Integrating Research into Undergraduate Laboratory Courses

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1 INTRODUCTION

In science and engineering curricula, most traditional laboratory courses engage students with routine experiments that do not involve scientific research. For these courses, the topic and methods are instructor defined and most often there are clear directions and a predetermined outcome that is known to students and the instructor. In recent years, more research opportunities have been provided to students in undergraduate laboratory courses, including inquiry laboratory courses, Course-Based Undergraduate Research Experiences (CURE), and research internships. In an inquiry laboratory course, students participate in many of the cognitive and behavioral practices that are commonly performed by scientists. The inquiry laboratory course is designed to challenge students, rather than to contribute to a larger body of knowledge[1]. In a CURE, students address a research question or problem that is of interest to the broader community with an outcome that is unknown both to the students and to the instructor[2]. For a research internship, a student is apprenticed to a senior researcher to help advance a science research project[3].

For research internships, students typically can receive more mentoring than can be achieved in a single laboratory course. However, due to the limited availability of undergraduate research assistant positions, it is difficult to scale this approach more broadly. Inquiry laboratory courses and CURE modules can be more broadly accessible to students. For CURE, Auchincloss et al. identified fundamental principles that ensure the practice of authentic research: use of scientific practices, discovery, broadly relevant or important work, collaboration, and iteration[2]. Although many CURE modules have been published, a recent review found that of the 224 CURE modules published from 2000 to 2020, only 5 (or 2.2%) of them are in engineering[4]. For chemical engineering more specifically, published inquiry laboratory courses and CURE modules are also limited.

Additionally, most of the published studies on undergraduate laboratory courses rely solely on student perceptions through surveys, with limited quantitative measures[5]. Although students' perceptions offer useful information about students' interest in the courses, students' estimation of their skill levels can be inaccurate[6]. Furthermore, the assessments are often not directly aligned with the course learning objectives[5].

To address these gaps, in this study, we propose to integrate a research-based laboratory module in an undergraduate laboratory course. The specific context of the module is mass spectrometry.

Mass spectrometry (MS) is an analytical method used to identify the chemical composition of a sample by measuring an ion's mass to charge ratio. The technique consists of ionizing the sample, separating the ions based on their mass, detecting the ion abundance, and then creating a spectrum to display the molecular structure and composition of the sample. MS serves as a foundational tool across a wide range of scientific and engineering disciplines. In biotechnology, MS is crucial for protein characterization, drug identification, and quality control. Similarly, environmental engineers use mass spectrometry for pollution detection, contaminant identification, and highly sensitive chemical quantification[7]. In medical research, MS covers metabolomics, lipidomics, proteomics, and more[8,9]. Broader applications include food safety testing[10], forensic toxicology, and clinical work[11,12]. Mass spectrometry provides precise molecular information across all these fields, making it a vital tool in scientific investigation and industrial settings. Given its broad relevance and widespread use, developing a conceptual understanding of mass spectrometry and gaining hands-on experience with MS data could have a significant positive impact on students' technical competence, career preparation, and readiness for research or industry roles.

Mass spectrometry has been incorporated into undergraduate laboratories in various ways, often through CURE-style modules designed to give students hands-on exposure to analytical techniques. These approaches emphasize conceptual understanding and active engagement in technical tasks such as sample preparation, data collection, and interpretation. Some examples include Stock & March (2014)[13], who developed a hands-on ESI-MS lab where students generated and analyzed their own caffeine spectra, and Jouaneh et al. (2022)[14], who integrated Liquid Chromatography Mass Spectrometry (LC-MS/MS) analysis on the extracts from a few medicinal plants into an upper-division course. Mass spectrometry can be integrated into undergraduate labs to give students hands-on experience with environmental analysis, metabolomics, lipidomics, proteomics, and forensic or toxicological analysis, demonstrating how MS is applied in real scientific contexts[15,16,17,18,19]. While these studies offer valuable insights into the use of MS in undergraduate education, they often lack quantitative assessments of student improvement.

This study aims to evaluate whether integrating a research-based mass spectrometry (MS) experiment into an undergraduate laboratory course (CEE 125: Analytical Methods for Chemical and Environmental Engineers) enhances both student learning and enthusiasm for the lab. Specifically, this research aims to address the following questions:

(1) Does adding a mass spectrometry lab module improve students' understanding of mass spectrometry?

(2) How does incorporating research activities influence students' attitudes toward laboratory experiments?

(3) How does incorporating research activities into an undergraduate laboratory course influence students' understanding of research and interest in participating in undergraduate research?

To address these questions, we embedded a mass spectrometry experiment directly derived from an active research program focused on artificial photosynthesis and sustainable food production into the course. Professor Robert Jinkerson, the primary instructor for CEE 125, leads a research group that investigates how algae and plants can be engineered to grow using alternative carbon sources, including electrochemically produced acetate. This work builds on recent advances in hybrid inorganic–biological systems that convert CO_2 into acetate, enabling plant and microbial growth independent of biological photosynthesis and offering a potentially more energy-efficient route to food production[20,21]. A central component of this research is understanding how exogenously supplied acetate is assimilated into plant metabolic pathways, which is commonly evaluated using ^{13}C-labeled substrates and liquid chromatography–mass spectrometry (LC-MS)–based metabolomics.

LC-MS plays a critical role in this research by enabling the identification of metabolites, confirmation of compound identities, and quantification of isotopic carbon incorporation into central metabolic pathways. These same analytical approaches were adapted into the undergraduate laboratory setting to provide students with exposure to authentic, research-relevant data and analysis workflows. For the experimental cohort, a mass spectrometry lab module based on acetate metabolism in plant cell cultures was integrated into the course. The control group consisted of students enrolled in the same course during the previous year, who received traditional lecture-based instruction on mass spectrometry without a hands-on data analysis component. To evaluate the impact of this research-based module, multiple assessments were implemented, including an in-class quiz, an online exam, and a course survey designed to measure both conceptual understanding of mass spectrometry and interest in undergraduate research participation.

2 METHODS

2.1 Context of the Course

CEE 125 is a technical elective that introduces upper division engineering students to core analytical chemistry techniques used in chemical and environmental engineering. The course consists of lectures on topics such as titration, the electromagnetic spectrum, spectrochemical methods, atomic spectrometry, and chromatography. This instruction is combined with hands-on laboratory experiments where students apply these concepts using four analytical instruments: a UV/Vis spectrometer, a high-performance liquid chromatograph (HPLC) system, a gas chromatograph equipped with a flame ionization detector (GC-FID), and an atomic absorption spectrometer (AAS). Through theoretical instruction and practical experimentation, students develop skills in measurement, sample preparation, instrument operation, and data interpretation related to chemical and environmental systems. The Winter 2024 session of CEE 125 served as the control group that learned MS exclusively through lecture-based instruction, consisting of 28 enrolled students and 21 students who gave consent. The Winter 2025 session served as the experimental group where 19 enrolled students, and 17 students who gave consent, learned MS through both lecture-based teaching and hands-on mass spectrometry experiment. This project was reviewed and approved by the university's Institutional Review Board (IRB protocol number: 30255).

2.2 Mass Spectrometry Experiment

Because mass spectrometers are typically prohibitively expensive and therefore unavailable in undergraduate teaching laboratories, this experiment was intentionally designed to leverage existing campus mass spectrometry facilities while still providing students with an authentic, research-relevant MS learning experience. The mass spectrometry experiment was developed to enable students to analyze metabolic pathways in plant cell cultures using ^{13}C-labeled carbon sources and liquid chromatography–mass spectrometry (LC-MS)–based metabolomics. The experimental workflow consisted of the following steps: (1) culturing two grapefruit (Citrus paradisi “Marsh”) plant cell lines, one wild-type and one mutant line that had been adapted to growing in media with acetate, (2) growing each cell line in sucrose-based media either supplemented with 2 mM ^{13}C-labeled acetate or without acetate as a control, (3) preparing harvested plant cell cultures for metabolomic analysis by removing growth media and freeze drying samples, (4) performing LC-MS analysis, and (5) conducting data analysis with MZmine (version 4.5.2)[22]. LC-MS analysis was performed by the UCR Metabolomics Core using an untargeted metabolomics approach. Samples were extracted using a methanol–water solvent system to capture a broad range of polar and semi-polar metabolites and analyzed using reversed-phase liquid chromatography coupled to mass spectrometry in positive ion mode. This approach enabled the detection of diverse metabolite classes, including organic acids, lipids, and central metabolic intermediates. Students did not perform the physical culturing of plant cells or operate the LC-MS instrumentation directly, but instead, were provided with the LC-MS datasets generated by the core facility.

Students analyzed four LC-MS datasets corresponding to wild-type and acetate-adapted cell cultures grown with and without ^{13}C-labeled acetate. Using MZmine, students visualized base peak chromatograms, extracted ion chromatograms, and corresponding mass spectra to identify metabolites of interest. Particular emphasis was placed on examining isotopic distributions to quantify ^{13}C incorporation into metabolites. Students exported isotopic peak intensities and performed normalization and comparative analyses to determine the fraction of metabolite carbon derived from ^{13}C-labeled acetate. These analyses formed the basis of the laboratory report, in which students evaluated acetate utilization and compared metabolic incorporation between wild-type and acetate-adapted cell lines.

2.3 Assessments

To give students multiple opportunities to practice skills related to mass spectrometry and to offer feedback about the course, we designed and implemented multiple teaching modules and assessments. Figure 1 summarizes the course activities that are related to mass spectrometry for the control group (Winter 2024) and the experimental group (Winter 2025). The boxes with white background and green borders indicate teaching modules and the boxes with blue background indicate assessments. The new additions in Winter 2025 are the mass spectrometry experiment, the lab report, and the homework.

Quiz: Students were assigned a five-question quiz that covered different topics about mass spectrometry. The first four questions on the quiz are related to materials covered in the video lecture, whereas the fifth question on the quiz is much harder than the other questions and is related to the data analysis students did in the MS experiment. Specifically, Quiz Question 5 covers stable isotope tracing and requires students to calculate fractional ^{13}C incorporation into malate using isotopic labeling data derived from a mass spectrum. This question was graded with a 7 point rubric that allowed several opportunities to earn credit based on calculation steps and reasoning. The remaining questions were graded on a credit/no-credit basis, with full points awarded only for completely correct answers. We expected questions 1-4 on the quiz to measure

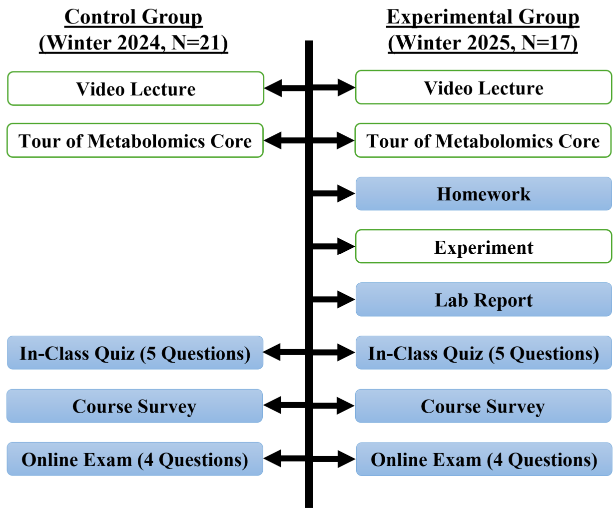

Figure 1: Summary of course modules related to mass spectrometry.

students' baseline knowledge about mass spectrometry after they watched the video lecture. Therefore, the scores for questions 1-4 should not be too different for the control group and experimental group. For question 5, we expected students in the experimental group to perform much better than the control group. Because the quiz will continue to be used in future iterations of this course, the detailed rubric is not included here. Other instructors interested in implementing the quiz or other assessments discussed in this work can contact us for more details.

Homework Assignment: Students in the experimental group were also assigned a homework set to reinforce key concepts in mass spectrometry (MS) through conceptual and data-based questions. Students applied basic MS principles to interpret spectra, analyze molecular composition, and connect theoretical knowledge to practical examples. The rubric for this homework assignment was out of 20 points and partial credit was offered for all questions. Each question was weighted based on its difficulty, with multi-part or calculation-based problems weighted with more points than straightforward conceptual ones.

Lab Report: The lab report was assigned to only the experimental group. This assignment introduced students to mass spectrometry–based metabolomics analysis. Students compared wild-type and acetate-adapted cell lines to determine the effect of long-term cultivation with acetate and if it enhanced the plant's use of this carbon source. The activity helped students explore data collection, normalization, and isotopic enrichment calculations using LC-MS data. Part of the data analysis needed in the lab report was structurally and conceptually similar to Quiz Question 5, which also covered interpreting isotope peaks and performing quantitative analysis. The students' lab reports were evaluated across three categories: (1) their theoretical understanding of MS, (2) their analysis of raw data to generate relative abundance vs. m/z plot, and (3) their calculations based on relative abundance vs. m/z plot.

Survey: Both the control and experimental group students were given the survey. It gave students an opportunity to self-measure their skills and to reflect on their own experiences about CEE 125 and research. The control group survey had nine questions, while the experimental group had twelve questions. Questions in the survey ranged from what students found was most useful and enjoyable for learning mass spectrometry, their confidence in performing various laboratory skills, to their favorite experiment in CEE 125 and why that was. The additional questions added in the survey for the experimental group asked for students' background experience in research and laboratory skills (whether they have had undergraduate research experience and where they have acquired certain lab skills) and whether the mass spectrometry experiment sparked their interest in research.

2.4 Analysis of Assessments

Survey responses were analyzed using protocol coding and emergent coding[23,24]. For the question "Do you see yourself as a researcher?" we categorized responses as "Yes", "Maybe", or "No". For other questions that can be quantified, the analysis was performed on and reported as a percent of students who gave consent. For open-ended questions that do not result in just a yes/no, but ask students to explain their reasoning, emergent coding was used. Rather than having a predetermined set of codes, emergent coding is an approach where codes and themes arise from the data itself (in this case, survey responses). We read through each participant's survey responses and then looked for common themes in their responses that could be classified as a code. The first and second authors each independently analyzed a subset of the survey questions. The codes were then discussed with the other authors. This emergent coding approach allows us to discover unexpected patterns, concepts, and meanings relevant to the participants' experiences.

3 RESULTS

3.1 Adding the mass spectrometry lab improves students' understanding of mass spectrometry

Table 1: Quiz Question 5 Summary Statistics

	Quiz Q5 2024 (Control, N=21)	**Quiz Q5 2025 (Experimental, N=15)**
Average	0.69	2.47
Total Points	7.00	7.00
Average Percent	9.9%	35.2%
Standard Deviation	1.36	2.68
Max	4.00	7.00
Min	0.00	0.00
Median	0.00	1.50
t statistic	2.36**	
p-value	0.0289	

** indicates the result of the t-test is statistically significant at 5% level.

Note: In 2025, 17 students gave consent for using course data for research, but only 15 students completed the quiz.

The comparison of quiz scores between the control and experimental group demonstrated the impact of adding a mass spectrometry laboratory on students' understanding of mass spectrometry. Performance differed substantially on Quiz Question 5, the most conceptually and mathematically demanding question. The control group averaged 9.98%, whereas the experimental group averaged 35.2% (Table 1). The average on Quiz Question 5 for the experimental group is 3.5 times higher than that for the control group. This increase in the score is statistically significant at 5% level (t-test), which indicates a stronger performance on the quiz by students who participated in the lab.

3.2 Exposing students to research-based experiments helps them more accurately estimate their skill levels.

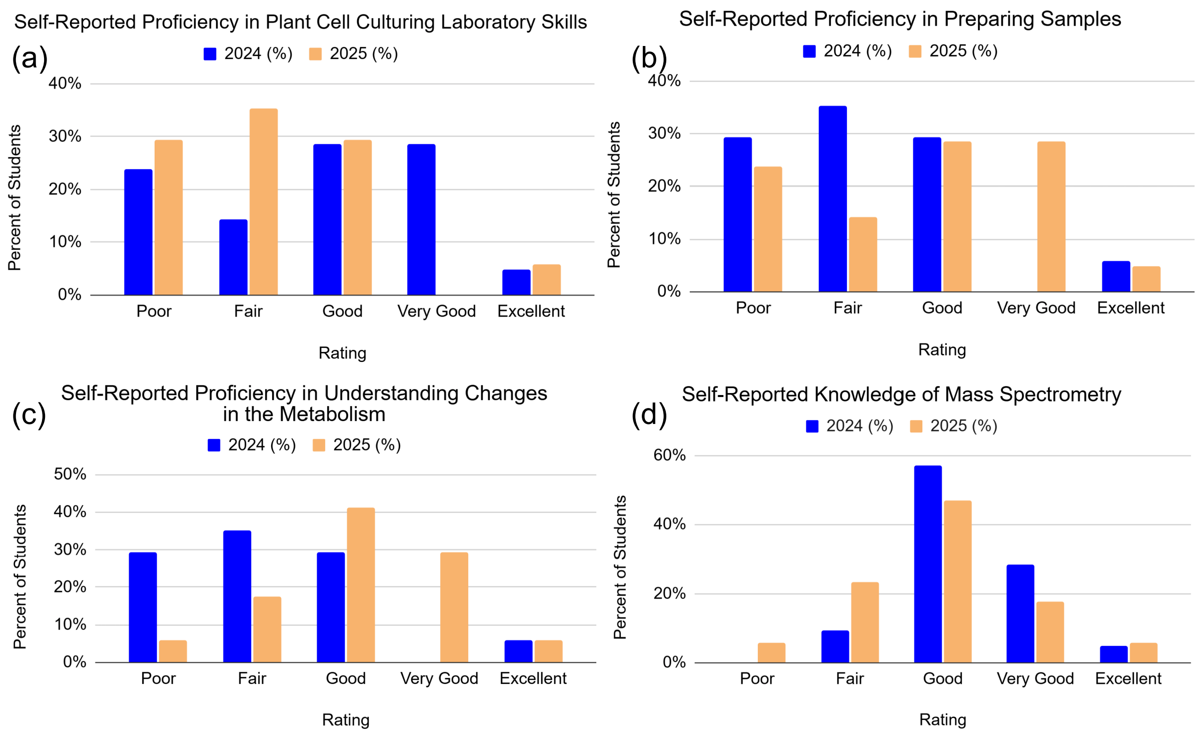

Figure 2: The difference in self assessments between the control group and experimental group across different mass spectrometry related skills: (a) plant cell culturing, (b) sample preparation for metabolic analysis, (c) using mass spectrometry to understand metabolism change and (d) knowledge of mass spectrometry.

Exposing students to research-based labs appears to improve the accuracy of their self-assessments in the survey across multiple laboratory skills. In this analysis, ratings of "Very Good" or "Excellent" were considered positive, while "Poor" or "Fair" were considered negative (Figure 2). In the control group (which did not participate in the lab), students tended to rate their skills highly: 33% rated their Proficiency in Culturing Plant Cells as positive while only 24% rated themselves as negative. In Preparing Samples, the experimental group had a 11% increase in negative ratings and relatively consistent positive ratings, indicating more realistic evaluation of proficiency. Similarly, for Using Mass Spectrometry to Understand Changes in the

Metabolism, from the control group to the experimental group, negative ratings increased by about 10% and positive decreased by about 8%, suggesting that direct engagement helped students better recognize the complexity of mass spectrometry tasks.

Additionally, results show that self-assessments do not always align with measured performance. Unlike many prior inquiry based labs and CURE studies that focus primarily on self-reported confidence and perceived learning gains, this study compares how research-based instruction influences both perceived and demonstrated understanding as self-assessments do not always align with measured performance.

These trends suggest that participation in research-based experiments can enable students to more accurately gauge their skills. Traditional instruction alone may lead students to overestimate their capabilities. Actively engaging with experimental procedures may help students gain insight into the challenges of each task, allowing a more accurate understanding and self-assessments. This self-awareness is critical as it allows learners to better identify areas for growth ultimately enhancing both confidence and competence in scientific skills.

3.3 Incorporating research activities in laboratory experiments seems to have a positive influence on students' attitudes toward laboratory experiments.

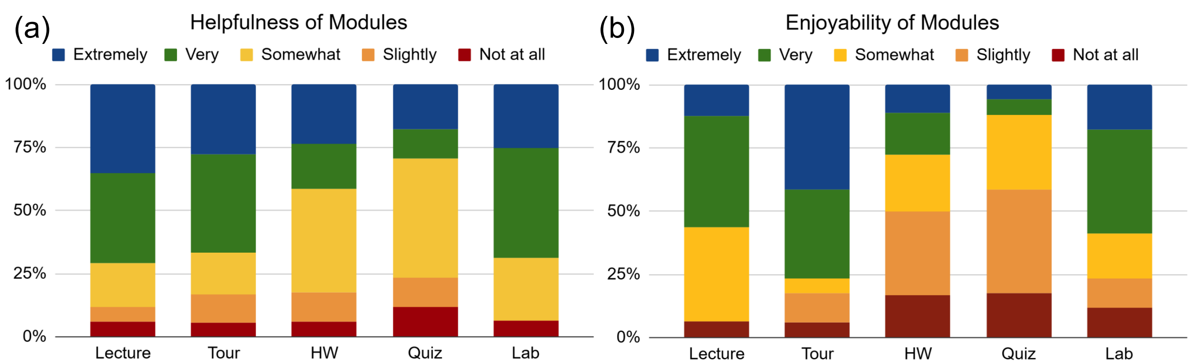

Figure 3: (a) The helpfulness of modules for students in learning mass spectrometry and (b) the enjoyability of modules for students in learning mass spectrometry (Winter 2025).

For the experimental group (Winter 2025 cohort), students were asked to rank the mass spectrometry modules (lecture, tour, homework, quiz, and lab) in terms of helpfulness and enjoyability. There was a five-tiered ranking system: "Not at all, Slightly, Somewhat, Very, and Extremely" (Figure 3). In this analysis, ratings of "Extremely" or "Very" were considered positive, while "Slightly" or "Not at All" were considered negative. In terms of helpfulness, the tour was found to be the most helpful module with 12 students ranking it positively, and the lab was ranked the second most helpful with 11 students ranking it positively. Similar results were found in the enjoyability aspect as well. The tour was considered to be the most enjoyable with 13 students ranking it positively, and the lab was ranked the second most enjoyable with 10 students ranking it positively. These responses suggest that students find hands-on experiences more enjoyable and helpful-whether it is being able to view the apparatuses at the UCR Metabolomics Core tour or by performing the experimental analysis on their own. Enjoyability does not come at a cost in learning. Instead, it can be used to boost motivation and retain engagement, leading to improved learning. This was seen with the increased Quiz Question 5 scores in the experimental group compared to the control group.

3.4 What does research mean to undergraduate students?

Students were asked whether they saw themselves as a researcher and were then asked to further elaborate on their responses in the survey. The experimental group's answers included varying answers of "yes, no, maybe". On the other hand, the control group had several "in the future" and "I don't know" responses along with the "yes, no, maybe". The "I don't know" and "in the future" responses were classified under the "maybe" category when coding (Figure 4). The experimental group had more conclusive answers compared to the control group, which could be attributed to the experimental group being able to perform the research-based experimental portion. Because the control group was unable to gain a glimpse into experimental research, the students were more unsure of what conclusions to draw about research. Those in the control group cohort felt more unsure of being a researcher or needed more time. Students from the control group who answered under the "maybe" category cited being uncomfortable with their current skillset and still needing guidance, needing to explore for the right field/topic, and the overall time commitment. Many students seem to misconstrue the idea of what being a researcher is; they think it depends on the skill level one has. While having the skills to operate the equipment and different experimental techniques are important, it relies on one's ability to stay curious and to continue to persevere. One student of the 2025 cohort (experimental group) was able to explain it aptly: "I do see myself as a researcher as I tend to have a curious mind. I like finding answers to random questions or even explaining random phenomenons that may occur. Sometimes curiosity gets the best of us and the only way to "figure out" an answer is by testing it, if applicable". Students from the experimental group who answered under the "maybe" category mostly cited that it depends on the research coursework or topic along with answers of disliking lab work and needing more experience or exposure. With an increased access to the inner workings of research with the application of the mass spectrometry experiment, students were able to rely less on skills as a determining factor of what research is.

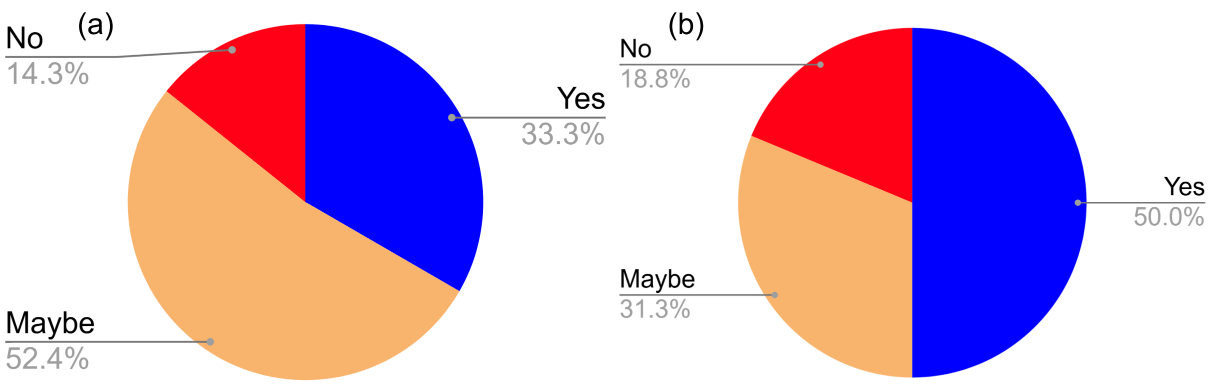

Figure 4: Compare the answers between (a) the control group (Winter 2024 cohort) and (b) the experimental group (Winter 2025 cohort) for the survey question "Do you see yourself as a researcher?". For the control group, the maybe category includes "maybe", "in the future" and "I don't know".

3.5 Adding the mass spec lab increases students' interest in participating in undergraduate research.

Adding the mass spectrometry experiment does spark a good majority of students' interest in undergraduate research based on a Winter 2025 survey question (Figure 5). Many students cited their increased interest in undergraduate research with reasons such as real-life application, interesting software/equipment, and being related to their future field of research. One student interested in air pollution research stated, "Mass Spectrometry can really help in this field, like ionizing different pollutants from an air sample. Help us identify and quantify the pollutant." Another student interested in artificial photosynthesis spoke about "This lab showed me that we are, and have been, as a science community considering both the utility and importance of this earth-shattering concept." Those that disagreed stated that it was of no interest to them or it was too complicated for them to learn. As one student stated, "Mass spectrometry is really important in a variety of fields in science...". Learning how to utilize mass spectrometry could not only assist them in the present but also with future endeavors due to its wide applications.

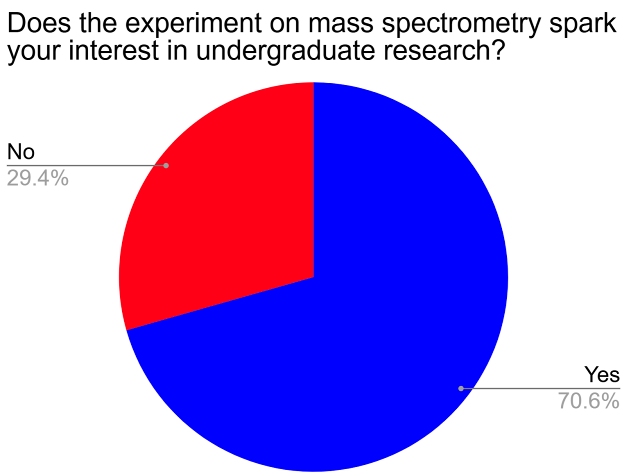

Figure 5: Percent of students from the experimental group (Winter 2025 cohort) that agreed/disagreed that using mass spectrometry increased their interest in undergraduate research (12 students said yes, 5 students said no).

4 DISCUSSION

Our results suggest that integrating a research-based mass spectrometry module into an undergraduate chemical engineering class can provide educational benefits for students. The module introduces metabolomics data analysis and spectral interpretation in the context of real-world research questions. By using biological samples and raw LC-MS data, students were able to contextualize the information learned in lecture and apply it to experimental procedures and processes. The module also contributed to student engagement and motivation. Many students reported an increase in interest in participating in undergraduate research. In our view, the most important features of our teaching intervention are 1) relevance to the professor's research, 2) opportunities for students to perform data analysis, and 3) quantitative assessment of students' conceptual understanding.

In this study, prior to the mass spectrometry experiment, the instructor gave a presentation to students to explain how the mass spectrometry experiment fits in his overall research program. Students appreciated this real-life application as evident in the survey responses. Previous studies have suggested that relevance is important to show students the value of scientific research and participation in relevant research experiences helps students make sense of science[25,26]. Additionally, letting students perform the data analysis gives them the opportunity to practice using scientific methods instead of only learning the conceptual knowledge. Furthermore, unlike many previous studies that rely solely on self-reported data from surveys, we implemented both a survey and a mass spectrometry quiz for more quantitative assessment of students' skills.

These findings ultimately align with Inquiry-Based Learning and CURE methods, suggesting that even a single lab session with hands-on research work can influence student engagement and mastery of course material. Our approach offers an alternative to CURE modules while still including some of the key components of authentic research. CURE modules are typically quite time-consuming and resource-intensive to implement. For instructors who have limited resources, implementing one research-based module can still benefit students. Additionally, this approach can be more broadly implemented in lecture-based courses as well. For example, instructors can redesign some homework questions to include real-life context from the instructor's research and give students opportunities to analyze research data.

5 LIMITATIONS AND FUTURE WORK

During the project, there were some inconsistencies that limited our ability to thoroughly compare and analyze the data. The sample size was relatively small with a control group of 21 participants and an experimental group of 17 participants. This hindered the generalizability of the results to a greater student population. This issue is difficult to work around as CEE 125 was designed to accommodate a small group of students and participation within this research study is voluntary.

Additionally, the survey was altered between groups. In the Winter 2024 survey, students seemed to misunderstand the question about which module was the most helpful and most enjoyable for learning MS. Specifically, 52.4% of students found the experiment most helpful in learning and 66.7% found the experiment most enjoyable. There was no mass spectrometry experiment for the control group in Winter 2024. Because of these results, the wording for the questions regarding the most helpful and enjoyable component of learning MS was adjusted to prevent this misunderstanding for the Winter 2025 cohort.

For the two years, the timing of the quiz was different. The control group (Winter 2024 cohort) had the quiz implemented soon after the students watched the mass spectrometry lecture video provided in the class, while the experimental group (Winter 2025 cohort) took the quiz on the same day as their class final presentation. Although the experimental group had a much higher score on Quiz Question 5 compared to the control group after having practiced data analysis in the MS lab, the experimental group had a lower score than the control group for the first four questions on the quiz. The first four questions cover topics students learned in the video lecture. The difference in timing of the quiz may have affected their performance.

Moving forward, we aim to strengthen the project in multiple ways. For example, we would like to teach students the full cell culturing process rather than just the data analysis. Additionally, we hope to include more comprehensive student performance data, such as final course grades and GPA, to better assess learning outcomes. We hope to encourage other lab instructors to integrate research into their laboratory courses as well.

6 AUTHOR CONTRIBUTIONS

Sarah Fan and Hiranya Selvakumar contributed equally to the manuscript. Sarah Fan and Hiranya Selvakumar performed data analysis, survey-response coding, assessment analysis, and preparation of figures and results. Jonathan Meuser contributed plant cell culture materials and mass spectrometry. Jiamin Zhang and Robert Jinkerson conceived and led the project, designed the research-based laboratory module, supervised the work, and guided manuscript development. Robert Jinkerson acquired funding for the project. All authors contributed to writing, reviewing, and editing the manuscript. Co-corresponding authors: Jiamin Zhang (jiaminz@ucr.edu) and Robert Jinkerson (robert.jinkerson@ucr.edu).

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