n=2), diverse datasets (n=1), simpler explanations (n=1). All respondents reported absolute value improvement on multiple aspects of confidence working with quantitative methodologies (Figure 8). No tests of significance done due to small sample size.

Figure 8. Self-Rated Gains in Confidence in Quantitative Methods (n=5)
(Scale: 1=not at all to 7=extremely)



The workshop series had a clear effect on participants' sense of preparation as an investigator, and they also informed future research and professional/career plans (Figure 9 below).

Figure 9. Rating of Impact of Workshops on Career Preparation (n=5)



Response numbers were small on the post-workshop survey summaries shared by the R25 team to date. Data collection is ongoing and will be compiled across the four years for further review this year.

9-3 Accessibility of training across universities and disciplines. PreMiEr's core technical training series provides hybrid access for the majority of workshops across university partners. The subset of Technical Workshops co-hosted by Industry partners have been offered across two or more campuses to allow in-person attendance. All of PreMiEr's partner universities are located within driving distance of each other which also allows for attendance of in-person events such as the annual Industry Summit meeting. Select center-wide meetings rotate among campuses. Supplemental series (such as the Seminar Series and Journal Club are all hosted virtually). All training events are advertised by weekly newsletter, website, and email reminders. Faculty success integrating multidisciplinary content and engineered systems focus into courses is shown in Table 2 below across years 1 and 2 (data under collection for year 3). For multidisciplinary content, 100% integration was reported for new courses, 89% for courses with added Center content, and 52% for workshops. Engineered system focus was reported for 25% of new courses, 39% of courses with PreMiEr related content and 21% of workshops. For workshops, 71% were accessible across university partners.

Table 2. PreMiEr Courses and Additional Training Across Two Years (9/1/22-10/31/24)

Training Elements	Engineered Systems Focus		Multidisciplinary Content		Team Taught-Faculty > 1 Department		Undergrad. Level		Graduate Level		Used at > 1 ERC Institution		Total-All Years
	N	%	N	%	N	%	N	%	N	%	N	%	N
New Courses	1	25%	4	100%	2	50%	1	25%	4	100%	2	50%	4
Courses with ERC Content	11	39%	25	89%	6	21%	13	46%	20	71%	1	4%	28
Workshops, Short Courses, Webinars	12	21%	29	52%	5	9%	25	45%	53	95%	40	71%	56

9-4 Linkage of Training Elements to Targeted Outcomes**.* To understand which training elements were linked to development of desired skills, doctoral students were asked to rate elements (Annual Multi-Site Survey) that contributed to development of their skills in targeted areas**.** The percentage of doctoral students endorsing each element for development in each area is shown in Tables 3 and 4 below. The number of students' ratings each element varied by participation in each activity, so percentages were used to offset uneven Ns. The patterns of endorsement indicate that for both years 3 and 4, key revised training elements are associated with intended outcomes across targeted areas. For example, for both years, participation in the Use Case and Industry Summit meetings showed strongest endorsements for gains in collaboration, understanding PreMiEr's Vision as well as state-of the art of MoBE. The Scholars Leadership Council (SLC)*** meetings showed strongest endorsement both years for building collaboration skills. The Seminar Speaker series, which included exceptional state-of-the art landscape overviews of MoBE engineering, received strongest endorsements for understanding in this area as did the SLC Journal Club in which state of the art articles are reviewed (100% endorsement Year 4). Technical gains were most strongly associated with the Technical Workshop series.

Table 3. Yr 3 Doctoral Students' Ratings of Training Linked to Learning & Skill Development

2024-25 Elements Linked to Learning & Skill Development *Dark Green=highest impact Medium Green=mid-range Light Green=lowest impact*	Targeted Skills and Understanding			
	Collaboration	Understanding PreMiEr's Vision	Understanding State of the Art of MoBE	Technical Skills
Use Case Meeting (n=17)	76%	88%	53%	18%
SLC Journal Club (n=16)	63%	44%	75%	13%
SLC Meetings (n=15)	93%	53%	27%	7%
Seminar Speaker Series (n=18)	39%	28%	89%	22%
Technical Workshop Series (n=11)	45%	18%	18%	91%
Industry Summit Meeting (n=10)	80%	80%	60%	20%

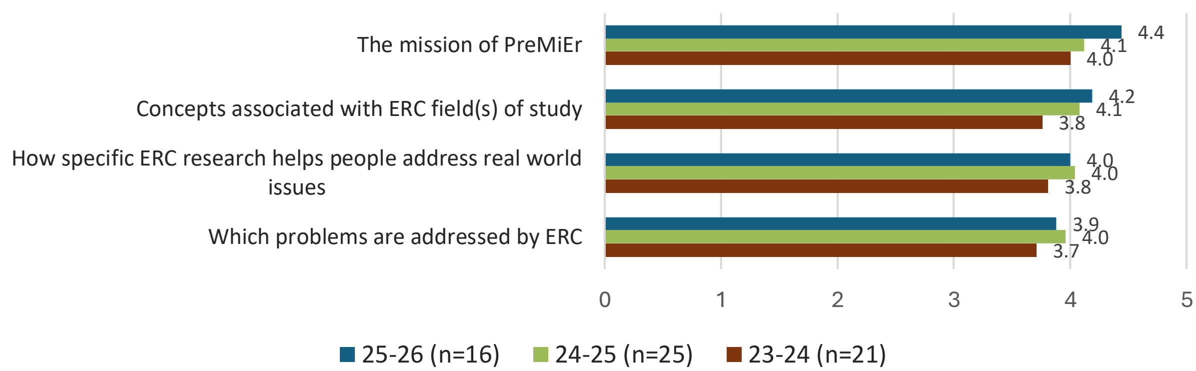
Table 4. Yr 4 Doctoral Students' Ratings of Training Linked to Learning & Skill Development

2025-26 Elements Linked to Learning & Skill Development *Dark Green=highest impact Medium Green=mid-range Light Green=lowest impact*	Targeted Skills and Understanding			
	Collaboration	Understanding PreMiEr's Vision	Understanding State of Art of MoBE	Technical Skills
Use Case Meeting (n=10)	80%	80%	60%	40%
SLC Journal Club (n=6)	17%	0%	100%	50%
SLC Meetings (n=7)	86%	57%	14%	0%
Seminar Speaker Series (n-8)	38%	13%	100%	38%
Technical Workshop Series (n=7)	43%	0%	0%	86%
Industry Summit Meeting (n=11)	82%	64%	73%	36%

10- Findings- Summative

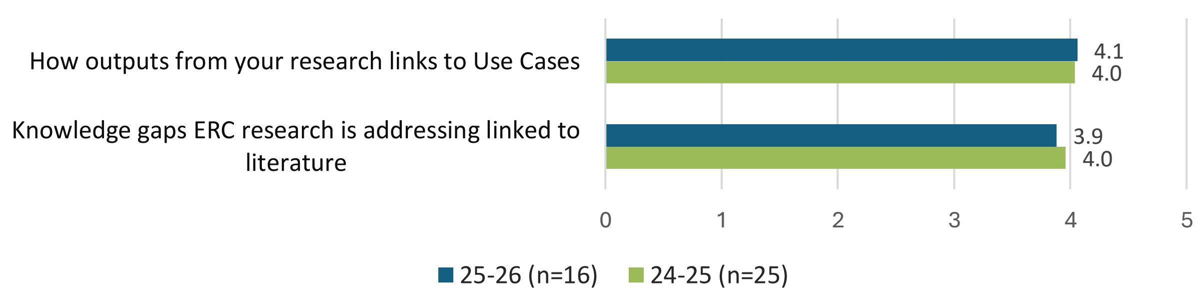
10-1 *Gains in understanding PreMiEr's Mission.* Doctoral students gave positive self-ratings (Annual Multi-Site Survey) all three years for understanding PreMiEr's Mission, concepts, problems addressed, and how Center research helps people address real world problems. Comparison of ratings showed slight absolute value increases from years 2 to 4 (Figure 10).

Figure 10. Doctoral Students' Ratings-Understanding PreMiEr Mission Years 2-4
(Scale: 1- not at all, 2- very little, 3- somewhat, 4- quite a bit, 5-a great deal)



10-2 *Increases in students' systems thinking and application to research.* When asked on survey (last two years) to rate their understanding of how outputs from their research links to Use Cases and of knowledge gaps PreMiEr addresses linked to literature, doctoral students indicated "quite a bit" of understanding (Figure 11) in both areas over the last two years.

Figure 11. Doctoral Students' Ratings- Understanding Linkages of Research to Use Cases and Knowledge Gaps Years 3-4
(Scale: 1-not at all, 2- very little, 3- somewhat, 4-quite a bit, 5-a great deal)



Furthermore, doctoral students report impacts that Use Case meetings are having on their *systems thinking, collaborative learning and integration.* Doctoral students were asked by survey "What has been the value added of Use Case meetings for you as a researcher in PreMiEr?". One student's verbatim response is shown below, punctuated as written. It is representative of collective responses across the majority of student respondents (n=16) on "value added" of these meetings.

"To effectively evaluate the value added by Use Case meetings, let's break it down into key aspects.
<u>Bridge Research and Application</u>: By focusing on specific use cases, meetings help researchers align their work with real-world problems, enhancing translational impact of their findings.
<u>Collaborative Learning:</u> These meetings promote cross-disciplinary collaboration, allowing researchers to exchange ideas, learn from peers, and integrate diverse perspectives.
<u>Focus and Direction:</u> Researchers gain clarity about objectives and deliverables of their projects, enabling better prioritization and strategic planning.
<u>Feedback and Iteration:</u> Discussions in Use Case meetings provide constructive feedback, helping refine methodologies, improve design, and troubleshoot issues".

10-3 *Development of competencies for MoBE research and engineering.* Doctoral students were asked on PreMiEr's Annual Multi-Site Survey to rate their knowledge and/or skills in microbiome engineering in the BE space at entry and currently. Figures 12-14 below show significant gains for doctoral students' ratings from entry to current status (t-tests- significant at **p≤ 0.0005 to *p≤ 0.0001 range; bars show standard error of the mean).

Ratings across the three MoBE competency areas indicate advances from *some/intermediate* ability to *above average* knowledge and understanding of the MoBE landscape, and ability to appraise and apply MoBE engineering solutions. Students' year in program [(1st (n=3), 2nd (n=5), 3rd (n=4), 4th (n=2)] was mixed for ratings of skill levels with more data needed to elucidate trends. These findings will be compared with research advisor ratings of student skills in MoBE competency areas for further validation.

Figure 12. Knowledge and Understanding of MoBE Landscape
(1=No ability, 2=Some ability, 3=Intermediate, 4=Above average, 5=Proficient, n=14)

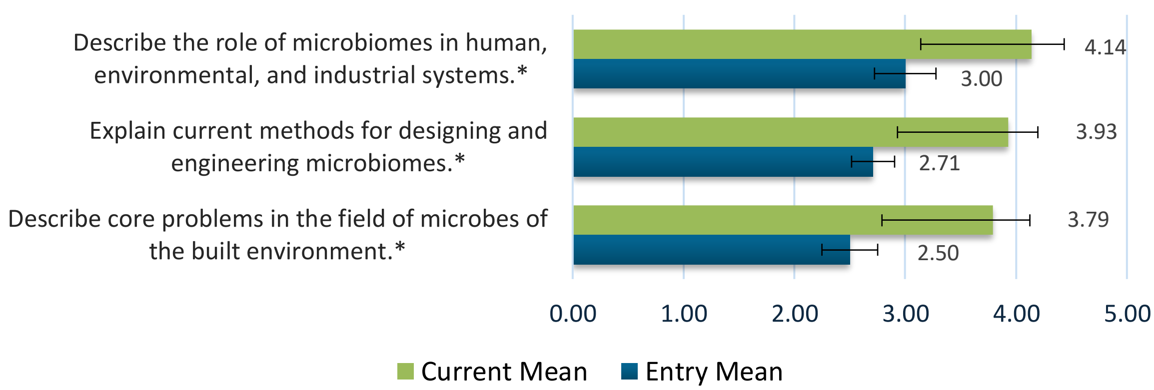


Figure 13. Appraisal/Evaluation of MoBE Research and Engineering Solutions
(1=No ability, 2=Some ability, 3=Intermediate, 4=Above average, 5=Proficient, n=14)

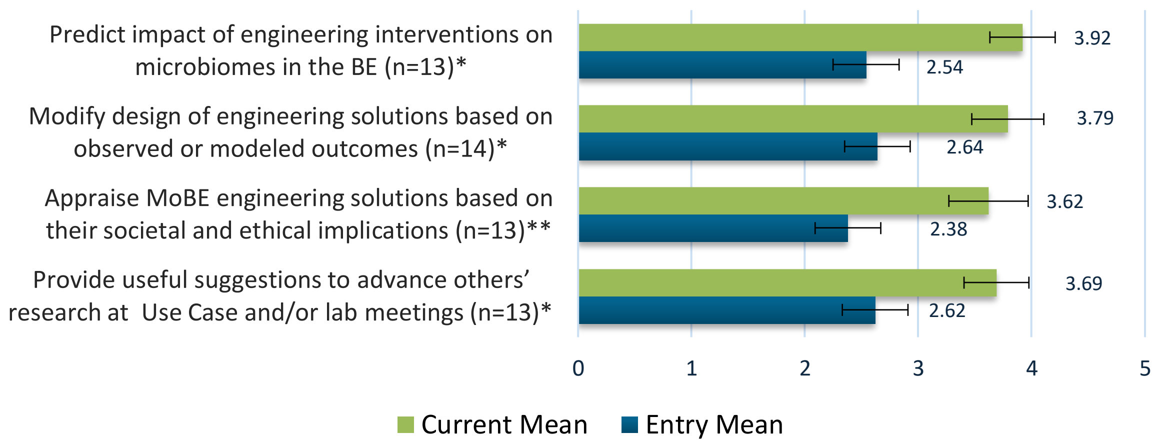
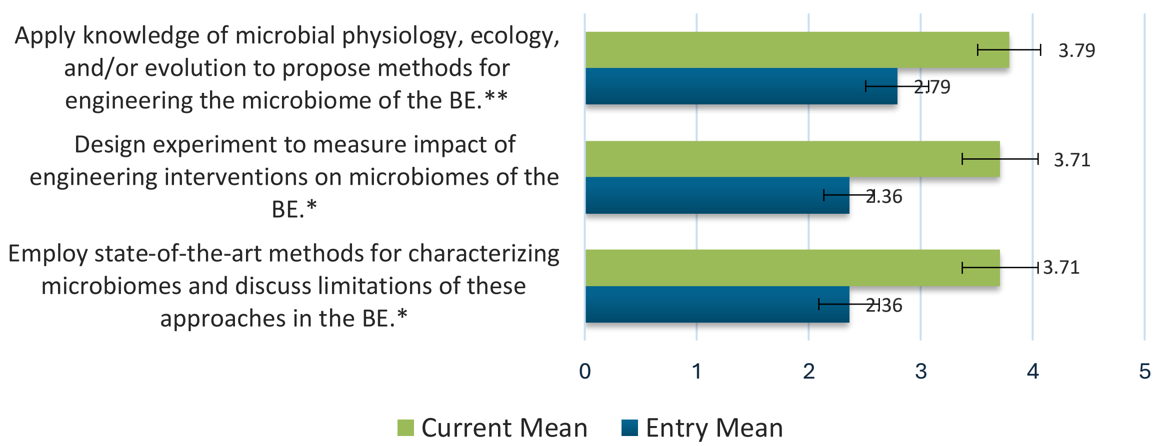


Figure 14. Application of MoBE and Microbiome Engineering Knowledge
(1=No ability, 2=Some ability, 3=Intermediate, 4=Above average, 5=Proficient, n=14)



11- Discussion and Conclusion.

This current paper describes advances in a graduate training model developed and refined by PreMiEr, an NSF funded Engineering Research Center (ERC) that spans five university partners, with the vision of enabling bioinformed design and operation of smart, healthy built environments by developing innovative approaches to engineer built environment microbiomes that promote beneficial microbes while preventing spread of pathogens. Achieving this vision requires training the next generation of engineers and scientists to work across disciplines in this emerging field. At startup, this center created an array of interdisciplinary training components that span technical, professional, and entrepreneurial training woven across partner universities. Initial research training focused on building general research skills along with core technical skills, not covered by courses but needed for MoBE research and engineering.

Evaluation findings indicate that PreMiEr has successfully developed a core technical curriculum which continues to deliver comprehensive technical training mapped to key skills needed for MoBE research. The majority of technical workshops are hybrid and accessible across all partner universities and rated positively for relevance, quality, and engagement. Faculty have also integrated PreMiEr content into 28 courses over two years across sites.

As PreMiEr's research became focused on two unifying Use Cases: Healthcare and Residential applications, new MoBE training components were needed. Evaluation team and NSF Site Visit review feedback identified the need for landscape analysis and increased MoBE specific engineering training. In response, PreMiEr developed an additional array of interactive training elements that include: a revised Seminar Series providing cutting edge overviews of relevant MoBE research; a trainee led Journal Club with landscape analysis of modern MoBE methods, knowledge gaps and scaffolding linking students' work to literature; and Center-wide Use Case meetings for accelerating convergent system integration and providing an umbrella structure to design, refine and link research across projects and focus areas. Doctoral student ratings of new MoBE training link these elements to development of targeted knowledge and skills that include increased collaboration, understanding of PreMiEr's vision, state of the art of MoBE, and building technical skills.

Defining competencies for microbiome research and engineering in the built environment, in particular, has provided a foundation for assessing outcomes of MoBE training initiatives and is important to current graduate training models due to the lack of defined microbiome engineering competencies in the built environment space. This initial pilot assessment of MoBE competencies was effective in capturing statistically significant self-rated gains in doctoral students across three key areas of MoBE engineering: a) knowledge and understanding of MoBE landscape, b) appraisal of MoBE research and engineering solutions, and c) application of MoBE and microbiome engineering knowledge. This assessment will be further validated by independent faculty advisor ratings of doctoral students' progress in these areas.

In summary, PreMiEr is successfully delivering key technical and MoBE training in parallel with new alignments in research focus areas. Ratings of core training elements indicate alignment of training with targeted goals. Gains in doctoral students' development in MoBE engineering competency areas were substantial and linked with multiple new elements. Use Case meetings have exceptional value as integrators across projects, increasing systems thinking, and accelerating the pace of research. This initiative to define and begin to assess core competencies in MoBE is highly significant and will continue to evolve as part of this Center and will be shared at MoBE engineering and research conferences.

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