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A plant mutant screen CURE integrated with core biology concepts showed effectiveness in course design and students' perceived learning gains

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Abstract

Course-based undergraduate research experiences (CUREs) provide students with valuable opportunities to engage in research in a classroom setting, expanding access to research opportunities for undergraduates, fostering inclusive research and learning environments, and bridging the gap between the research and education communities. While scientific practices, integral to the scientific discovery process, have been widely implemented in CUREs, there have been relatively few reports emphasizing the incorporation of core biology concepts into CURE curricula. In this study, we present a CURE that integrates core biology concepts, including genetic information flow, phenotype–genotype relationships, mutations and mutants, and structure–function relationships, within the context of mutant screening and gene loci identification. The design of this laboratory course aligns with key CURE criteria, as demonstrated by data collected through the laboratory course assessment survey (LCAS). The survey of undergraduate research experiences (SURE) demonstrates students' learning gains in both course-directed skills and transferrable skills following their participation in the CURE. Additionally, concept survey data reflect students' self-perceived understanding of the aforementioned core biological concepts. Given that genetic mutant screens are central to the study of gene function in biology, we anticipate that this CURE holds potential value for educators and researchers who are interested in designing and implementing a mutant screen CURE in their classrooms. This can be accomplished through independent research or by establishing partnerships between different units or institutions.

KEYWORDS

core biology concepts, course-based undergraduate research experiences (CUREs), genetic information flow, LCAS, mutation and mutants, phenotype–genotype, structure–function, SURE

1 | INTRODUCTION

As a pedagogical approach that integrates science research into curricula, course-based undergraduate research experiences (CUREs) can offer research opportunities to more undergraduate students, create an inclusive research environment for students from diverse backgrounds, and influence students' academic and career trajectories.[1–3] Different from the traditional "follow the procedure and conduct the experiment" laboratory experimental courses, students in CUREs can gain experience of what it means to be a scientist by engaging in scientific practices such as asking questions, forming hypotheses, designing experiments, conducting investigations, analyzing and interpreting data, drawing conclusions, and communicating their findings.[4] It has been reported that CUREs not only facilitate students' learning of specific laboratory skills and techniques but also enhance their ability to think scientifically and systematically.[5–7] Furthermore, CUREs have shown positive impacts on improving students' self-confidence, promoting thoughtful career planning, cultivating interest in STEM careers, and increasing retention in scientific research.[5,7–9] CUREs can also benefit faculty in their research progress and career advancement. By developing and teaching CUREs, faculty members can pilot research projects, accelerate research progress, build collaborations, recruit undergraduate research assistants, and ultimately publish research findings.[1,7,10–12] Aside from enhancing chances for federal grant funding when integrated into the objectives of a research proposal meeting broader impact goals, teaching a CURE can also be rewarding, fulfilling, enjoyable, and can contribute to professional promotion.[7,10]

However, it is important not to overlook the challenges associated with CURE development and implementation. Shortlidge et al. have identified various challenges that faculty members have experienced when conducting CUREs, including logistics, time and work investment, funding support, instructor's multiple roles, the need for research projects, and uncertainty about research results.[10,13,14] Additionally, institutions may face barriers in finding suitable research projects for CUREs, and faculty prioritizing scientific research may find the necessary time investment challenging when developing CUREs, even if they have ideal projects for CUREs.[10,15–17] These challenges can create gaps between science and education, hindering scientists from bringing their research projects into the classroom for broader community impact.

Efforts have been made to address these types of barriers. For example, well-established CUREs, such as the genomics education partnership and SEA PHAGE, have formed partnerships with educators from different institutions nationwide[17–20] and have trained educators to teach the CUREs in the trainee's classrooms. Other resources, such as the CURE Institute and CUREnet (https://serc.carleton.edu/curenet/index.html), have emerged to help educators develop their own CUREs and provide CURE examples as reference for CURE design and development. These efforts have played a critical role in connecting educators who prioritize teaching and have established a community of CURE practitioners. We previously also reported our CURE effort in building connections between research and education and explored its impact on students' learning gains,[11] and shared the original curriculum on the CUREnet (https://serc.carleton.edu/curenet/collection/245156.html).

The American Association for the Advancement of Science issued the call to action to improve undergraduate biology education and suggested "integrated core concepts and competencies throughout the curriculum."[21] Woodin et al. presented the five core concepts in their recent essay: evolution; structure and function; information flow, exchange and storage; pathways and transformations of energy and matter; systems.[22] We propose that CURE curricula can serve as an excellent platform for integrating these core concepts. A mutant screen CURE is ideal to practice core biology concepts and scientific practices and can be beneficial for both research and education for the following reasons: First, mutant screening is a common reductionistic approach that has been widely used in the field of biology research to seek the functions of genes of interest. Scientists have employed various strategies to generate mutants, including ethyl methanesulfonate (EMS) treatment, CRISPR, T-DNA insertion, and other mutagenizing techniques.[23,24] Second, the laboratory techniques in a mutant screen CURE are suitable for undergraduate classrooms. The screening for genetic mutants after mutagenesis to enhance the mutation frequency typically involves observing mutant growth and morphological phenotypes, analyzing mutants for their physiological or chemical or other traits using specialized techniques, evaluating mutant genetic backgrounds, and identifying candidate genes. Experiments may include, but are not limited to, measuring and describing organismal morphology, using simple analytic techniques targeting metabolites, extracting DNA, performing polymerase chain reaction (PCR), conducting agarose gel electrophoresis, and potentially carrying out downstream DNA sequencing and data analysis. Third, the underlying concepts and knowledge covered can include genetic information flow, genotype–phenotype relationships, distinction between mutations and mutants, and structure-function relationships. Fourth, the research

groups can claim broader impacts in grant proposals by translating research into CUREs and involving more undergraduates in research. Here, we describe the development of a mutant screen CURE well integrated with core biology concepts and scientific practices, and its impact on students learning outcomes.

2 | RESEARCH QUESTIONS

In this study, we aimed to address the following questions about the mutant screen CURE: (1) Did the students' self-efficacy in concept learning align with the intended design of the course? (2) Did students perceive the curriculum design as meeting the criteria for a CURE? (3) What impact did this CURE have on students' learning gains of concepts and skills by using scientific practices?

3 | CONCEPTUAL FRAMEWORKS

We designed this CURE by following the definition and framework of CUREs.[16,25] We integrated the core concepts suggested by the vision and change for undergraduate biology education,[21] into the curriculum.

4 | METHODS

4.1 | Course description and enrollment

This CURE was designed for an entry level cell and molecular biology course at a large 4-year research intensive university. This laboratory course is required for undergraduate students majoring in the life sciences. Students are expected to have completed, or be concurrently taking, a prerequisite lecture course covering fundamental cell and molecular biology concepts before enrolling in this CURE. The same instructor facilitated two sections of this CURE each semester, with a maximum of 24 or 28 students per section. Students worked in groups of 3–4 individuals, and the class met twice each week with a 3-h lab and a 50-min recitation. For more detailed course background information, please refer to our previous report.[11] Throughout the two semesters of this study (Fall semesters of 2021 and 2022), a total of 93 students participated in the CURE. Of these 67% were female and 33% male. The racial composition included 61% White, 10% Hispanic/Latino, 8% Asian, 6% Black/African American, and the rest of students belong to two or more races, "Not specified," or "International."

4.2 | The mutant screen CURE curriculum and course schedule

This CURE project is part of a larger effort to discover lipid-based signaling processes. It was based on our previous scientific discovery of a plastid lipase, PLIP3, from the model plant Arabidopsis.[26] This enzyme functions as a lipase in chloroplasts releasing polyunsaturated fatty acid from membrane lipids, which are then converted to the plant stress hormone jasmonic acid.[11,26] When the *PLIP3* is overexpressed in transgenic plants, the resulting increased level of jasmonic acid triggers changes in gene expression, affecting different biological processes including plant defense against stresses, and ultimately causes stunted plant growth.[11,26,27] The goal of the science research was to discover novel enzymes or proteins that are either involved in the biosynthesis of jasmonic acid and related oxylipins, or their perception and signal transduction. Towards this goal, we conducted a suppressor mutant screen in the *PLIP3* overexpressing plants to identify mutants that reverted the phenotype from stunted growth to normal or near-normal growth. The early stage work included genotyping the plants and examining their lipid profiles, which led to the development of a CURE we implemented during 2018–2019.[11] As the project progressed in the research laboratory during the past several years, we identified and characterized the first suppressor mutants and completed the whole-genome resequencing for several mutants leading to the identification of the respective causal mutations. This research progress provided new opportunities to engage the students in the class room and led us to evolve the curriculum for this CURE to the next level by incorporating a set of core concepts and adding a phenotyping experiment to establish a connection between phenotype and genotype (Figure 1). The specific research goals for this evolved CURE course (BS 171) are as follows: (1) Qualification and quantification of plant phenotypic traits through visual observation and measurement; (2) identification of promising mutants using laboratory techniques such as DNA extraction, PCR, and agarose gel electrophoresis; (3) analyzing DNA sequencing data and evaluating published information to narrow down the candidate genes involved in the jasmonic acid and other oxylipin biosynthesis and signaling processes. The detailed procedure is shown in Figure 1.

The CURE schedule includes the following activities: (1) The research laboratory provided mutagenized and control Arabidopsis seeds for students to sow in the classroom. Each group was provided with a flat containing 32 pots of soil with 4 pots for controls and the remaining 28 pots for mutagenized seeds. Students were instructed to sow 4 seeds per pot, meaning about 128 seeds from the

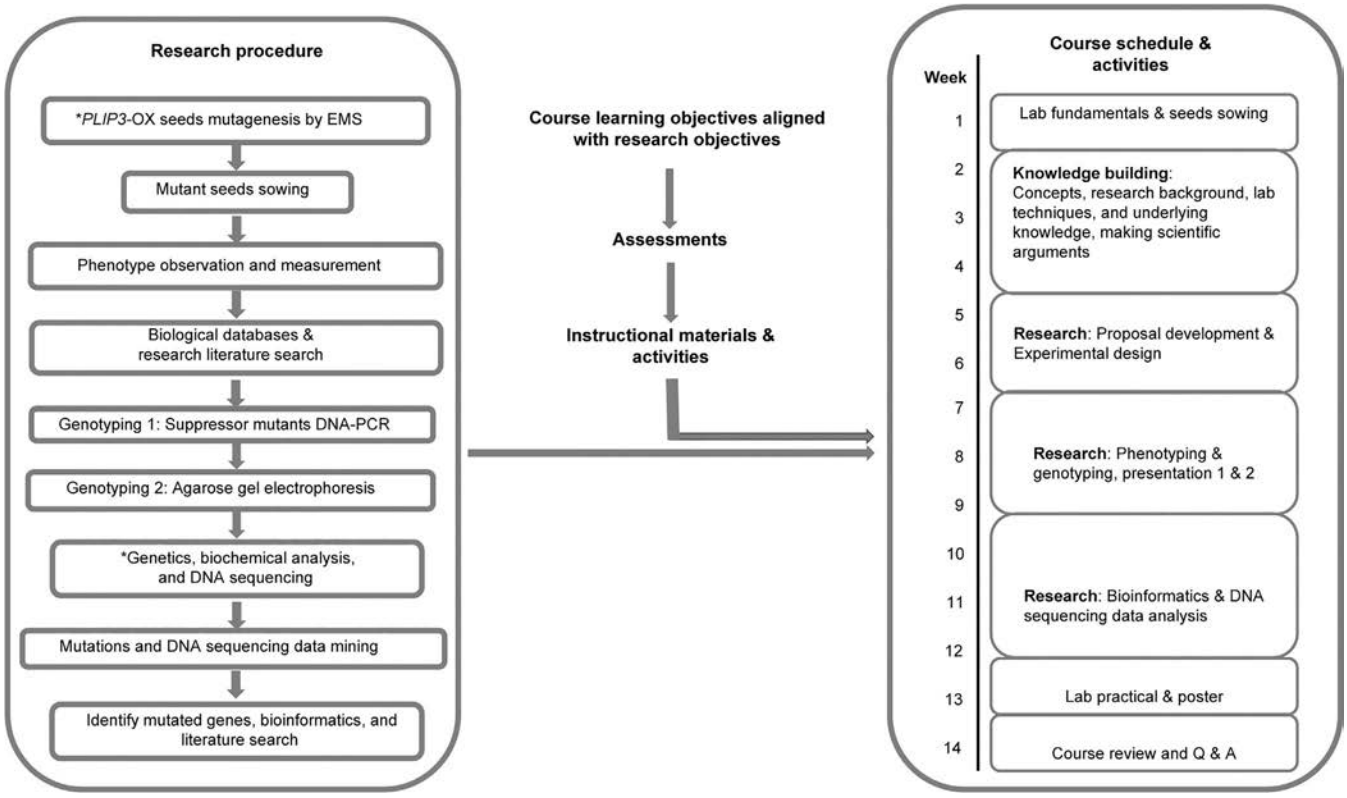

FIGURE 1 Using backward design to transform the research procedure to the course-based undergraduate research experiences (CURE) lab schedule. * These steps were performed in the research laboratory. Please note there were no classes for weeks 8 and 12 scheduled during the semesters.

mutagenized lines were sown. (2) For the next 4–5 weeks, while waiting for the seeds to germinate and the plants to grow, students learned or reviewed biology concepts, practiced laboratory skills such as pipetting, gained an initial understanding of the underlying scientific knowledge, and familiarized themselves with the research project. (3) By the end of the knowledge-building phase, the plants were about 1 month old showing observable phenotypes (leaf shape, size, color etc.), typically with phenotypes similar to the transgenic *PLIP3* lines but with some (putative suppressor mutants) closer resembling the wild-type plants. Students selected mutants meeting the hypothesis (partially or fully restored wild-type growth and morphology), described the phenotypes and measured the phenotypic traits. Typically, each group had a couple of plants with characteristics resembling those of the wild-type plant, however, occasionally, a group might not obtain any plants with the suppressor-like phenotypes. We coordinated with the students to share the mutants so each group could have the mutants to continue their research. (4) Following the phenotyping experiment, students began genotyping the plants to examine their genetic backgrounds. (5) Promising mutants discovered in the classroom were transported to the research laboratory (alternatively, mutants could stay in the classroom for seed harvesting), and next-generation DNA sequencing data from the research laboratory on specific F2 segregating mutant populations following back crossing were provided to the students for further bioinformatic analysis. (6) Students learned about basic DNA sequencing technologies, reviewed or learned basic knowledge of mutations and their use in genetic analysis, and learned whether and how the mutations would affect a protein's structure. This knowledge was to prepare students for analyzing DNA sequencing data. We then shared a list of candidate mutant loci generated by the research lab through the genome resequencing of selected populations with students so they could start analyzing the data by selecting candidate genes from the list, searching databases (www.arabidopsis.org and www.ncbi.nlm.nih.gov) for the relevant literature to learn about the functions of the candidates if applicable, evaluating the published information, and making predictions regarding whether the candidates could be involved in jasmonic acid biosynthesis or the respective signaling pathway. Bioinformatic applications were also incorporated into the practice to help students understand the related concepts.

4.3 | Key concept integration and concept survey design

We aimed to integrate several core concepts into the CURE curriculum. More details regarding the alignment between the concepts with research questions, laboratory questions, scientific practices, and major assessments can be found in Table 1. We developed a Likert scale survey (Data S1) to assess students' self-perceived understanding of concepts, and we administered this survey at the beginning and end of each semester to cross-check the concept coverage from the students' perspective. We collected pre- and post-course data and performed a paired *t*-test to analyze the data.

4.4 | The scientific practices

Throughout the CURE, students engaged in scientific practices during both the knowledge building stage and the research stage. As indicated in Table 1, during the knowledge building stage, students analyzed and interpreted data to address research questions and formulated scientific arguments using the "claim, evidence, reasoning" format.[28] Once the knowledge building stage was completed, students transitioned to the research stage, where they developed a guided research proposal and designed experiments. They constructed models and provided explanations for the hypotheses. Students shared their findings with the classroom and learned from each other through two presentations, with one focusing on mutant phenotypes and the other on genotypes. During the final poster session, students had an opportunity to communicate their findings to a broader community, which included students from the other CURE section, scientists from the research laboratory, or other undergraduate students.

4.5 | Incorporation of key CURE criteria

We followed the conceptual framework for the CURE design and aligned it with the key CURE criteria.[4,25] First, *broad relevance* was provided through the connection between the research laboratory and the CURE classroom, encompassing sharing of material and exchange of data. The research laboratory provided experimental materials and other resources for the classroom, while students isolated new mutants for further study in the laboratory. Subsequently, the laboratory provided DNA sequencing data on specific mutants for further bioinformatic analysis by the students. Second, *collaboration* was fostered through group work, with students forming teams of 3–4 individuals and engaging in regular collaborative activities throughout the semester. This structure allowed students to learn from each other and collectively contribute to their learning experience. The team-based and classroom-wide discussions and reflections enhanced collaboration. Third, the course promoted *discovery* by enabling students to generate novel mutants through classroom activities. Novel mutants represented potential for new scientific discoveries and contributed to the advancement of knowledge in the field of biology. Fourth, the course incorporated the *use of science practices* by providing opportunities for students to engage in various scientific activities. These activities included building models, developing hypotheses, making scientific predictions, designing experiments, collecting and analyzing data, and interpreting data to draw conclusions. Lastly, the course design embraced *iteration* by offering opportunities to discuss, repeat, reflect, and revise students' work. Students presented their findings to their peers, received feedback and critiques from other teams, and submitted revised versions of their presentation files for grading. The final poster session allowed students to further learn and interact across both sections of the CURE course. Additionally, two open labs were scheduled to provide students with the opportunity to repeat experiments as needed and to promote further iteration and refinement of the scientific process. Because seed sowing and phenotyping were straightforward processes, the repetitions during the open labs were mainly for the genotyping experiments, including PCR and agarose gel electrophoresis.

4.6 | Course assessments

We utilized both formative and summative assessments to evaluate students' learning, with assignments often building upon one another. Formative assessments included various activities such as worksheets, laboratory notebooks, database practices, literature searches, and short pre-lab quizzes. Guided proposal development and experimental design were also implemented to help students consolidate their learning and plan their research. Major summative assessments included two class presentations, during which students presented their findings based on the phenotype and genotype data, respectively, and three essays that focused on genotype–phenotype relationships and the application of scientific practices. The research projects culminated in a final poster session, providing students with an opportunity to communicate their findings to students outside of the classroom, sometimes with the participation of scientists from the research lab. Additionally, laboratory skills were

TABLE 1 Alignment of the concepts, scientific practices, and assessments.

Learning stage	Concepts	Research question	Laboratory activities	Scientific practices and major assessments
Knowledge building	1. Genetic information flow 2. Genotype–phenotype 3. Mutation and mutants 4. Pathway and system response	Does overexpression of the lipase gene cause the phenotype change?	Plant phenotype observation and measurement	1. Laboratory notebook: protocol, experiment, data analysis and conclusion. 2. Essay report 1: biological principles linking the concepts, research question, experimental design, data analysis, and conclusion. Report was in "claim, evidence, reasoning" format
		Does the *PLIP3*-OX mutant have the correct genotype (contains both the genomic DNA and the coding sequence of *PLIP3*)?	DNA extraction, PCR, agarose gel electrophoresis	1. Laboratory notebook: protocols, experiments, data analysis and conclusion 2. Essay report 2: biological principles linking the concepts, research question, experimental design, data analysis, and conclusion. Report was in "claim, evidence, reasoning" format
Research	1. Genetic information flow 2. Genotype–phenotype 3. Mutations and mutants 4. Structure–function 5. Pathway and system response	Research question 1: Does the presumed suppressor mutants have the correct genotype?	Literature search, proposal development, experimental design, perform phenotyping and genotyping experiments	1. Laboratory notebook: protocols, experiments, data analysis and conclusion 2. Phenotype presentation: Communicate the findings for mutant phenotypes with the class: Research goal, hypothesis, prediction, experimental design, conducting experiments, data collection and analysis, conclusion drawing 3. Genotype presentation: Communicate the genotyping results of the mutants with the class (in a similar science process with phenotype presentation) 4. Essay report 3: Genotype–phenotype scientific argument with data provided
		Research question 2: Are the mutated genes possibly involved in the biological process?	DNA sequencing data mining, select mutated gene candidates, obtain gene information from database, search literature	1. Research goal: Identify gene(s) involved in the hormone biosynthesis and signaling process 2. Team learning worksheets guiding students to address the following questions: Whether and how a mutation would affect the amino acid sequence; whether a mutation would change the property of the amino acid, affecting intra and inter molecular forces, protein folding, and structure 3. Make a scientific argument on whether the gene(s) play a role in the hormone biosynthesis and signaling processes
Knowledge synthesis	Same as the research stage			1. Poster presentation covering research questions 1 and 2. 2. Final essay report with the integration of scientific process and the core concepts listed

assessed through two lab-practicals. Further details on the alignment of concepts, science practice, laboratory activities, and the assessments, can be found in Table 1.

4.7 | Evaluation of the CURE design

We administered the laboratory course assessment survey (LCAS) at the end of the semester of Fall 2022 to determine the three-dimensional factors of laboratory courses: collaboration, discovery, and iteration. Students were asked to respond using a Likert scale for these three factors, with the response scales being 1–4, 1–6, and 1–6, respectively.[29] We excluded responses indicating "I don't know" or "I prefer not to respond" from analysis, which may result in different samples sizes for the items within the collaboration factor.

4.8 | Evaluation of students' perceived learning gains

We evaluated students' self-perceived learning gains using the survey of undergraduate research experiences (SURE) instrument, a Likert survey with scales of 1–5 indicating 1 worst 5 best.[30] We obtained the national SURE data from 2011 to 2018 at (https://sure.sites.grinnell.edu/wp-content/uploads/2019/11/The-SURE-Survey-Descriptive-Statistics.pdf), and we used these data as a reference for comparison with the data from our CURE.

4.9 | IRB approval

This study received approval from the MSU Institutional Review Board under IRB number STUDY00008234.

5 | RESULTS

5.1 | The concept integration in CURE curriculum

We designed the first two modules of this CURE to cover the concepts of genetic information flow, genotype–phenotype, and mutations and mutants. We developed the new bioinformatic module to further expand upon these concepts, focusing on the different types of mutations, the impact of mutations on protein structure, and the relationship between structure and function (Figure 1). The alignment of the concepts, laboratory techniques, scientific practices, and assessments is presented in Table 1.

5.2 | The design met the Key criteria of a CURE

(1) The students' perception data revealed that the *collaboration* items ranged from 3.51 to 3.90 (with sample size from 39 to 42) (Table 2), and the range of the LCAS reported was from 3.05 to 3.73). The paired *t*-test analysis showed a *p*-value of 0.008, suggesting a significant increase in the collaboration factor in this CURE. The total score of the *collaboration* items in this CURE ranged from 22.02 to 23.72, which was higher than the LCAS data.[29]

(2) The total scores of the *discovery* items ranged from 23.31 to 26.46, aligning well with the LCAS total score of 24.35. Specifically, the mean scores and standard deviations for DR1-DR5 were 4.51 (SD = 0.17), 4.83 (SD = 0.17), 4.86 (SD = 0.15), 4.88 (SD = 0.15), and 4.88 (SD = 0.14), respectively (Table 2). The paired *t*-test analysis showed a *p*-value of 0.065, indicating no significant difference was observed in the *discovery* factor between this CURE and the Corwin data. Upon closer examination of each item, we noted that four out of the five items scored slightly higher than the LCAS data,[29] while the DR3 "I was expected to formulate my own research questions or hypothesis to guide an investigation" was lower. This provided valuable feedback for us to review the course design and implementation, as further elaborated in the discussion section below.

(3) The means of each of the six *iteration* items ranged from 4.56 to 5.14, with standard deviations ranging from 0.14 to 0.18 (Table 2). These *iteration* items, as determined by the paired *t*-test analysis ($p = 0.005$), were significantly higher (4.32–4.71, SD = 1.03–1.41) than the Corwin et al. data (Table 2). The total iteration factor score ranged from 28.98 to 29.6.

Overall, the LCAS measurement showed that students perceived this CURE design as meeting the three key criteria of the CURE.

5.3 | The SURE survey data suggested students benefited from participating in this CURE

The SURE survey data ($n = 91$, 98% response rate), along with the national SURE data (2011–2018), are presented in Table 3. The data suggest that students perceived comparable learning gains with SURE data in

TABLE 2 The LCAS survey data comparison between this CURE and the Corwin et al.[29] data.

Items		This CURE ($n = 37$–42)		Corwin et al.[29] ($n = 176$)		p-value (t-test)
In this course....	**Code**	**Mean**	**SD**	**Mean**	**SD**	
I was encouraged to discuss elements of my investigation with classmates or instructors	C1	3.83	0.58	3.73	0.67	0.3318
I was encouraged to reflect on what I was learning	C2	3.90	0.37	3.72	0.67	0.0201
In this course, I was encouraged to contribute my ideas and suggestions during class discussions	C3	3.74	0.63	3.66	0.69	0.469
I was encouraged to help other students collect or analyze data	C4	3.78	0.66	3.25	1.04	0.0001
I was encouraged to provide constructive criticism to classmates and challenge each other's interpretations	C5	3.51	0.82	3.05	1.07	0.0032
I was encouraged to share the problems I encountered during my investigation and seek input on how to address them	C6	3.79	0.52	3.51	0.85	0.007
I was expected to generate novel results that are unknown to the instructor and that could be of interest to the broader scientific community or others outside of class	DR1	4.51	1.02	4.21	1.49	0.139
I was expected to conduct an investigation to find something previously unknown to myself, other students, and the instructor	DR2	4.83	1.06	4.39	1.5	0.0282
I was expected to formulate my own research questions or hypothesis to guide an investigation	DR3	4.86	0.95	5.07	1.14	0.2182
I was expected to develop new arguments based on data	DR4	4.88	0.98	4.7	1.24	0.3169
I was expected to explain how my work has resulted in new scientific knowledge	DR5	4.88	0.89	4.25	1.42	0.0004
I was expected to revise or repeat work to account for errors or fix problems	I1	4.98	0.90	4.71	1.11	0.0976
I had time to change the methods of the investigation if it was not unfolding as predicted	I2	4.56	1.16	4.32	1.31	0.2463
I had time to share and compare data with other students	I3	5.14	0.95	5.14	1.03	1
I had time to collect and analyze additional data to address new questions or further test hypotheses that arose during the investigation	I4	4.64	1.16	4.54	1.19	0.6181
I had time to revise or repeat analyses based on feedback	I5	4.90	0.98	4.59	1.29	0.0864
I had time to revise drafts of papers or presentations about my investigation based on feedback	I6	4.86	0.98	4.64	1.41	0.2356

Abbreviations: CUREs, course-based undergraduate research experiences; LCAS, laboratory course assessment survey.

discipline-specific skills and cognitive abilities such as laboratory techniques (3.87 vs. 3.80), research process (3.89 vs. 3.92), working on real scientific problems (3.79 vs. 3.84), ability to analyze data and other information (3.78 vs. 3.72), and data interpretation skills (3.84 vs. 3.69, $t = 0.1167$). There are a couple of factors that showed higher scores than the national SURE data, including scientific assertions requiring evidence (3.90 vs. 3.59) and skills in science writing (3.69 vs. 3.21). Students reported slightly lower or similar psychosocial gains in readiness for more demanding research (3.56 vs. 3.80), self-confidence (3.22 vs. 3.49), tolerance of obstacles (3.65 vs. 3.85), becoming part of a learning community (3.73 vs. 3.61), and clarification for career path (3.02 vs. 3.33). These findings indicate that the students benefited more in terms of discipline-specific skills than cognitive gains after participating in this CURE.

5.4 | Core concepts coverage

The concept learning reflection reported by students ($n = 87$, 95% response rate) indicated their increased self-efficacy in the core concepts learning, including genetics information flow, genotype–phenotype relationship, mutations and mutants, and structure-function relationship (Paired t-test, $p < 0.0001$, Figure 2), reflecting the coverage of these concepts in this mutant screen CURE.

TABLE 3 The SURE survey data comparison with the national data.

	This CURE ($n = 91$)		National UREs ($n = 23{,}406$)		
The SURE survey questions	**Mean**	**SD**	**Mean**	**SD**	***p*-value (*t*-test)**
Learning laboratory techniques	3.87	0.86	3.80	1.22	0.4393
Ability to analyze data and other information	3.78	0.84	3.72	1.00	0.4968
Skills in the interpretation of results	3.84	0.91	3.69	0.96	0.1167
Understanding that scientific assertions require supporting evidence	3.90	0.92	3.59	1.14	**0.0014**
Ability to integrate theory and practice	3.74	0.95	3.62	0.98	0.2292
Ability to read and understand primary literature	3.58	1.02	3.58	1.12	1
Ability to apply math in biology	3.11	1.11	n/a	n/a	n/a
Skills in how to give an effective oral presentation	3.49	1.06	3.43	1.20	0.5902
Skills in science writing	3.69	0.96	3.21	1.20	**<0.0001**
Understanding of the research process	3.89	1.02	3.92	0.93	0.7794
Understanding how knowledge is constructed	3.62	0.99	3.64	0.98	0.8475
Understanding how scientists think	3.63	1.04	3.84	1.05	0.0546
Understanding of how scientists work on real problems	3.79	0.98	3.84	0.96	0.6271
Ability to think critically about biology research	3.81	0.92	n/a	n/a	n/a
Self-confidence	3.22	1.13	3.49	1.14	0.0229
Learning to work independently	3.27	1.16	3.28	1.10	0.9346
Becoming part of a learning community	3.73	1.00	3.61	1.11	0.2535
Tolerance of obstacles faced in the research process	3.65	1.02	3.85	0.93	0.0619
Readiness for more demanding research	3.56	1.07	3.80	0.94	0.0327
Increased intentions to continue doing research	3.57	1.17	n/a	n/a	n/a
Increased intentions to pursue graduate degrees or science-related careers	3.49	1.33	n/a	n/a	n/a
Clarification of a career path	3.02	1.25	3.33	1.10	0.0182

Abbreviations: CUREs, course-based undergraduate research experiences; SURE, survey of undergraduate research experiences.

6 | DISCUSSION

While CUREs offer many advantages in terms of students' learning and career development, there are existing barriers to course design and implementation. One of these barriers is the increased time commitment required for a CURE due to the expanded roles of the instructor.[10,13] To address these barriers, one strategy is through partnership building, where established CURE programs offer training and collaboration opportunities for faculty members interested in designing or teaching the same CUREs in their classrooms.[17–20] This portability of the CURE allows faculty members from different institutions to apply it in their classrooms, fostering strong network and collaborative education communities. We propose that CURE collaborations can be further expanded in different dimensions, including partnerships between research intensive and teaching-focused units or institutions. We previously demonstrated a CURE collaboration between a research-focused laboratory and a teaching unit at an R1 institution, which showcased the feasibility of such collaborations and the benefits for stakeholders, including the research laboratory, the students, the instructor, and the teaching unit.[11]

This evolved CURE curriculum was designed to align with the progress of our research project and showcased the evolution of the CURE curriculum as the project proceeded. We initially developed a CURE curriculum when initiating the research project, which included a lipid analysis module to further characterize the mutants.[11] While this lipid module naturally advanced the research question and provided students with interdisciplinary knowledge in biochemistry, the addition of the new bioinformatic module not only allowed students to apply their knowledge of genetic information flow, genotype–phenotype, and mutations and mutants but also expanded the concepts further into the relationship between structure and function.

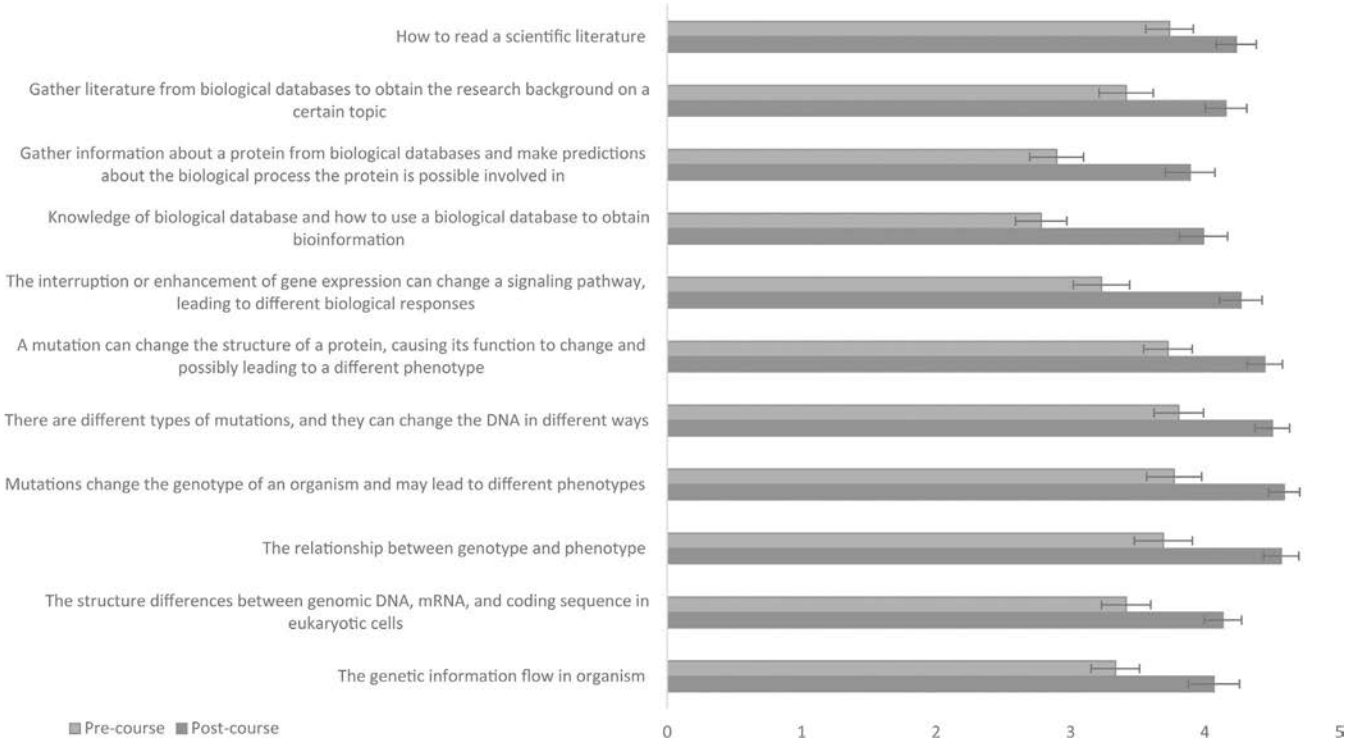

FIGURE 2 Concept survey data reflects the concepts coverage in the course-based undergraduate research experiences (CURE) design, and increased students' self-perceived learning gains ($n = 87$). Pre-course and post-course data were collected and analyzed with paired t-test in excel ($p < 0.0001$), and the difference was significant between the pre- and post-data for each of all the questions (t-test, $p < 0.0001$). Five-point Likert scale measurement, 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree.

We evaluated whether the CURE met the criteria of collaboration, discovery, and iteration by administering the LCAS instrument,[29] and the data suggests that students perceived the CURE design to largely meet these key criteria (Table 2). Although the majority of the data was higher or at the same level as the LCAS instrument, we observed a couple of items that scored slightly lower. These findings offer valuable opportunities for reflection on the CURE design and implementation, serving as guidelines for further revision of learning materials and adjustment in implementation. For example, the students gave slightly lower ratings on the DR3 item, "I was expected to formulate my own research questions or hypothesis to guide an investigation." Upon reflection, we concluded that this may be due to how we designed the learning materials and how we introduced research questions to the students. In the classroom, we initially introduced the long-term research goal to the students and then guided them in formulating the hypothesis, which left less room for students to explore and be aware of this critical thinking process. In the future, we plan to develop an activity focused on this aspect and allow students to actively engage in the research question formulation and hypothesis development. The LCAS scores can vary substantially among different laboratory courses,[31] and we also observed a difference between this mutant screen CURE and the data published along with the LCAS instrument.[29] There could be multiple elements contributing to the LCAS scores, in addition to the different laboratory courses mentioned above, and it would be interesting to find out what these elements are and how they are correlated with students' learning experiences in CUREs.

To cross-check the concepts coverage, we designed and implemented a course-specific concept survey at the beginning and end of the semesters. Because this is an evaluation of learning outcomes based on students' self-perceived data, we cannot conclude with certainty that the participating students increased their understanding of the concepts. However, the upwards trends in the self-perceived data suggest that the specific concepts that were covered in this CURE aligned with our goals of implementing the survey: analyzing students' initial understanding of concepts and utilizing that information to improve materials and bridge knowledge gap. Our future studies will involve collecting students' testing and homework data to gain direct insight into their concept learning by participating in this CURE.

In general, the SURE survey data (Table 3) showed higher self-perceived learning gains in discipline-specific

and cognitive skills, with slightly lower gains in psychosocial skills. We previously observed slightly higher learning gains in psychosocial skills.[11] We assume that the fluctuations may be attributed to the replacement of a hand-on lipid module with a computational bioinformatics module, although other variables such as students' prior knowledge, the classroom capacity, and the global pandemic may have played a role as well. Despite these differences, students from both curricula reported higher learning gains in their writing skills, which aligns with the emphasis on writing in this CURE, as indicated in the assessment column of Table 1.

Considering that mutant screens are commonly employed in the study of gene function within the field of biology research, we believe that this CURE can serve as a valuable resource for individuals interested in developing a mutant screen CURE curriculum that covers key biology concepts and apply science practice. Furthermore, we hope that our work can inspire collaborations between faculty members with different research or education responsibilities.

Additionally, a mutant screen CURE is feasible for undergraduate classroom implementation as it only requires basic laboratory cell and molecular laboratory equipment, such as micropipette, centrifuge, PCR machine, water bath, and gel electrophoresis apparatus. This CURE demonstrates the evolution of a CURE curriculum in response to the advancement of the research project. It establishes a dynamic learning-research community involving students, educators, and scientists, fostering collaboration and the exchange of knowledge.

This CURE also provided insight into the broader benefits of CUREs. For instance, in the C1 item of the collaboration factor, over 90% of students (corresponding to 3.83 in Table 2) reported that they were "encouraged to discuss elements of my investigation with classmates or instructors" on a weekly basis, suggesting a very dynamic and engaging classroom. In the SURE survey data, students rated "Becoming part of a learning community" at 3.73, a higher rating among the survey questions. These findings led us to ask the following questions: Do the students feel included in this classroom, especially the students from underrepresented groups? Do they have a sense of belonging in this CURE? What attributes of this CURE contribute to these features, if at all? Answers to these questions could provide us with a better understanding of our students' perspectives, and the diverse student body in our institution provides the basis allowing us to conduct such research. CUREs, by their nature, offer inclusive research opportunities to undergraduates,[2,32] and a further step built upon this nature is to create an inclusive learning environment where all students feel comfortable and can thrive. As Asai suggested,[33] "it is time to change the culture of science by putting inclusive diversity at the center," we expect that our future studies of these questions will provide insight into building a more inclusive classroom and contribute to the change of culture in education.

Furthermore, it would be interesting to conduct a study on whether and how this CURE affects students' life success skills. Hacisalihoglu et al. recently shared their experience in improving students' mindset and critical thinking through a life skill course.[34] This paper inspired us to ask questions about what this CURE experience really means to the students. For example, in the data we obtained from the LCAS and the SURE surveys, students reported learning gains in conducting research like a scientist, from asking question and formulating hypotheses all the way through data analysis and science communication. They also shared their attitude change in handling research difficulties and challenges and reported the impacts of this experience on their future endeavors. But would this CURE experience affect their life skills like mindset growth and critical thinking? If so, to what extent and how? Anecdotal evidence based on students that participated in the CURE, subsequently joined the participating research lab, and are now embarking on scientific careers in the biological sciences would suggest so. However, future studies generating qualitative and quantitative data are needed to address these questions.

7 | CONCLUSIONS

This evolved mutant screening CURE provides a comprehensive and engaging learning experience, integrating key biology concepts, scientific practices, and transferrable skills within a dynamic research-education environment. The course design was meeting the key criteria of a CURE laboratory course, and students reported positive learning gains in discipline-specific skills and cognitive abilities.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the authors.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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