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Review Article

Innovate and empower: the malate dehydrogenase course-based undergraduate research experiences and community of practice

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College science programs exhibit high rates of student attrition, especially among Students of Color, women, members of the LGBTQ+ community, and those with disabilities. Many of the reasons students choose to leave or feel pushed out of science can be mitigated through participation in faculty-mentored research. However, faculty resources are limited, and not every student has access to faculty mentoring due to systemic or structural barriers. By bringing authentic scientific research into the classroom context, course-based undergraduate research experiences (CUREs) expand the number of students who participate in research and provide benefits similar to faculty-mentored research. Instructors also benefit from teaching CUREs. Using a systematic review of 14 manuscripts concerning the Malate Dehydrogenase CUREs Community (MCC) and malate dehydrogenase (MDH) CUREs, we demonstrate that CUREs can be implemented flexibly, are authentic research experiences, generate new scientific discoveries, and improve student outcomes. Additionally, CURE communities offer substantial advantages to faculty wishing to implement CUREs.

Introduction

Nearly half of college science students leave, either switching to non-science degrees or dropping out of college entirely [1]. Marginalized Groups such as Students of Color, women, LGBTQ+ individuals, and those with disabilities are especially impacted [2–5]. Common reasons for departure include a lack of sense of belonging, inadequate support, and dissatisfaction with curriculum or teaching methods [5]. Participation in faculty-mentored research helps alleviate these issues and provides technical skills, networking, and increased science identity. Ultimately, undergraduate research experiences promote persistence in science, particularly for Marginalized Group students [6,7] but limited faculty resources exacerbate disparities [8–11]. One potential solution is Course-based Undergraduate Research Experiences (CUREs).

CUREs blend research into the classroom setting, providing students with hands-on experiences in tackling real-world problems under faculty guidance [12]. CUREs emphasize scientific practices such as literature review, experimental design, data collection and data analysis, and peer review within an authentic research project. Traditional laboratories often include several of these elements, most commonly data collection and analysis but do not combine them into one research project. Instead traditional laboratories use different data collection and analysis techniques to confirm concepts taught in lecture. While inquiry-based labs have known outcomes, the outcomes in CUREs and discovery-based laboratories are still unknown to the broader scientific community. Additionally, CUREs utilize scientific questions that students find relevant (Figure 1) [13]. CUREs significantly enhance student outcomes, fostering not only content mastery and technical proficiency but also a stronger sense of belonging and persistence in STEM disciplines [6,14–18].

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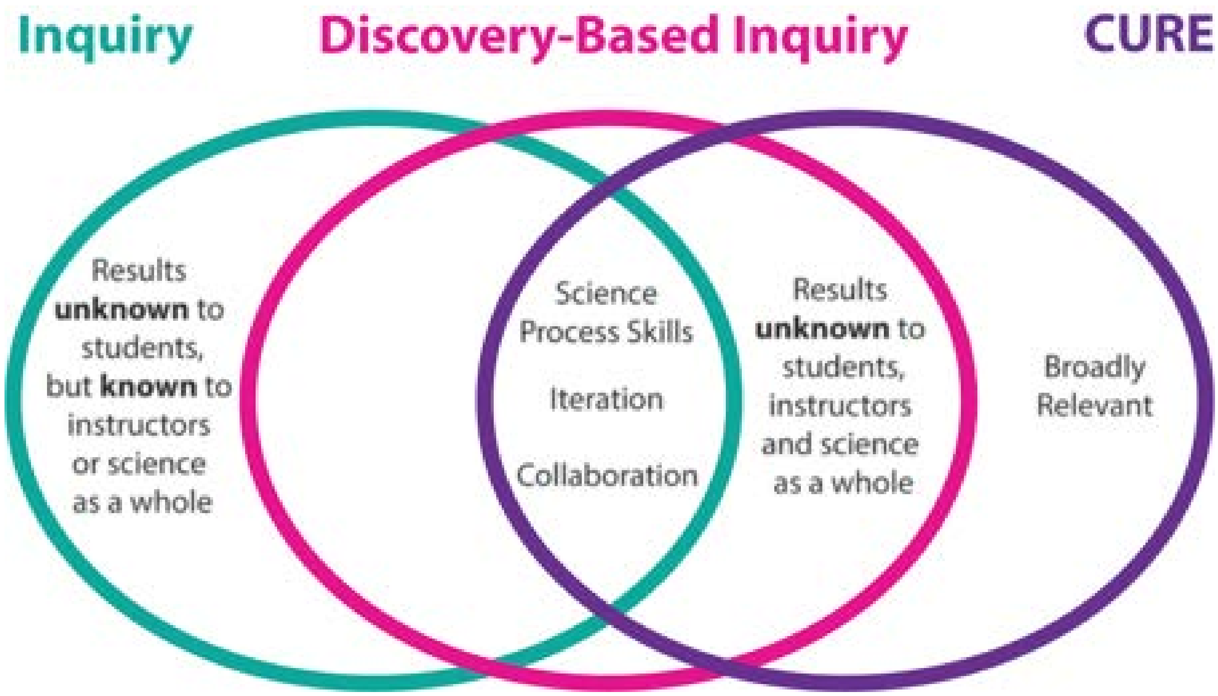

Figure 1. Differences and similarities among inquiry-based labs

These present students with a range of opportunities for engaging in the process of science. CUREs are unique curricula because the questions asked are broadly relevant to science and the students themselves. Image source: Adapted from Ballen et al., 2017 [53].

By taking place within the classroom, CUREs expand access to research opportunities, reaching a broader spectrum of students than traditional one-on-one mentoring models [11,19]. Faculty constraints include: finances, time, and space. These factors collectively impact the number of students that they can effectively mentor [9]. For students, there are several barriers to accessing mentored research experiences including: knowledge of their existence, understanding of their benefits, being intimidated by faculty, and financial barriers [8]. Engaging in CUREs can accommodate students with diverse obligations outside of academia, who may not have the time to engage in extracurricular activities. By offering a research experience that can be included in student course requirements many of these barriers are overcome [8]. This inclusive approach to learning not only benefits all students but also empowers those from marginalized backgrounds, including ethnic or racial minorities, by providing them with equitable access to enriching research experiences [16,20].

Faculty can also benefit from teaching CUREs. CUREs can integrate research and teaching leading to improved interactions with students, reinforced identity as a researcher, and excitement about teaching a dynamic curriculum [21,22]. However, adopting a new curriculum always involves uncertainty. CUREs with community support are more likely to be sustained because they provide support to help instructors navigate challenges [21,23].

In this review, we explore the malate dehydrogenase (MDH) CURE Community (MCC) and MDH CUREs. The MCC demonstrates how a community of practice for CUREs can evolve and provide multiple benefits to faculty. The MDH CUREs demonstrate how CUREs provide benefits for students, faculty, and scientific research. It is our hope that the information in this review will persuade faculty of the multiple benefits of CUREs whether engaged in individually or through a community of practice.

Methodology

We reviewed the eleven published papers [12,24–33], two manuscripts under review [34,35], and one thesis [36] that include the MCC or MDH CUREs. We organized the materials based on their content: reviews of the MCC, pedagogy of MDH CUREs, and research on the MDH CURE students or MCC faculty (Table 1). Student research data reported in this review is primarily a synthesis of data from two large research studies of 1,400 students [26,27], because other student research manuscripts contain preliminary data or data that are under review. Faculty research

Table 1 MDH CUREs and MDH CUREs Community Manuscripts

Manuscript	Type of Manuscript			
	Review	Pedagogy	Educational Research	
			Students	Faculty
The evolution of the malate dehydrogenase CUREs Community [24]	√			
Increasing access for biochemistry research in undergraduate education: the malate dehydrogenase CURE community [25]	√			
External collaboration results in student learning gains and positive STEM attributes in CUREs [26]			√	√
Length of course-based undergraduate research experiences (CURE) impacts student learning and attitudinal outcomes: a study of the malate dehydrogenase CURE community [27]			√	√
Course-based undergraduate research experience impacts on student outcomes at minority-serving community colleges [35]			√	
The influence of faculty peer network communication in the diffusion of a centralized CURE [36]				√
Construction of a CURE community to empower faculty and accelerate pedagogical change [34]				√
Developing course undergraduate research experiences (CUREs) in Chemistry [12]		√		
Teaching virtual protein-centric CUREs and UREs using computational tools [28]		√		
Using bioinformatics and molecular visualization to develop student hypotheses in a malate dehydrogenase oriented CURE [29]		√		
Impact of transition to a hybrid model of biochemistry course-based undergraduate research experience during the COVID-19 pandemic on student science self-efficacy and conceptual knowledge [30]		√	√	
Fostering student to student collaboration across institutions in a protein-centric CURE [31]		√	√	
Bringing the excitement and motivation of research to students; using inquiry and research-based learning in a year-long biochemistry laboratory [32]		√	√	
Using research to teach an 'Introduction to biological thinking' [33]		√	√	

data are a synthesis of all of the faculty data we collected. The rest of the manuscripts are used to describe the MCC, MDH CURE, and CUREs in general.

Depending on the study, the research on students ranged from one biochemistry classroom to multiple classrooms taught by 22 faculty members in biology, biochemistry, and chemistry. These faculty were from 19 United States institutions, including community colleges, primarily undergraduate institutions, and research-intensive [26,27]. Most often, the control courses were taught by the same instructors in the same course prior to converting the course to a MDH CURE. Alternatively, control courses were taught by a different instructor in the same course during the same semester. In some cases the MDH CURE was a new course. Students did not self-select into CURE courses. Study sample sizes ranged from 32 [33] to 1,400 students [26,27]. All students consented to contribute to this research. Depending on the study, various variables were measured. These included how the course was taught using the Laboratory Classroom Assessment Survey [37], student learning of experimental design using the Experimental Design Assessment Test [38], student self-reported learning gains from the CURE survey [39], faculty and student perceptions of their experiences [26,27,31,34,36], and retention [27,35]. An early study of MDH CUREs [32] utilized the Learning Assessment Guide Classroom Assessment Techniques Scoring Rubric [40] to assess student's critical thinking skills. Another early study of MDH CUREs [33] also utilized the Experimental Design Assessment Test [38]. For detailed methodologies, refer to the original manuscripts (Table 1).

Faculty research studies ranged from 13 to 19 faculty participants [26,27,34,36]. All faculty consented to participate in this research. Data collected from faculty included surveys, teaching inventories, and interviews. Data were de-identified for analysis. Due to the small sample sizes, faculty surveys and teaching inventories were reported with descriptive statistics [26,27,34]. Interviews and short answer questions [35,36] were analyzed with qualitative thematic coding techniques [63,64].

Artificial intelligence software (ChatGPT 3.5 and CoPilot) was used for enhanced editing techniques for this manuscript, ensuring concise writing, correct spelling, grammar, and punctuation. We utilized ChatGPT 3.5 in the first submission to condense the word count while preserving the original meaning. After the first draft was written, each paragraph was entered into ChatGPT 3.5 sequentially, with the following prompt: 'Rewrite the following passage to be more concise while retaining the original intended meaning'. Then the ChatGPT text was compared

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to the original text and revised paragraphs were written. When we received the revision comments, several new and more powerful artificial intelligence agents were available. In the revision, we used CoPilot with the Notebook feature to revise our writing. We did not use CoPilot's responses verbatim. We usually used a series of chat prompts to refine CoPilot's response. These 'conversations' were used to clarify language, provide alternative wording, change tone, condense word count, and rewrite long sentences. Once the CoPilot conversations produced text that met our purpose, we then used that response to write revised text.

Results

Malate dehydrogenase CUREs community

Early CURE networks were primarily within the realms of biology and microbiology [39,41,42]. To meet the educational requirements in protein-related learning [43], the MCC was created as one of the few protein-centric CURE networks [44,45]. A three-day think tank in 2015 brought together a group of faculty experts to discuss how to best deploy CUREs for students [46]. Following this gathering, 15 faculty from 12 institutions, including three research-intensive institutions, two community colleges, and seven primarily undergraduate institutions, began to integrate MDH CUREs into their curriculum (funded by the National Science Foundation) [47]. Within 5 years, the network grew to involve faculty from over 25 institutions [27].

In 2021, the success of the MCC led the National Science Foundation to fund a second grant to further expand and develop the community [48]. The MCC Fellow's training and mentoring program was launched to draw in faculty from varied backgrounds to adopt MDH CUREs [48]. Since then, nine new CURE instructors have been recruited annually, roughly three from each hub region, who are then paired with mentors and attend a workshop before implementing their first MDH CURE. Throughout their two-year fellowship program and beyond, these instructors engage in various professional development opportunities and potentially become mentors for future fellows. This broadens access to these influential research experiences for a larger and more diverse student population.

The MCC is organized at two levels: a national leadership group and regional hubs in the East Coast, Mid-Central, and West Coast/Southwest US. Additionally, a steering committee provides strategic oversight and guidance for the entire program. The regional hubs coordinate initiatives of the growing MCC, with each hub led by a director and a team of up to five hub mentors who are faculty members from diverse institutions. The national leadership group collaborates with hub directors to distribute support and resources, facilitating the expansion of hub networks.

MCC provides diverse MDH CURE curricula

Corwin et al. [17] suggested five common elements that should be included in a CURE: relevant problems, discovery of new knowledge, scientific processes, collaboration, and iteration. However, it is debated that all elements are needed for significant student outcomes [54–56]. The MDH CURE curriculum is implemented across biology, biochemistry, and chemistry programs at all undergraduate levels, resulting in diverse implementation approaches within each context. Therefore, all MDH CUREs are united by seven specific elements which incorporate Corwin et al.'s [17] elements (Figure 2). These include (1) relevance – discuss the significance and potential impact on the research field; (2) scientific background – introduce background foundational knowledge regarding MDH; (3) hypothesis development – formulate a testable hypothesis from primary literature and foundational knowledge; (4) proposal – outline the hypothesis with supporting evidence in a brief paragraph for introductory courses or in a formal proposal for capstone courses; (5) experiments, teamwork, collaboration, and reproducibility – perform experimentation to test the hypothesis and obtain reproducible data through iterative processes; (6) data analysis and drawing an evidence-based conclusion – draw conclusions based on the analyzed experimental data and discuss implications; and (7) presentation – present results in a written or oral format to peers and faculty [46]. The common elements of the MDH CURE continue to evolve as a result of ongoing research into crucial elements of a CURE.

MDH CUREs can be a module within a course or a complete semester

MDH CUREs can be categorized based on CURE length, as a modular CURE (mCURE) or full semester CURE (cCURE) (Figure 2) [25,27]. The Control (non-CURE) courses adopt a conventional semester structure without most of the CURE components (Figure 2). In the Control condition, each lab introduces the scientific background for that lab, and students follow manuals to conduct experiments in a step-by-step 'cookbook' style, aiming for known results. In comparison, the mCUREs begin with similar typical labs to teach foundational skills like pipetting and instrument operation. The scientific background is introduced in the context of MDH. An MDH CURE project is then incorporated, starting with initial relevance and hypothesis development [29]. This is followed by several weeks of experimentation to test the hypothesis, conclusion drawing, and discussion of implications, culminating in a final

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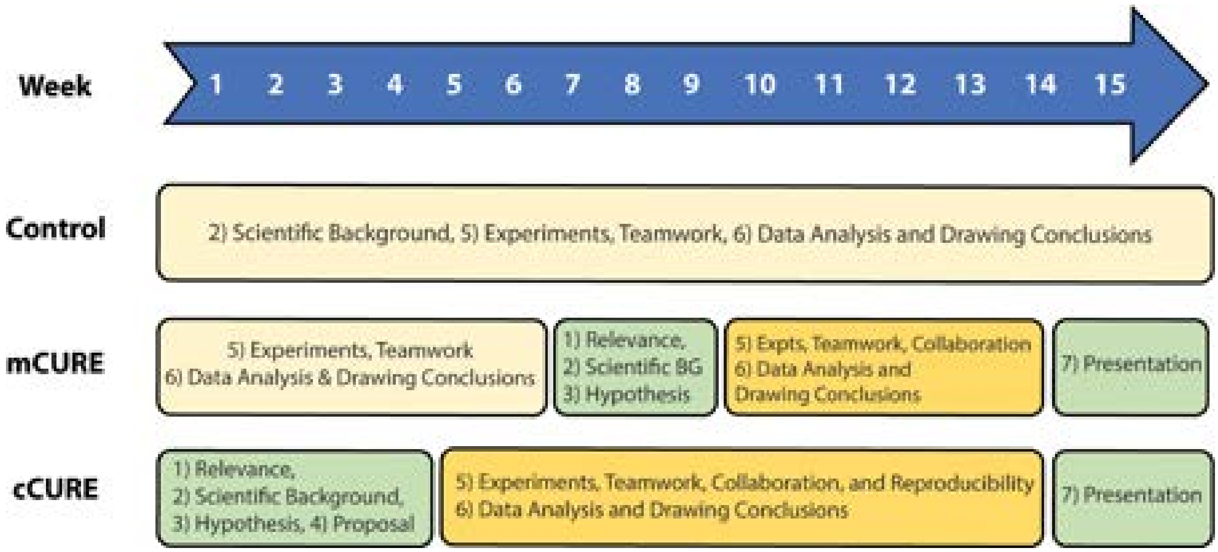

Figure 2. Organization of the control, mCURE, and cCURE courses by the Seven Common Elements of MDH CUREs
Seven common elements of MDH CUREs: (1) relevance, (2) scientific background, (3) hypothesis development, (4) proposal, (5) experiments, teamwork, collaboration, and reproducibility, (6) data analysis and drawing an evidence-based conclusion, and (7) presentation. Light yellow boxes indicate procedures commonly done in control laboratories, while dark yellow boxes indicate similar procedures done in the context of the CURE while adding collaboration and iteration to element 5. The green boxes indicate new procedures done within a CURE with the scientific background in element 2 specific to MDH research.

Table 2 Comparison of Control, mCURE, and cCURE courses without (I-CURE) or with external collaboration (EC-CURE)

7 Common Elements of MDH CUREs	Control	mCURE (6 week CURE)		cCURE (full semester CURE)	
		No external collaboration (I-CURE)	With external collaboration (EC-CURE)	No external collaboration (I-CURE)	With external collaboration (EC-CURE)
(1) Relevance		√	√	√	√
(2) Scientific background	√	√	√	√	√
(3) Hypothesis development		√	√	√	√
(4) Proposal				√	√
(5a) Perform experiments and teamwork, collaborate with home institution faculty and students	√	√	√	√	√
(5b) Perform experiments and teamwork, collaborate with faculty and possibly students from external institution			√		√
(6a) Data analysis and draw conclusions with faculty and students from home institution	√	√	√	√	√
(6b) Data analysis and draw conclusions with faculty and possibly students from external institution			√		√
(7) Presentation		√	√	√	√

project presentation. The mCUREs are typically done in collaborative groups with each group working on a hypothesis they have generated. A cCURE, on the other hand, substitutes the typical lab with a semester-long CURE. It extends the duration for hypothesis development and provides opportunities for iterative experimentation, thus more closely mirroring the real-world research process.

MDH CUREs can incorporate external collaboration

A critical variable in MDH CUREs involves collaboration with faculty from an external institution. This is known as an external collaborative CURE (EC-CURE) and can apply to both mCURE and cCURE formats (Table 2) [26]. Unlike an independent CURE (I-CURE) which operates without external collaboration, EC-CURE students typically

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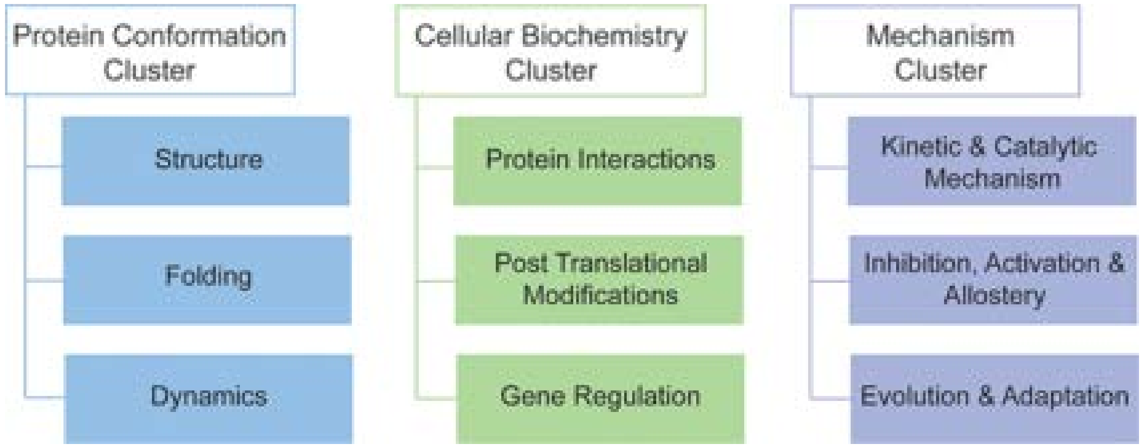

Figure 3. The three research clusters of MDH CUREs

Protein Conformation, Cellular Biochemistry, and Mechanism. Image source: adapted from DeChenne-Peters et al., 2023 [27].

participate in two virtual meetings with external faculty during their lab classes. Initially, students prepare by reviewing the literature, formulating hypotheses, and a research proposal, which they then present to the external faculty for feedback. This process often leads to adjustments in their hypotheses and/or research proposals. At the end of the semester, a final meeting with the external faculty involves students presenting and discussing data, addressing potential pitfalls, and proposing new questions for investigation. Additionally, some EC-CUREs extend collaboration to include students from the external institution, working together on complementary experiments that explore more complex hypotheses [31]. Based on the needs of the course, institution, and infrastructure, faculty can choose how to combine a mCURE or cCURE with an I-CURE and EC-CURE (e.g. external collaboration mCURE or independent cCURE, Table 2). This gives a wide range of flexibility for delivering the MDH CURE.

The MCC provides flexible curricular support

With readily available resources and ready-to-adopt sample curricula and experimental protocols from the MCC, instructors need minimal MDH- or protein-specific knowledge to start an MDH CURE. They also receive additional support from a well-organized community at regional and national levels, with the flexibility to incorporate their ideas into existing themes or to develop their own MDH-related CUREs [30]. This adaptable model contrasts with other CURE networks like SEA-PHAGES and GEP, which employ closely aligned curricula [39,42,50].

Enhancing Insights into MDH Science through MDH CUREs

The MCC comprises three research clusters: (1) Protein Conformation – studying protein structure, folding, and dynamics; (2) Cellular Biochemistry – investigating protein interactions, post-translational modifications, and gene regulation; and (3) Mechanism – exploring MDH kinetics and catalytic mechanism, inhibition and activation, and evolution (Figure 3) [27]. To date, MDH CUREs have generated over twenty bacterial-expressed His-tagged MDH wild-type isoforms, including both mitochondrial and cytosolic MDH from a variety of organisms, such as bacteria, yeast, and humans. Students in MDH CUREs have produced over one-hundred site-directed mutants, providing a valuable resource for MDH CURE adopters to explore significant research questions. They have also investigated MDH gene expression and effects on cell growth as well as studied MDH in a variety of organisms. Additionally, the MCC has formed partnerships with Addgene to maintain MDH and MDH-related protein clones and expression systems, and with Bio-Rad to create kits for specific MDH research themes. Both companies host customized web pages for MCC participants.

Thus far, MDH CUREs have generated data for 51 MDH scientific abstracts presented at meetings and then published in the *FASEB Journal* and the *Journal of Biological Chemistry*, all involving student authors and presenters. Abstracts have been published in all three clusters of MDH scientific research (e.g. Protein Conformation [51,57,58], Cellular Biochemistry [59,60], and Mechanism [61,62]). These abstracts represent students from primarily undergraduate institutions. Notably, one abstract has been cited seven times [51]. Faculty across institution types are leveraging the MDH CURE to address multiple facets of their work including: teaching, scholarship, and service. The MDH CURE is a key component of most faculty's teaching portfolios. A number of faculty members have also incorporated

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the MDH CURE into their own scholarship. They employ the MDH CURE to generate and test ideas, and recruit undergraduate research students. Some faculty have even shifted their research focus to MDH, recognizing the MCC is also a supportive research community. For faculty whose institutions consider mentoring undergraduates as service, the MDH CURE can contribute to all three aspects of their work. The data produced in MDH CUREs is proving generative, and is being used for a national grant application (cellular biochemistry cluster), seven manuscripts that are currently in progress (all clusters), and one manuscript that is under review. In this issue of *Essays in Biochemistry*, one of the articles incorporates data generated by students in MDH CUREs [52].

Student pedagogical research

Students report laboratory activities and learning consistent with a CURE

While MDH CURE faculty reported teaching courses consistent with the elements of a CURE [26,27], this was corroborated with student experiences of the MDH CURE through the Laboratory Course Assessment Survey [37] and 25 items from the CURE survey [39]. The Laboratory Course Assessment Survey surveys the students' perception of their experiences in laboratory courses across three dimensions: discovery/relevance, iteration, and collaboration. Discovery/relevance measures students' perception of the extent to which the students are discovering new and pertinent scientific information. Iteration reflects student perceptions of the frequency of repeated experiments, while collaboration assesses student perceptions of student interaction levels. The Laboratory Course Assessment Survey confirmed that students had contrasting experiences in MDH CUREs compared with control labs. Most control labs were taught by the same faculty in the same course in preceding semesters. Many faculty had minimal prior experience teaching CUREs. Across all MDH CURE variations, discovery/relevance and iteration were significantly higher than in the control courses (Figure 4) [26,27]. While collaboration typically does not differ between CURE and control courses [37], it was significantly higher in the cCURE compared with the mCURE and control courses. Although the EC-CUREs showed no overall difference in collaboration compared with the I-CUREs and control classes, they exhibited significantly higher scores for two items of the collaboration scale: discussing elements of their research with their classmates, and contribution of ideas in class discussions.

MDH CUREs improve student outcomes

CURE student perception of their learning significantly surpassed that in the control classes for several student self-reported learning items (Figure 5) [26,27]. The CURE survey [39], composed of 25 learning activity statements, revealed that students in both mCUREs and cCUREs reported significantly greater learning from 10 of the 25 activities. The EC-CURE students outperformed those in the I-CURE and Control conditions on two of those items (Figure 5). Figure 5 displays the estimated marginal means for each significant student perception of the learning gain from the ANCOVA. From post-hoc tests, the significant differences are: student knows outcome (control and mCURE > cCURE), instructor knows outcome (control > cCURE and mCURE), no one knows outcome (cCURE > mCURE > control and EC-CURE > I-CURE and control), students have some input (cCURE > mCURE and control), students responsible for part (cCURE > control), students entirely design project (cCURE > mCURE and control), students read primary literature (cCURE > mCURE and control), students write a research proposal (cCURE > mCURE > control), students present results: poster (cCURE > mCURE and control), and students present results: oral presentation (cCURE > mCURE and control and EC-CURE > I-CURE and control).

Objective tests of student learning in MDH CUREs showed enhanced critical thinking [32], content mastery [30], and experimental design skills [26,27,33]. An early MDH CURE study employing the Learning Assessment Guide Classroom Assessment Techniques Scoring Rubric [40], found increased critical thinking skills including hypothesis identification, experimental design, and communication of results [32]. During the COVID-19 pandemic, a hybrid MDH CURE (alternating online and face-to-face activities weekly) showed increased conceptual knowledge scores over the semester and higher scores than the post-pandemic face-to-face MDH CURE course. However, both were lower than the pre-pandemic face-to-face MDH CURE [30]. The Experimental Design Ability Test [38] measured students' capacity to design experiments in contexts beyond MDH. It demonstrated increased experimental design proficiency among early MDH CURE participants [33]. In recent studies comparing CURE conditions and control courses experimental design skills (Figure 6), cCURE students significantly outscored control students. However, mCURE students' learning gains were not significantly different from either (Figure 6A) [27]. Additionally, EC-CURE students scored significantly higher than those in the I-CURE and control conditions (Figure 6B) [26].

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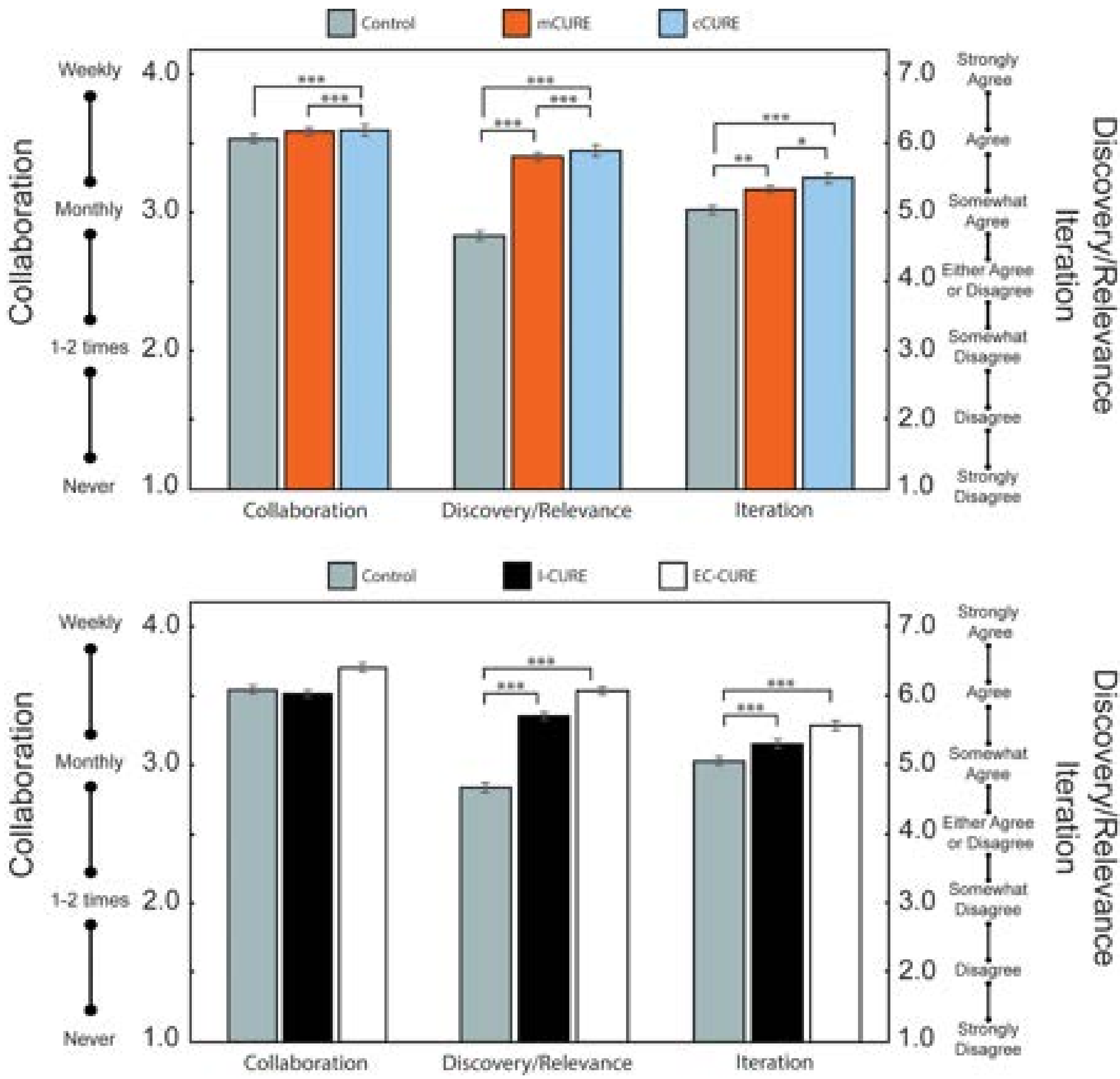

Figure 4. MDH CUREs deliver more CURE elements than control courses

Using the Laboratory Course Assessment Survey [37], students reported their perception of the amount of collaboration, iteration, and discovery/relevance they experienced during their course [26,27]. Iteration and Discovery/Relevance were measured using a Strongly Disagree (1) to Strongly Agree (7) scale. Collaboration was measured on a Never (1) to Weekly (4) scale. ANCOVAs with follow-up post-hoc tests identified significant differences. Control $N = 563$, mCURE $N = 512$, cCURE $N = 323$, I-CURE $N = 557$, EC-CURE $N = 279$. These two studies used the same student sample to study two different CURE variables (length and collaboration). *$P<0.05$, **$P<0.01$, ***$P<0.001$ Image Source: Adapted from DeChenne-Peters et al., 2023 [27] and Callahan et al., 2022 [26].

Marginalized groups impacted similarly in MDH CUREs except in Community Colleges

In recent studies, student data was categorized by race and ethnicity, distinguishing between traditionally Marginalized Groups (e.g. African American, Native American, and Hispanic) and those over-represented in scientific endeavors (i.e. White and Asian American) [2]. In the overall MDH CURE student sample, differences in learning gains were minimal, except that more marginalized students in the mCURE reported planning to conduct undergraduate research than their White and Asian peers [27]. However, among community college students, taught by the

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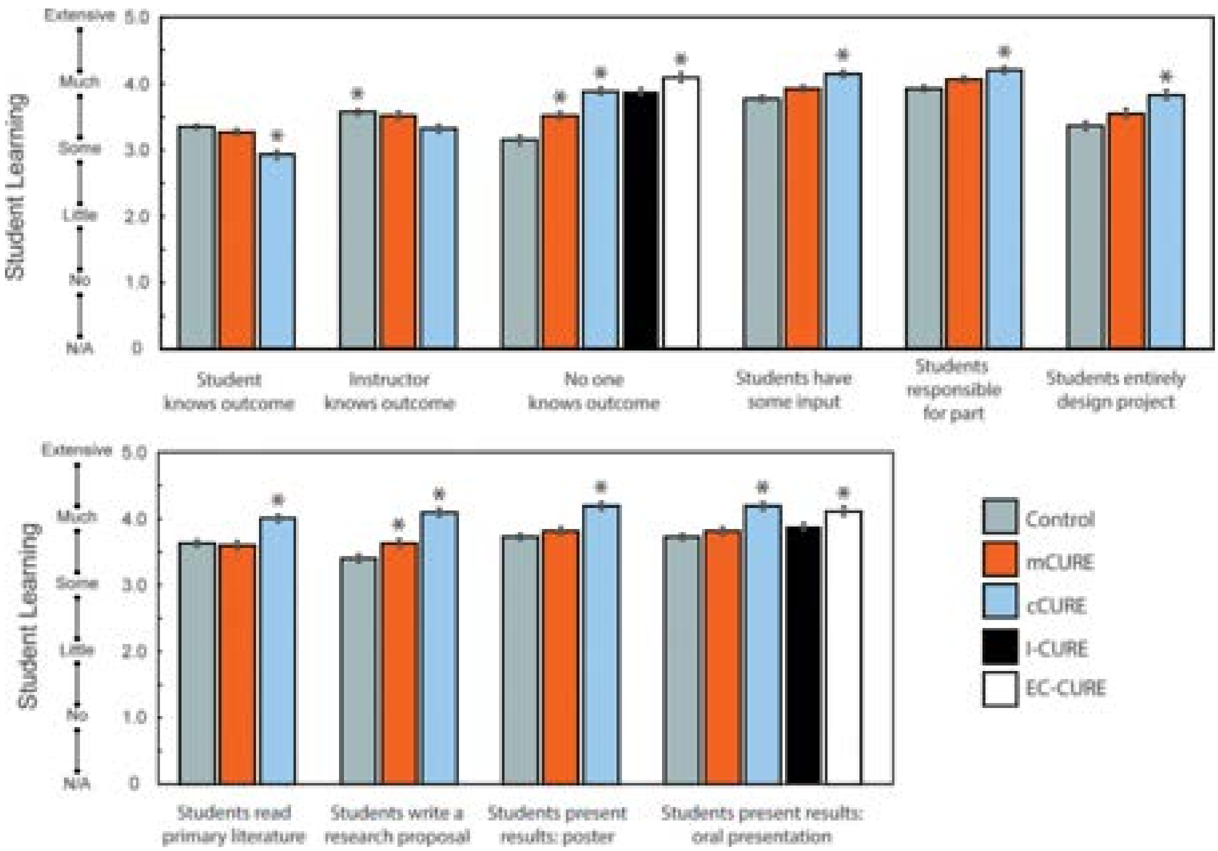

Figure 5. Students Reported Learning Gains Consistent with a CURE

Students rated their proficiency for 25 laboratory activities on a scale of 1 (no experience/feel inexperienced) to 5 (extensive experience/feel mastery), indicating their pre-test experience and post-test learning gains [39]. An ANCOVA, controlling for pretest scores with a Bonferonni correction (*$P<0.002$), indicated significant differences across 10 activities based on CURE length [27], and two of those activities were also significantly higher in the EC-CURE [26]. Control $N = 563$, mCURE $N = 512$, cCURE $N = 323$, I-CURE $N = 557$, EC-CURE $N = 279$. These two studies used the same student sample to study two different CURE variables (length and collaboration). Image Source: Adapted from DeChenne-Peters et al., 2023 [27] and Callahan et al., 2022 [26].

same instructors in both CURE conditions and control courses [35], students from Marginalized Groups were significantly different in scientific literacy. The CURE conditions reversed the lower scientific literacy of Marginalized students compared to their White and Asian peers from the control. In the control, the Marginalized Groups students had lower scientific literacy, in the mCURE the literacy between the two groups was equal and in the cCURE the Marginalized Group students had higher scientific literacy scores. Additionally, community college retention was significantly higher among Marginalized Group students in the MDH mCURE compared to the control Marginalized Group students [35].

External collaboration is important for student outcomes

Among the EC-CURE instructors, the majority emphasized the importance of external collaboration for student learning, student attitudes toward the scientific process, and satisfaction with teaching the MDH CURE course (Table 3). Similarly, in a survey of students collaborating across courses at two institutions [31], at least 75% thought that external collaboration was important to their learning. The primary learning outcomes identified from student-to-student external collaboration were improved scientific communication skills and heightened attentiveness to research methodology. Students also highlighted the importance of collaboration assignments in facilitating the organization of meetings with their collaborators from the other institution (Table 4).

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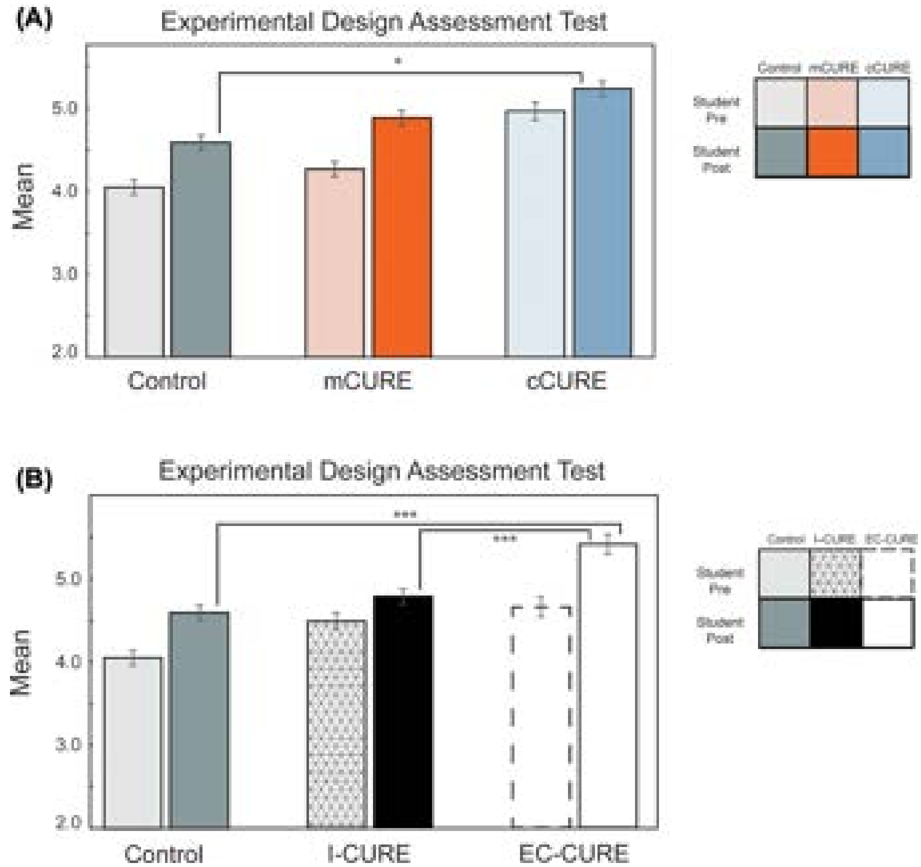

Figure 6. MDH CUREs improve students' experimental design skills

Students took the Experimental Design Assessment Test [38] pre- and post-semester [26,27]. Their responses were scored from 0 to 10. An ANCOVA compared the students' post-semester mean scores between conditions. Post-hoc tests indicated students in the cCURE condition scored significantly higher than the control condition (**A**), while students in the EC-CURE scored significantly higher than students in I-CURE and control (**B**). Control $N = 563$, mCURE $N = 512$, cCURE $N = 323$, I-CURE $N = 557$, EC-CURE $N = 279$. These two studies used the same student sample to study two different CURE variables (length and collaboration). $^{*}P<0.05$, $^{**}P<0.01$, $^{***}P<0.001$ Image Source: Adapted from DeChenne-Peters et al., 2023 [27] and Callahan et al., 2022 [26].

Table 3 Faculty perceptions of impact of external collaboration

How did external collaboration affect	Critically important	Important	Somewhat Important	Not important
student learning gains?	64%	27%	9%	0%
student attitudes towards the scientific process?	64%	18%	18%	0%
your satisfaction with the course?	55%	36%	9%	0%

Source: **Adapted from Callahan et al., 2022**.

The MCC is a community which supports faculty

The MCC is a network of MDH CURE practitioners that supports teaching MDH CUREs, conducting MDH science research, and conducting pedagogical research. The MCC serves as a community of practice [49], in which members interact regularly to learn from each other and exchange ideas, insights, experiences, and best practices. Members engage through mentorship, idea exchange, resource sharing, and emotional support; this fosters connections within the community that reinforce the community's aims of producing sustainable protein-centric CUREs [36]. The MCC supports instructors of diverse backgrounds with accessible resources, reducing the barriers to implementing a new

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Table 4 Student perceptions of impact of student-to-student external collaboration

Survey question	Critically important	Important	Somewhat important	Not important
How do you think that collaboration with a different institution helped improve your scientific communication skills?	10%	46%	38%	6%
How did collaborating with students from another institution affect your understanding of biochemistry concepts relevant to your research project?	13%	15%	52%	20%
Did working with students from another institution encourage you to be more cautious in your experiments and data collection?	35%	27%	24%	14%
How did the collaboration assignments assigned by your instructors assist you in organizing meetings with student collaborators from other institutions?	27%	49%	20%	4%
Do you think that collaboration helped you keep better records (notebooks, notes) of your experimental procedures and data collection?	17%	18%	40%	25%
How do you think that collaboration with a different institution affected your satisfaction with the course?	8%	25%	46%	21%

Source: **Martinez-Vaz et al., 2023**.

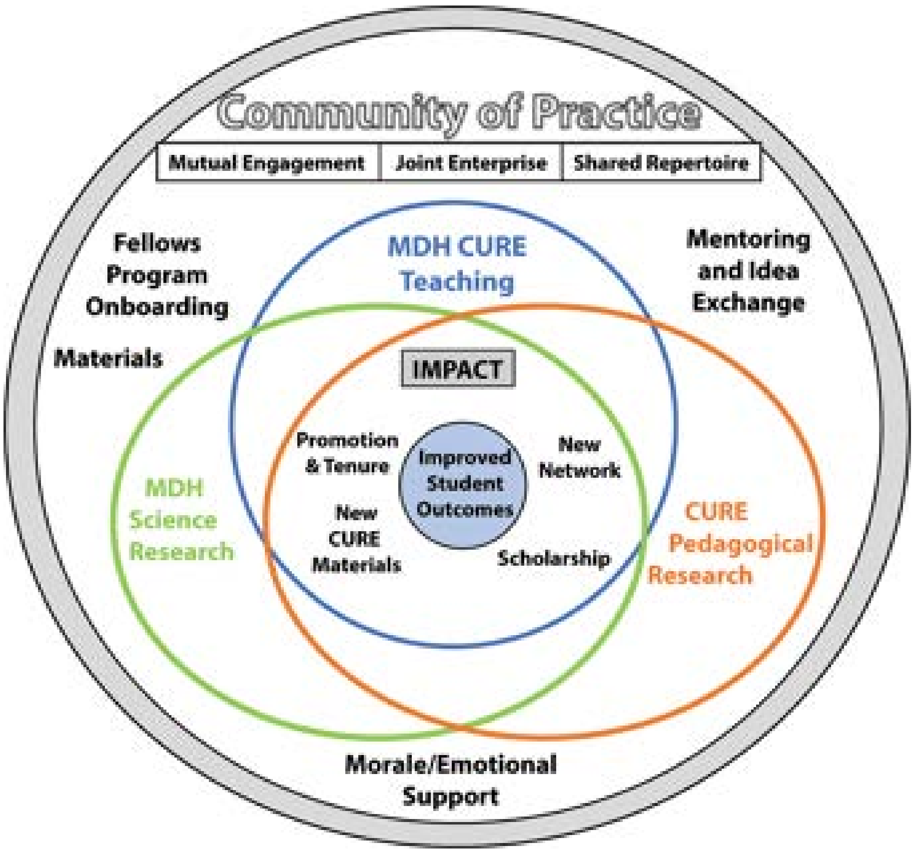

Figure 7. MCC as a Community of Practice: Impacts on Faculty and Instructors
These are the intersecting features of the MCC as a community of practice [49]. Faculty interact in this community through teaching MDH CUREs and conducting research on MDH science and CURE pedagogy. The community empowers instructions through onboarding, material sharing, idea exchange, mentoring, and emotional support. These components ultimately lead to impacts on faculty and improved student outcomes.

curriculum by providing teaching materials, expertise, and mentorship, as well as career advancement opportunities (Figure 7) [34,36].

"I think it was way better for our students in the long run; wouldn't have done it without the Community. No way." – Biochemist, minority-serving research-intensive institution [36].

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Designed for varying knowledge levels and teaching contexts, the community aids instructors with diverse backgrounds in CUREs, science disciplines, research, and teaching. Accessible resources and expertise are provided, fostering connections across disciplines and institutions. The MCC's strength lies in mentorship and innovation derived from the diversity within the community [36]. It also continually evaluates and improves the experience of incoming members through 'onboarding' to integrate newcomers into the wider community.

The community reduces uncertainties around adopting a new curriculum by providing teaching materials, access to experts, and mentorship [34,36]. These elements are crucial for making CURE adoption feasible, as described by members:

" . . . to implement a CURE at my institution, I needed a lot of help, and I think that's where the MCC really shines. In terms of the expertise, [community leaders] have done an amazing job of documenting everything and having all the resources, and everybody's very good about sharing and helping out, so I think without that, I mean it just really wouldn't have been possible." – Biochemist, community college [36].

While most members initially sought material support and access to experts, upon joining, many discovered the importance of moral support in teaching CUREs and conducting MDH science research [36]. Teaching MDH CUREs helped instructors doing protein-centric or pedagogical research to align their teaching and research efforts [36]. Instructors appreciated that MDH CUREs allowed them to conduct research in their classrooms, especially those whose research did not align with the lab courses they teach [36].

Community membership served as a catalyst for new interests, projects, and collaborations [36]. This boosted instructors' confidence in teaching CUREs and prompted the development of new CUREs or integration of MDH CUREs into additional courses. The MCC supported the transition to online teaching during the COVID-19 pandemic, developing hybrid MDH CUREs [30] and completely asynchronous MDH CUREs [28]. By adopting MDH CUREs, instructors served as models for teaching a CURE to their colleagues, and increased interest in CUREs among their institutions' faculty [36]. Members have been able to leverage their experiences and community involvement in hiring processes and career advancement [36].

Summary

In this review, we used the MCC and MDH CUREs to demonstrate the following:

- **CUREs can be flexible in implementation.** Based on faculty needs, MDH CUREs are implemented in different ways and adapted to all institutional types.MDH CURE research indicates that any duration of a MDH CURE is generally more effective for at least some of the students in the course than not participating in a CURE. Instructors who cannot incorporate a full-semester CURE can include modular CUREs in their current laboratory courses.

- **CUREs can generate novel data that contributes to scientific research.** The MDH CUREs generated data for many abstracts and several manuscripts. Undergraduate students were coauthors and presenters on those publications.

- **CUREs improve student learning.** Students in MDH CUREs perceive that they are learning more, and objective measures of learning experimental design corroborate this perception. In the experimental design assessment, students demonstrated their ability to apply their learning of experimental design from the MDH context to a completely different scenario.

- **CURES with external collaboration enhance student learning and faculty satisfaction.** Given the significant benefits for students demonstrated by the collaborative MDH CUREs, CUREs should integrate collaboration into their framework where possible. While student-to-student collaboration requires more extensive coordination, arranging for a faculty collaborator to join the class via Zoom twice per semester offers an easy way to enhance the CURE's impact for both students and faculty.

- **A CURE community offers vital faculty support.** While CUREs are high-impact and evidence-based teaching practices, implementing a new curriculum can be resource-intensive.

However, with community support like the MCC, many barriers to adopting CUREs can be mitigated. The MCC provides extensive support for MDH CUREs instructors, offering materials, expertise, networking, mentoring, and moral support, regardless of experience or discipline. Incorporating MDH CUREs benefits both students and instructors, with instructors particularly benefiting from the wide-ranging support and opportunities provided by the associated community.

Competing Interests

The authors declare that there are no competing interests associated with the manuscript.

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Author Contribution

We acknowledge that all the authors have direct or peripheral involvement with the MCC. Authors S.E.D.P., A.D.P., and J.Z. are active members of the MCC, who teach MDH CUREs and conduct research on MDH and MDH CUREs. N.L.S. participated in an MDH CURE as an undergraduate and collected and analyzed data from the MCC for a master's thesis. SEDP contributed to the conception and design of this paper as well as conducting data analysis for several of the reviewed articles. She drafted the article, reviewed it for important intellectual content, and approved this version for publication. J.Z. contributed to the conception and design of this paper as well as conducting data analysis for several of the reviewed articles. She drafted the article, reviewed it for important intellectual content, and approved this version for publication. N.L.S. contributed to the conception and design of this paper as well as conducting data analysis for a reviewed article. She drafted the article, reviewed it for important intellectual content, and approved this version for publication. A.D.P. contributed to the design of the figures and conducted data interpretation for a reviewed article. She reviewed this article for important intellectual content and approved this version for publication.

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Abbreviations

cCURE, A full semester CURE course; **CURE**, Course-based Undergraduate Research Experience; **EC-CURE**, external collaboration CURE; **I-CURE**, independent CURE; **MCC**, malate dehydrogenase CURE community; **mCURE**, modular CURE course; **MDH CUREs**, malate dehydrogenase CUREs; **MDH**, malate dehydrogenase; **STEM**, Science, Technology, Engineering, and Mathematics.

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