Current Status and Implementation of Science Practices in Course-Based Undergraduate Research Experiences (CUREs): A Systematic Literature Review

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ABSTRACT

A systematic review of the literature was conducted to identify course-based undergraduate research experiences (CUREs) in science, technology, engineering, and math (STEM) courses within the years 2000 through 2020. The goals of this review were to 1) create a resource of STEM CUREs identified by their discipline, subdiscipline, and level; 2) determine the activities included in each CURE, particularly the primary components listed in the CURE definition as well as specific science practices we identified as key to scientific reasoning; and 3) identify the next steps needed in CURE creation and implementation. Our review found 242 CURE curricula described in 220 total articles, with most described in biology, although STEM disciplines, including chemistry and biochemistry, have begun to publish CURE curricula as well. We also found that most CUREs include the primary components. However, when we look at the specific science practices essential to scientific reasoning, we found that these are less common in many CUREs and are implemented differently. We encourage CURE authors to consider including these science practices and potentially measuring their impact on student outcomes. The present work provides a summary of the current published CUREs, their disciplines, course levels, primary components, and specific science practices.

INTRODUCTION

It has long been recognized that there is a need for more workers in the science, technology, engineering, and mathematics (STEM) disciplines. Thus, there has been a push for universities to address this need (National Research Council [NRC], 2002, 2013a,b; American Association for the Advancement of Science [AAAS], 2011; President's Council of Advisors on Science and Technology [PCAST], 2012) and colleges and universities have begun to examine factors that increase retention of students in STEM. Research has shown that student participation in undergraduate research experiences (UREs) can have this impact (Espinosa, 2011; PCAST, 2012). Although UREs can be quite diverse, the traditional image of a URE is when a student conducts research in the lab of a faculty mentor on a topic specific to that faculty's research (National Academics of Sciences Engineering and Medicine [NASEM], 2017). These types of UREs have clear benefits for students, such as increased technical skills, a greater understanding of the research process, enhanced abilities to prepare for future careers, and an increase in intrinsic motivation and persistence in STEM (Sabatini, 1997; Mabrouk and Peters, 2000; Bauer and Bennett, 2003; Lopatto, 2004, 2007; Lopatto and Tobias, 2010; Buckley, 2008; Searight *et al.*, 2010; Craney *et al.*, 2011; Thiry *et al.*, 2012; Stanford *et al.*, 2015; Fuchs *et al.*, 2016).

Due to these factors, UREs tend to increase graduation rates (Kim *et al.*, 2003; Nagda *et al.*, 1998) and are likewise seen as a partial answer to the call for more workers in STEM fields (NRC, 2002; AAAS, 2011; PCAST, 2012). However, the traditional URE model, in which students engage in research in the laboratory of a faculty

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member, is restricted to a small number of students (Harrison *et al.*, 2011). Thus, faculty and departments have sought out other mechanisms to provide similar opportunities to students. One of the more common methods to create a research experience for students has been to create course-based undergraduate research experiences (CUREs), which are implemented within the context of a course, so that all students enrolled in the course are able to participate (Auchincloss *et al.*, 2014). CUREs therefore increase access to research opportunities for students, especially historically minoritized groups, which is an additional motivating factor for incorporating CUREs into the college experience (NASEM, 2017). By including more students in research, we are able to increase the diversity and points of view inherent in science (Bangera and Brownell, 2014).

CUREs

CUREs are quite different from the traditional laboratory experience, because CUREs require students to perform the scientific research process, rather than simply follow a series of instructions to arrive at a predetermined outcome. Investigations into the benefits of CUREs have indicated that CUREs give students an appreciation for the work of scientists and increase student confidence in their science skills (Brownell *et al.*, 2012, 2015). Furthermore, CUREs also give students the skills they need to successfully perform research (Alneyadi *et al.*, 2019; Chaari *et al.*, 2020), and can increase project ownership (Hanauer *et al.*, 2017; Corwin *et al.*, 2018b; Cooper *et al.*, 2019). Overall, students who participate in a CURE have a greater degree of persistence in STEM fields than students who are not able to participate in a CURE, and thus CUREs are a potential avenue for increasing retention of students in STEM (Drew and Triplett, 2008; Harrison *et al.*, 2011; Bascom-Slack *et al.*, 2012; Hanauer *et al.*, 2012; Jordan *et al.*, 2014; Shaffer *et al.*, 2014; Brownell *et al.*, 2015).

As the benefits of CUREs have become clearer, there has been an increase in the number of CUREs created (Alkaher and Dolan, 2014) and a concomitant increase in the examination of the specific student outcomes of these CUREs (Shaffer *et al.*, 2014; Brownell *et al.*, 2015; Pontrello, 2015; Hanauer *et al.*, 2016; Olimpo *et al.*, 2016; Rodenbusch *et al.*, 2016; Shanle *et al.*, 2016; Wooten *et al.*, 2018). Auchincloss and colleagues (2014) created a logic model (Figure 1) that identifies potential outcomes linked to specific activities commonly performed in CUREs. These activities are: 1) use of scientific practices, wherein students participate in activities including but not limited to designing studies, evaluating models, analyzing data, and communicating findings; 2) discovery, which requires that new knowledge or insight is obtained; 3) relevance, in which student work has an impact outside the CURE classroom; 4) collaboration, for which groups of students all contribute to answer questions or solve problems during the CURE procedure; and 5) iteration, in which students must continue to build upon their knowledge and reassess as things go awry (Auchincloss *et al.*, 2014). Auchincloss and colleagues posit that participation in a CURE with these activities will lead to student outcomes such as development of technical skills, self-efficacy, scientific aspirations, science identity, and science expertise.

Based on this initial logic model, Corwin and colleagues (2015) proposed a more comprehensive framework to explain the potential relationship between short-, medium-, and long-term student outcomes associated with different components of a CURE. This model features specific components of CUREs such as collection of novel data, investigation of the primary literature, student collaboration, dissemination of work outside class, and project design. Corwin and colleagues then propose relationships between these components and student outcomes, as well as relationships between student outcomes (for more detail, see Corwin *et al.*, 2015). The goal of this more complex model was to predict relationships that could then be rigorously examined. However, there has been limited research investigating these relationships. Some authors have indicated that students report positive shifts in their self-determination, self-efficacy, and overall motivation in a CURE as compared with a traditional laboratory experience (Olimpo *et al.*, 2016; Cooper *et al.*, 2019). Another study found that discovery, iteration, and collaboration in a CURE have a positive impact on student ownership and career goals (Corwin *et al.*, 2018b). Ballen and colleagues (2018) investigated the effects of discovery and relevance in one short-duration CURE for nonmajors and reported these components did not significantly affect students' academic performance, self-efficacy, or project ownership. Others raised questions about the CURE being studied and the measurement methods being used (Corwin *et al.*, 2018a), highlighting the need to use measurements that align with clear definitions of CURE elements so that these experiences and student outcomes are adequately compared. It is also possible that differences in CURE outcomes may be because different CUREs were examined, and each CURE was composed of different components. Thus, it is critical that researchers compare CUREs with similar components and that these components be clearly defined.

When examining CUREs in this systematic review, we were interested in elucidating the components that these experiences include. In the framework devised by Corwin *et al*. (2015), science practices are identified as one of the key aspects of CUREs, but there are many activities that can fall under the broad umbrella of what are considered to be science practices. To determine which science practices are critical in CUREs, we examined the science practices identified by the NRC (2012) and Laverty and colleagues (2016). The NRC report presents a conceptual framework describing eight major science and engineering practices (Table 1). While these standards were developed for K–12 students, they include many components that can be applied to the college classroom (Laverty *et al.*, 2016). In fact, Laverty and colleagues (2016) built upon the NRC framework in their assessment of science practices in college classrooms. They modified the NRC framework and created their own framework of "three-dimensional learning," as shown in Table 1 (Laverty *et al.*, 2016). However, because they were focused on science practices specific to the classroom environment, they removed some key aspects of the NRC's framework, including 1) asking questions, 2) carrying out investigations, 3) obtaining information, and 4) communicating information—all of which they considered to be laboratory-specific practices (Laverty *et al.*, 2016).

In our examination of the science practices in CUREs, we chose to include the four practices that Laverty and colleagues (2016) noted as laboratory specific. This decision was based on the theoretical framework of Chinn and Malhotra (2002), who argue that a primary goal of science education should be

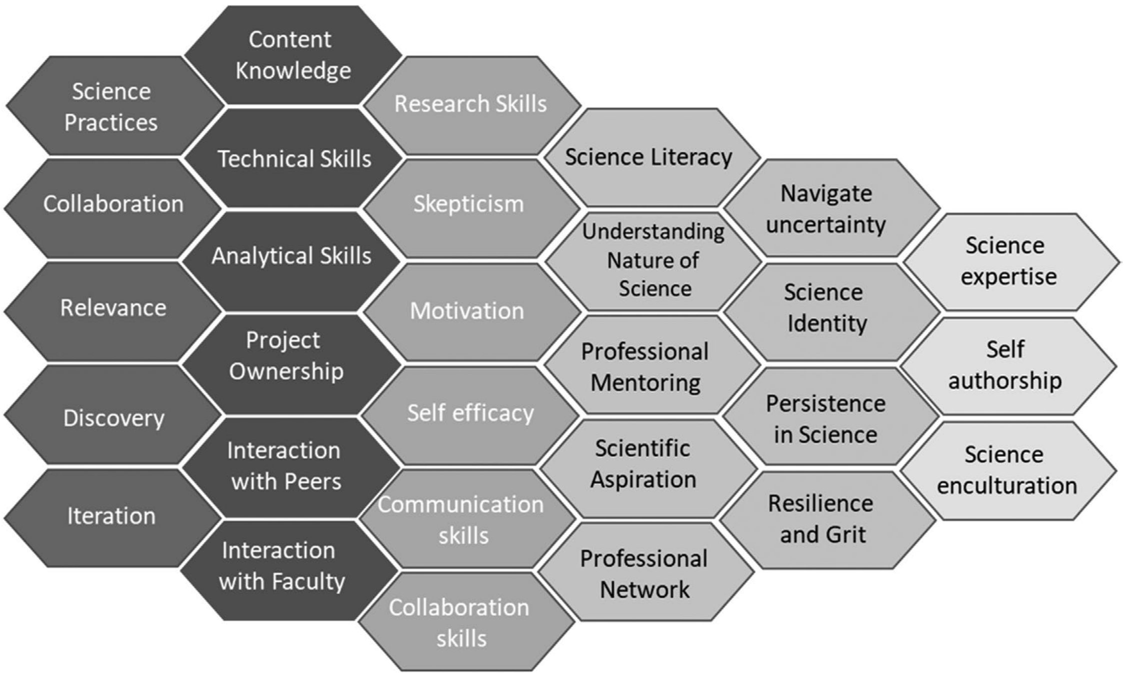

FIGURE 1. Logic model identifying potential outcomes linked to specific CURE activities (column on the far left). The outcomes closest to the specific CURE activities are more likely to occur from a single CURE or a short CURE, while outcomes moving toward the right are more likely to occur if students participate in multiple CUREs or longer-term CUREs. Modified from the model created by Auchincloss and colleagues (2014).

helping students to learn scientific reasoning. They state that scientific reasoning is key to the type of research that scientists perform in their careers and that the activities involved in this reasoning should be included in laboratory experiences for students. They created a theoretical framework to identify the activities associated with scientific reasoning as compared with inquiry-based science. Chinn and Malhotra (2002) based their framework on the *Benchmarks for Science Literacy* (AAAS, 1993) and the *National Science Education Standards* (NRC, 1991), both of which highlight the complex nature of scientific reasoning. Therefore, Chinn and Malhotra (2002) developed their framework by drawing on a number of fields, including the psychology, sociology, philosophy, and history of science. They then identified seven cognitive processes that are critical to authentic research but are often not as developed in simple inquiry (Table 1). These cognitive processes included the four science practices that Laverty and colleagues (2016) considered laboratory specific, as well as a more detailed explanation of

TABLE 1. Scientific practices identified by the National Research Council Framework and the three-dimensional framework aligned with the cognitive processes in authentic science inquiry and the specific science practices assessed in this systematic review

National Research Council framework	Three-dimensional framework (Laverty *et al.*, 2016)	Cognitive processes in authentic science inquiry (Chinn and Malhotra, 2002)	Specific science practices identified in each CURE in this review
Asking questions		Generating research questions—scientists generate their own questions	Students develop the research question or select a hypothesis.
Developing and using models	Developing and using models		
Planning and carrying out investigations	Planning investigations	Designing studies Making observations	Students design the methodology.
Analyzing and interpreting data	Analyzing and interpreting data	Explaining results	
Using mathematics and computational thinking	Using mathematics and computational thinking		
Constructing explanations	Constructing explanations		
Engaging in argument from evidence	Engaging in argument from evidence	Developing theories	
Obtaining, evaluating, and communicating information	Evaluating information	Coordinating results from multiple studies Studying research reports	Students review the primary literature. Students disseminate the results.

the cognitive processes involved in each. Thus, we combined the theoretical frameworks of Laverty *et al*. (2016) and Chinn and Malhotra (2002) in the current project to identify four specific science practices we assessed in each CURE we reviewed. These were: 1) students select their hypothesis, 2) students design the methodology, 3) students review the primary literature, and 4) students disseminate the results. Each CURE was examined to determine whether it contained these specific science practices as well as whether or not it contained the five primary CURE components listed by Corwin and colleagues (2015a) (science practices, discovery, collaboration, relevance, and iteration).

Goals of the Current Study

One of the primary goals of this project was to create a summary of presently existing STEM CUREs in the published literature. In recent years, there has been a significant increase in the number of CUREs, but no current systematic review of CUREs currently exists. Harris and colleagues (2015) provided a review of CURE models and practices with a focus on the outcomes for CUREs and recommendations for CURE implementation. They analyzed 41 CUREs, found multiple benefits for students, and highlighted aspects of CUREs that led to these benefits (Harris *et al.*, 2015). Their work provides a strong foundation for our work, but we feel that an updated review of CUREs is necessary due to the significant increase in their implementation in recent years. Another review of CUREs was specific to those in biochemistry (Bell *et al.*, 2017) and identified key components of CUREs and CURE implementation with the goal of increasing the number of CUREs in biochemistry courses. In addition to these published reviews, CURE authors can upload their CURE curricula on the CUREnet website (https://serc.carleton.edu/curenet/index.html). However, this site has a smaller number of CUREs and therefore represents a small minority of published CUREs. Although the previously mentioned reviews and CUREnet are strong resources, they are limited to an earlier time frame (Harris *et al.*, 2015), a specific discipline (Bell *et al.*, 2017), a non-STEM discipline (Dvorak *et al.*, 2019), or a smaller number of CUREs (CUREnet). Thus, we felt that there was a need for a systematic review of STEM CUREs to increase awareness of the number of CUREs in the literature and to provide one location where instructors could find potential CUREs for their classrooms.

The second goal of this systematic review of CUREs was to analyze each CURE to determine which primary CURE components and specific science practices were included. The primary CURE components examined were those defined by Corwin and colleagues (2015) in their definition of what constitutes a CURE. The specific science practices examined were chosen based on the theoretical frameworks of Laverty and colleagues (2016) and Chinn and Malhotra (2002) to ensure that we were identifying practices that were laboratory specific and included scientific reasoning. Analyzing each CURE for its inclusion of these components provides a considerable area for continued research to better understand the outcomes that are associated with CUREs. While we are not assessing outcomes in this work, we do want to provide a resource for others to be able to assess outcomes associated with different science practices in CUREs. The framework by Corwin *et al.* (2015) provides the hypothetical relationships between science practices and potential outcomes, and we feel that our resource of published CUREs and their associated components will allow for robust testing of these relationships. The final goal of the current project was to summarize the characteristics of current CUREs in STEM to determine what the next steps should be. In this review, CUREs are categorized by discipline (biology, chemistry, biochemistry, interdisciplinary, other), biology subdiscipline, course level (introductory or advanced), length of CURE, and the inclusion of primary CURE components and specific science practices. This work serves as a means of characterizing the existing CUREs in STEM and identifying areas of need in CURE implementation across STEM disciplines.

METHODS

Identification and Screening

We followed the PRISMA Checklist (Page *et al.*, 2021) and conducted a systematic review of relevant literature to identify articles that described existing CUREs and their implementation in a classroom setting (Figure 2). We began by identifying our inclusion criteria, which were that articles were peer reviewed, published within the years 2000 through 2020, and written in English with full text provided, and that they included a description of an undergraduate CURE curriculum in a STEM field. We also determined our exclusion criteria as follows: dissertations, abstracts, preprints, or websites that were not peer reviewed; curricula explicitly for graduate students or high school students; publications outside the 2000–2020 date range, and publications that were not written in English. Using these criteria, we searched the following databases: Google Scholar, ERIC, EBSCOhost, Web of Science, and Summon. We also searched the website for the journal *CourseSource*, whose articles are peer reviewed but not listed in the databases we searched. In each database, the following search terms were used: 1) "course-based undergraduate research experience", 2) "course based undergraduate research experience", 3) "authentic research experience", 4) "CURE" AND "course-based research experience", 5) "CURE" AND "course based undergraduate research experience", 6) "CURE" AND "authentic research experience", 7) "class-based research", 8) "class based research" AND "CURE", 9) "research-based course", and 10)"discovery-based course".

The authors worked independently to search each database for relevant articles using all search terms. Initial database searches yielded 8050 results. From these results, the authors reviewed each article by title to remove duplicates, leaving us with 7113 articles. Each author then reviewed abstracts to determine whether the articles appeared to meet inclusion criteria. Of the abstracts reviewed, only 415 met the inclusion criteria. The authors then reviewed the full text of each article to determine whether it met inclusion criteria and described a CURE curriculum. For instances in which a CURE was described in multiple articles, the first-published article that described the curriculum was included. This resulted in 132 total articles included in the review. These 132 articles were then sampled through a backward snowball method (Wohlin, 2014), a process by which the literature cited within each article was screened to find any additional articles that met inclusion criteria. After an assessment of the full text of the relevant articles, an additional 89 articles were included in the sample. In total,

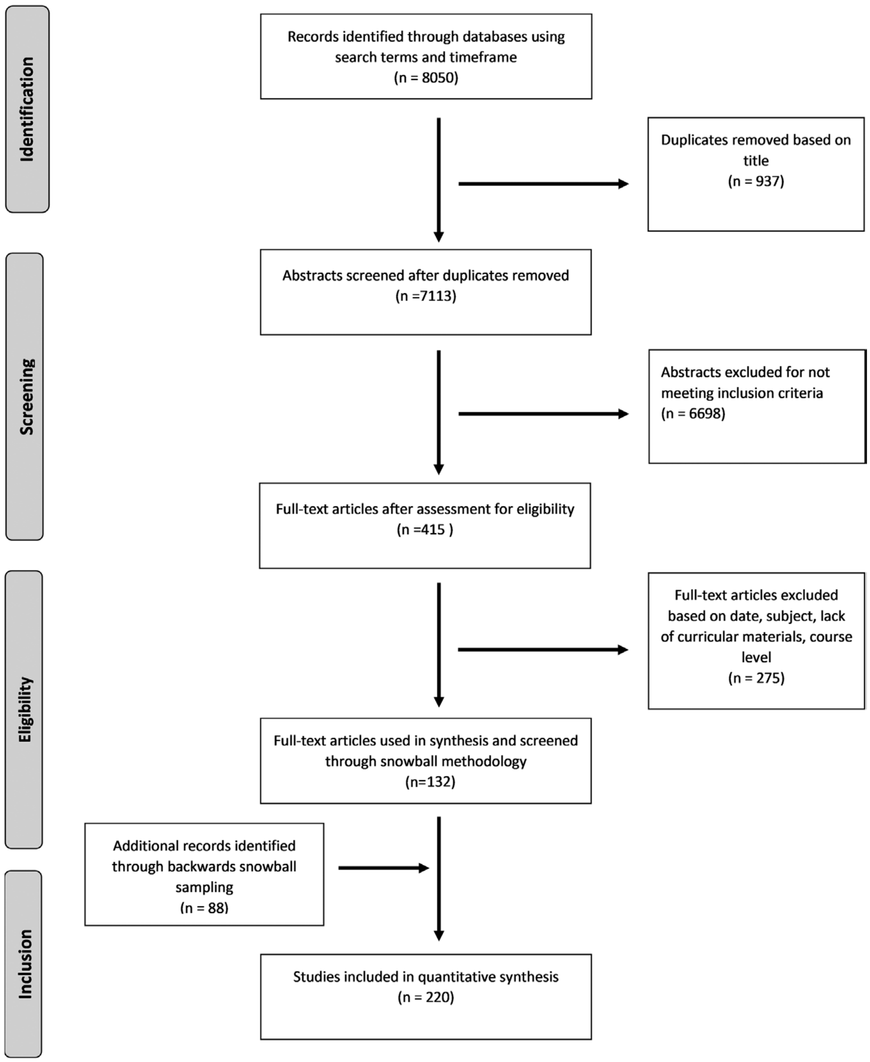

FIGURE 2. CONSORT diagram depicting article screening process.

220 articles analyzed by both authors were included in this review.

It is important to note that some articles included descriptions of more than one CURE; thus, while the total number of articles used in the review was 220, a total of 242 CUREs were described. Within those 242 CUREs, there are some whose authors may not have provided evidence of CURE components such as discovery or iteration. While we feel that these components are necessary in a CURE, these articles were still included in our synthesis, because their authors designated the curriculum as a CURE, and we consider it necessary to provide a comprehensive resource of all published CURE curricula.

Data-Collection Process

All CUREs that met the inclusion criteria were examined independently by both authors to determine which components of the conventional CURE definition (Auchincloss *et al.*, 2014) were included. These primary CURE components include: 1) use of scientific practices, 2) discovery, 3) relevance, 4) collaboration, and 5) iteration. In addition to examining each CURE for the primary CURE components, both authors also determined whether each CURE implemented the specific science practices of interest. These practices are: 1) students select the hypothesis, 2) students design the methodology, 3) students review the primary literature, and 4) students disseminate the results (Table 2). Students were considered to have selected their own hypotheses if they were clearly involved in developing or choosing the hypotheses for their projects. For example, students who were given autonomy to determine which avenue of research they would like to pursue with a model organism or were allowed to identify their own genes of interest were considered to have selected their own hypotheses. Additionally, if students were given options for hypotheses and chose one that appealed to them most, they were considered to have selected their own hypotheses. Students were considered to have developed their own methodologies if they were involved in determining which methods would be used to address their research questions and hypotheses. A CURE was considered to include a review of the primary literature when students were required to use the literature to determine the state of knowledge known about their subjects. Finally, if students shared their results outside the classroom where the CURE was performed, this was identified as dissemination of their research. This included submitting their results to databases such as GenBank, presenting a talk or poster at a research symposium open to the entire campus, publication of their results in a journal, contributing their results to help further another researcher's work, or a community outreach project with results shared with the community. See Table 2 for definitions and examples of CURE components and specific science practices.

In addition to the identification of the activities found in each CURE, we also examined other curricular aspects of the CUREs. These aspects included the length of time it took to complete the CURE, the broad discipline in which the CURE was based, the subject matter of the CURE, and the level of students (freshman, sophomore, etc.) for whom the CURE was intended. The discipline of each CURE was determined based on the department in which the CURE was implemented, and the subdiscipline was determined based on the course in which the CURE was implemented. In cases in which a CURE was offered by two different disciplines, for example chemistry and biology, we considered this CURE to be interdisciplinary. A CURE was designated at the introductory level if it was explicitly designed for freshmen or required no prerequisite, while a CURE offered in a course that explicitly required a prerequisite or that was intended for students at the sophomore level and above was considered advanced.

TABLE 2. CURE components with cited authors' definitions and examples of each component from articles included in this review

Component	Definition	Example	Aspects that met criteria of the definition
General science practices	Students participate in activities, including but not limited to designing studies, evaluating models, analyzing data, communicating findings, and use of scientific techniques and methods.	"Techniques included: RNA isolation, reverse-transcription, polymerase chain reaction" (Periyannan, 2019, p. 3). "Students collect data according to project's scientific goals, but they also analyze data, and in lab reports interpret data, communicate their findings" (Petrie, 2020, p. 2).	Scientific techniques, methods, and tools were used. Collection of data, analysis, interpretation, communication of findings were noted.
Specific science practice: Student-selected hypothesis	Students generate hypotheses and/or are allowed to choose the direction of their research, their gene of choice, etc.	"The students identified questions of interest and created lists of differentially expressed genes for conditions relevant to their questions" (Makarevitch *et al.*, 2015, p. 5). "Each team's project is guided by a hypothesis it develops" (Kean *et al.*, 2019, p. 67).	Students selected the genes for their research. Students developed their hypotheses.
Specific science practice: Student-designed methodology	Students determine how best to answer their questions by creating their own methods or selecting an option from existing methods.	"This involves performing a literature survey, developing a hypothesis and designing experiments to test the hypothesis" (Coticone and Van Houten, 2020, p. 2). "Having chosen one target gene to test, students will then design gene specific primers for qPCR" (Idica *et al.*, 2015, p. 3).	Article explicitly states design of experiments. Students were required to design their own primers.
Specific science practice: Student review of primary literature	Students use literature to determine the state of knowledge surrounding their research topics.	"Write a short summary of an article from the primary literature on animal movement" (Ouifiero, 2018, p. 6). "Students conducted a literature search" (Indorf *et al.*, 2019, p. 5).	Students summarized primary literature. Students consulted the primary literature.
Specific science practice: Student dissemination	Students share results outside the class where the project took place; this may be through a poster, a presentation, a publication, or sharing results with another researcher.	"Students use a Google Form to submit their results to the online database" (Bell *et al.*, 2020, p. 7). "Student groups presented their research findings … at a symposium" (McLaughlin *et al.*, 2018, p. 104).	Results were shared to an online database available to other researchers. Students shared their results at a symposium.
Discovery	New knowledge or insight is obtained from student work.	"Analysis affords students the opportunity to discover novel sequences … of previously undetected microorganisms" (Sanders and Hirsch, 2014, p. 2). "Each student's ultimate goal is to biochemically determine the function of their protein … for which no experimental functional data exist" (Gray *et al.*, 2015, p. 245).	Students discovered novel sequences from undetected microbes. Students determined the function of a protein whose function was yet unknown.
Relevance	Student work has an impact outside the classroom.	"The main goal of this program is to help predict shifts in the patterns of canid species space-use in response to perturbation" (Sorenson *et al.*, 2018, p. 3). "Bean beetles are agricultural pests that occur throughout the tropics and subtropics" (Cotner and Herbert, 2016, p. 233).	Student data would predict real-life species' distributions. Student data would provide information about an agricultural pest and its impacts.
Collaboration	Students work in groups throughout the CURE.	"The group research model in this study attempts to balance group and individual accountability for work" (Kinner and Lord, 2018, p. 51). "Each mutant strain was generated at least in duplicates by groups of three or four students" (Bakshi *et al.*, 2016, p. 452).	Article explicitly stated that groups were formed in this CURE. Article clearly stated that students worked in groups.
Iteration	Students continue to build upon knowledge and reassess when procedures must be modified and/or continue to build upon knowledge from other students.	"Students isolated total RNA … visualized their RNA by agarose gel electrophoresis and determined the RNA concentration by UV spectroscopy" (Griffin *et al.*, 2003, p. 54). "Feedback was provided … so students could identify gaps in their knowledge" (Ochoa *et al.*, 2019, p. 550).	Students used multiple techniques to collect data within the same project. Students were required to make revisions based on feedback.

Certainty Assessment

Both authors independently reviewed all articles to collect all relevant data and then met to align their observations. To determine interrater reliability, Cohen's kappa was calculated to be 0.97 for this process, indicating near-perfect agreement between raters (Cohen, 1960). In any areas of disagreement, the two authors reviewed the CURE article together to determine whether they could come to agreement. In the instances in which agreement could not be reached (fewer than five), an external reviewer who had experience in CURE design and implementation was consulted. Once agreement was reached on all components of each CURE, descriptive statistics were calculated to determine relationships between CURE components and STEM discipline.

Statistical Analysis

CUREs were compared to identify differences in their inclusion of primary components and science practices. We conducted multiple Mann-Whitney *U*-tests (SPSS v. 24) to determine which differences, if any, were significant between discipline, subdiscipline, and course level. The alpha threshold was set to 0.05 to determine significance.

Limitations

While we are able to demonstrate the myriad of CUREs described within the primary literature, we acknowledge that there are potential limitations to our systematic review. We chose to examine CUREs within a specific time frame (within the years 2000 through 2020), and thus CURE curricula published outside this time frame were not included in this review. In addition, the search terms we used may not have been adequate to uncover all in-class research experiences in the literature. This is especially applicable to CUREs across STEM disciplines, as the terminology may differ between disciplines, making it difficult to fully capture the scope of CUREs within the STEM literature. Likewise, the definitions that we established for science practices provide another limitation, as there could be disagreement about the specific definitions of these practices. As a result, CURE authors may feel their curricula incorporate certain science practices, but if a practice did not meet our specific definitions, we listed that practice as absent from a CURE. Similarly, there were instances of ambiguity in the description of science practices in the CURE curricula that were assessed. While all possible effort was made to determine whether the primary components and specific science practices were included in each CURE, it is possible that those activities were included but may not have been specifically mentioned or explicitly defined, and thus were missed in our analysis. We encourage authors to be explicit in the description of their curricula so that the components may be better recognized by those who may want to implement the CURE or examine how the CURE components impact student outcomes.

A further limiting factor is that we are only able to include CUREs whose full curricula have been published. Based on our inclusion criteria, we were unable to include articles that discussed a CURE but did not describe the curriculum used. In addition, we acknowledge that there are likely many CUREs currently being taught that have not been published in the literature and therefore excluded from our sample. Because CUREs are often created by discipline-specific instructors and not education researchers, these instructors may be less likely to publish their curricula, and as a result, this review does not include all CUREs currently being taught. Due to this, we were left with small sample sizes in some disciplines which may affect the conclusions that can be drawn about CURE components, as we have an increased chance of having falsely positive significance. To rectify this limitation, we encourage all instructors who develop a CURE to publish the curriculum so that there is a better understanding of the breadth of CURE curricula.

RESULTS

Overall Summary of Existing CUREs

This systematic review found a total of 242 CUREs in 220 journal articles. All CUREs were assessed for their inclusion of the primary components and specific science practices, as shown in Appendix A in the Supplemental Material. This review spans publications within the years 2000 through 2020, but the term "CURE" was not defined until 2014. Thus, in the earlier literature, we were careful to identify and include research experiences that met the CURE criteria, even though they did not carry that specific name designation. For the purpose of this review, these curricula are included in our analysis of CUREs and have likewise been included in Appendix A. As some CUREs were published in multiple papers, we selected the first published paper that described a curriculum for analysis. Before 2014, 41 CUREs were published, indicating that faculty have been implementing research experiences in their courses for quite some time, even before the term "CURE" was developed. However, between the publication of the CURE definition in 2014 (Auchincloss *et al.*, 2014) and December of 2020, an additional 201 new CUREs were published (Figure 3), for a total of 242 peer-reviewed published CURE curricula described in 220 articles. Thus, the results of our systematic review indicate that research experiences in the classroom setting are not a new phenomenon but have clearly become more common in recent years.

Concomitant with the increase in the number of CUREs over time, there has been an expansion of CUREs into a variety of STEM disciplines. Initially, CUREs were more commonly developed for biology classrooms, but we have seen the development of CUREs across other STEM disciplines in more recent years (Figure 3). While the largest number of CUREs were still in biology, we also saw CUREs developed for chemistry, biochemistry, engineering, public health sciences, and geosciences courses as well as interdisciplinary CUREs that were implemented in courses across different disciplines. However, CUREs outside biology were still relatively rare. Biology CUREs represented 67.8% of all CUREs, while chemistry represented 11.6%, biochemistry represented 7.9%, interdisciplinary CUREs represented 5.4%, and the other STEM fields combined represented 7.4% of the total CUREs analyzed in this review.

CUREs designed for both introductory and advanced courses occurred within each discipline (Figure 4), but more CUREs in the published literature were designed for advanced courses (64.5% of our sample). While there was an increase in the number of introductory-level CUREs across all disciplines (Figure 5), we found that the number of CUREs for advanced students likewise increased. For example, between 2016 and 2020, we saw 66 CUREs at the introductory level and 108 at the advanced level.

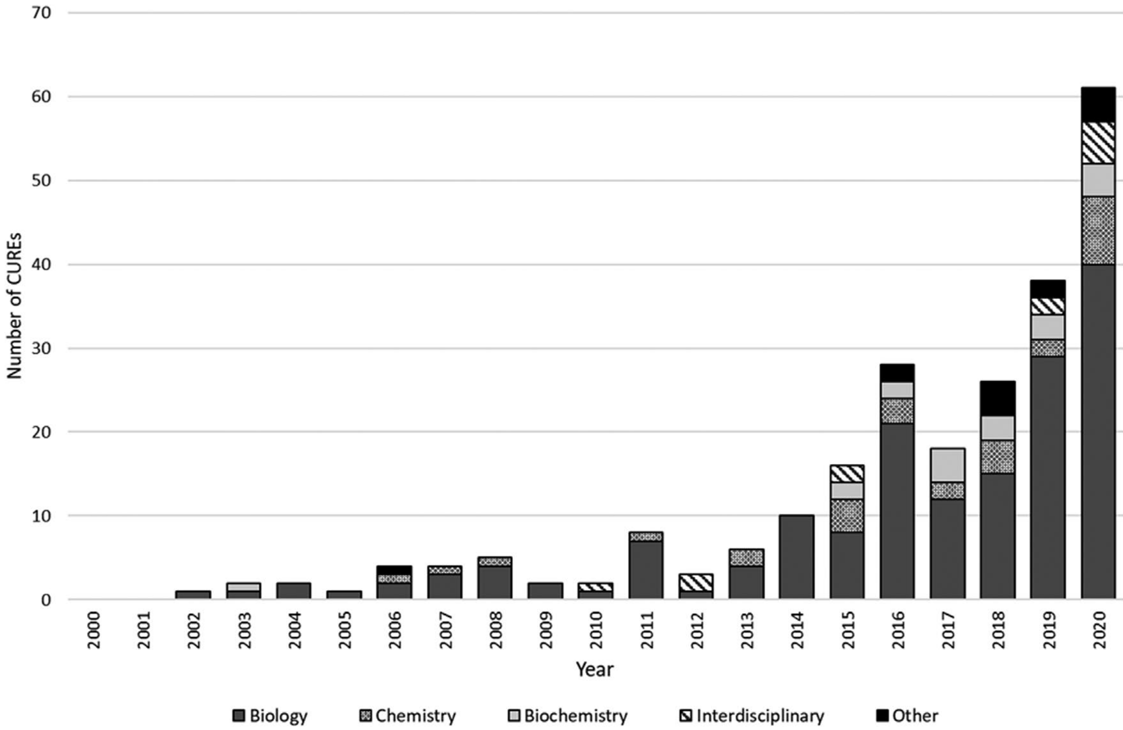

FIGURE 3. Number of CUREs published annually within the years 2000 through 2020 subdivided by STEM discipline.

CURE Components across Course Levels

When we examined CUREs for the presence of the five primary CURE components (use of scientific practices, discovery, relevance, collaboration, and iteration) by the CURE level (introductory or advanced), we did not find significant differences across disciplines (Table 3). All CUREs had a component of relevance, and the majority included discovery (97.7% for introductory and 98.1% for advanced) and collaboration (96.5% for introductory and 96.8% for advanced) and iteration (90.7% for introductory and 96.8% for advanced). When we examined CUREs for inclusion of our four specific science practices (student-designed hypotheses, student-designed methodology, student review of primary literature sources, and dissemination of results outside the classroom), we did find one significant difference between introductory and advanced CUREs. As can be seen in Table 3, advanced CUREs more commonly tasked students with designing or selecting methodology (72.4% in advanced, 59.3% in introductory; $U = 5827$, $p = 0.037$).

CURE Components across STEM Disciplines

When analyzing all of the STEM CUREs for their inclusion of the primary CURE components, we found that most CUREs included all five of these primary components (Table 3). For example, more than 99% of all CUREs had science practices and relevance as part of their curricula. Although iteration was the least common component, it was still present in more than 94% of published CUREs. However, when we examined the specific science practices, we found that they were implemented less commonly than the primary CURE components across all STEM disciplines. Student review of the primary literature was the most common of the specific science practices found across all CUREs, with 84.3% of CUREs incorporating primary literature into the curriculum. Student dissemination of their research outside the classroom was the least common specific science practice, with only 55% of CUREs requiring this component.

Nevertheless, when the CUREs were examined by discipline, subtle differences emerged between their implementation of both primary CURE components and specific science practices. Biology and interdisciplinary CUREs differed significantly in the incorporation of discovery in the curriculum (99.4% for biology, 92.3% for interdisciplinary; $U = 990$, $p = 0.02$). However, the rest of the primary CURE components were incorporated at roughly similar rates across all disciplines. When examining the specific science practices, we found that biochemistry and interdisciplinary CUREs were significantly different in their inclusion of students selecting a hypothesis, with 84.2% of all biochemistry CUREs integrating this design component compared with 46.2% of interdisciplinary CUREs ($U = 76.5$, $p = 0.025$). It is important to note that we found only a small number of CUREs in some of these disciplines, which must be taken into consideration when drawing conclusions.

Biology

When we examined CUREs in biology based on course level (introductory or advanced), we saw that they followed the trend of more CUREs offered at the advanced level. Nevertheless, 39.6% of CUREs in biology were offered at the introductory level (Figure 4), which is still a substantial number of CUREs ($n = 65$), because biology CUREs were the most prevalent. When these CUREs were examined for the components they included, we found that advanced and introductory CUREs in biology showed no significant difference in terms of the primary components or specific science practices used as design elements (Table 4).

FIGURE 4. Distribution of CUREs across STEM disciplines, including the proportion offered at introductory and advanced levels for each discipline.

Subdisciplines of Biology

Because biology CUREs were so common, we were able to divide the biology CUREs into 13 subdisciplines for further analysis and summary (Figure 6). The most common biology subdisciplines were genetics, microbiology, molecular biology, introductory biology, and ecology, with all of these having at least 15 CUREs represented in our sample. As these are the most common subdisciplines represented among biology CUREs, we chose to examine them in more detail. When we assessed the five primary CURE components in these biology CUREs, we found that all five are well represented across each subdiscipline (Table 4). Closer examination reveals that all CUREs in the biology subdisciplines included the use of scientific practices and had students conduct relevant research. However, genetics CUREs differed significantly from CUREs in molecular biology in their inclusion of iterative activities. Genetics CUREs featured iteration 100% of the time, while molecular biology CUREs featured iteration 91.7% of the time (U = 528, p = 0.044). Genetics CUREs and microbiology CUREs also differed in their incorporation of iteration, with 85.7% of microbiology CUREs incorporating this component (U = 552, p = 0.006).

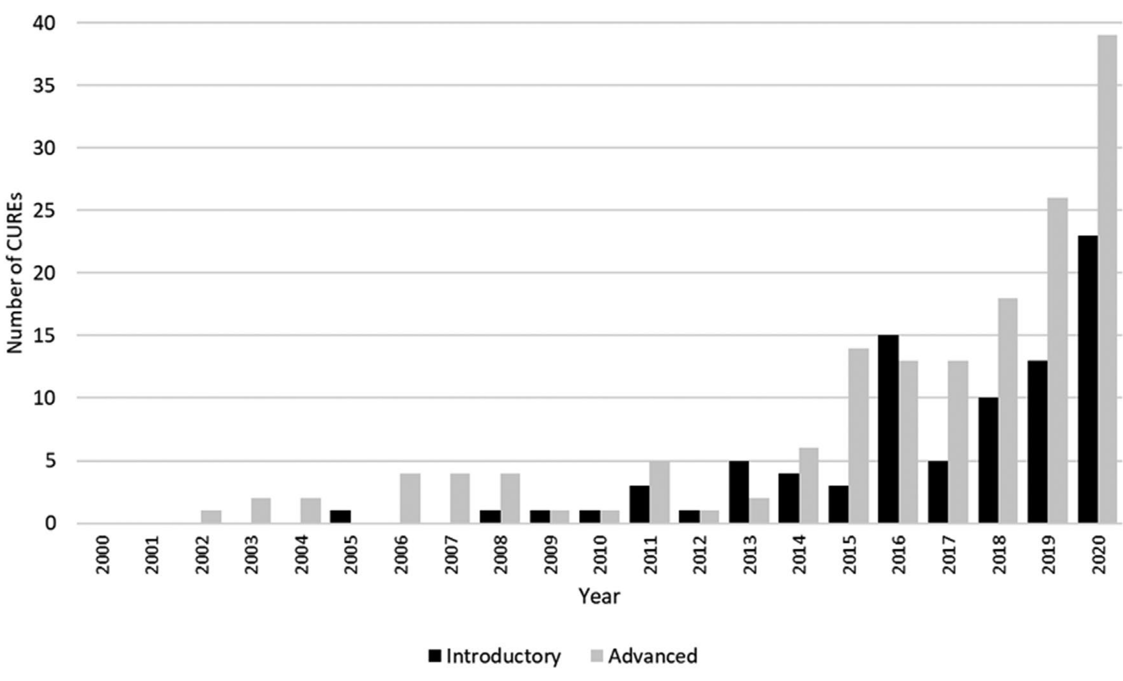

FIGURE 5. Number of CUREs in all disciplines published annually within the years 2000 through 2020, separated into introductory and advanced levels.

TABLE 3. Percentage of all published CUREs that include the five primary CURE components and the specific science practices, grouped by STEM discipline and course level[a]

	All CUREs (242)	Biology (164)	Chemistry (28)	Biochemistry (19)	Interdisc (13)	Other (18)	Introductory level (n = 86)	Advanced level (n = 156)
General science practices	99.6% (241)	100% (164)	96.4% (27)	100% (19)	100% (13)	100% (18)	100% (86)	99.4% (155)
Specific science practice: Student-selected hypothesis	71.1% (172) ab	71.3% (117) ab	75% (21) ab	84.2% (16) a	46.2% (6) b	66.7% (12) ab	73.3% (63)	69.9% (109)
Specific science practice: Student-designed methodology	67.8% (164)	64.6% (106)	78.6% (22)	63.2% (12)	76.9% (10)	77.8% (14)	59.3% (51) a	72.4% (113) b
Specific science practice: Student review of primary literature	84.3% (204)	85.4% (140)	85.7% (24)	89.5% (17)	69.2% (9)	77.8% (14)	79.1% (68)	87.2% (136)
Specific science practice: Student dissemination	55% (133)	57.9% (95)	46.4% (13)	42.1% (8)	69.2% (9)	44.4% (8)	61.6% (53)	51.3% (80)
Discovery	97.9% (237) ab	99.4% (163) a	96.4% (27) ab	94.7% (18) ab	92.3% (12) b	94.4% (17) ab	97.7% (84)	98.1% (153)
Relevance	100% (242)	100% (164)	100% (28)	84.2% (16)	100% (13)	100% (18)	100% (86)	100% (156)
Collaboration	96.7% (234)	97.6% (160)	89.3% (25)	100% (19)	92.3% (12)	100% (18)	96.5% (83)	96.8% (151)
Iteration	94.6% (229)	95.1% (156)	89.3% (25)	100% (19)	92.3% (12)	94.4% (17)	90.7% (78)	96.8% (151)

[a]Percentage is reported first with total number of CUREs in our sample that include the component listed in parentheses. Significant differences between disciplines for each component or science practice are indicated by different letters. Significance was calculated using Mann-Whitney U-tests with significance level set at 0.05.

When we looked for the presence of specific science practices across the biology subdisciplines, we found no significant differences. This may be due to smaller sample sizes in each subdiscipline. We do note that the specific science practices seem less common than the primary CURE components. For example, student design of methodology was only represented in 50% of genetics CUREs, student selection of hypotheses was found in only 45.8% of genetics CUREs, and student dissemination of research was included in only 37.5% of molecular biology CUREs (Table 4).

Chemistry

While there were chemistry CUREs at both the introductory and advanced levels, 64.3% were offered at the advanced level (Figure 4). Chemistry CUREs were similar to CUREs from all of the major disciplines in their inclusion of the primary CURE components (Table 3). When examining the specific science practices, we again found that CUREs in chemistry were similar to those from the other major disciplines. For example, chemistry CUREs incorporated student selection of their own hypotheses and review of primary literature at comparable rates to other CUREs.

Biochemistry

Biochemistry CUREs were still rare, with a total of only 19 representatives (7.9% of our sample), but they have become more common in recent years, with at least one being published every year since 2015 (Figure 3). Biochemistry CUREs were largely designed for advanced classes, with 84.2% of our sample offered at the advanced level (Figure 4). Biochemistry CUREs were similar to all other disciplines in terms of their primary CURE components (Table 3), but for the specific science practices, we did note that biochemistry CUREs featured students generating their own hypotheses significantly more often than interdisciplinary CUREs ($U = 76.5$, $p = 0.03$; Table 3). Biochemistry CUREs incorporated student-selected hypotheses 84.2% of the time, while interdisciplinary CUREs incorporated this practice only 46.2% of the time.

Interdisciplinary

Interdisciplinary CUREs were rare and comprised only 5.4% of our sample. These CUREs bridged a wide range of disciplines, including biology, public health, geosciences, hydrology, mathematics, and physics. For the primary CURE components, all interdisciplinary CUREs in our sample included scientific practices and relevance (Table 3). For the specific science practices, more than half of the interdisciplinary CUREs featured student-designed methodology (76.9%), review of primary literature (69.2%), and dissemination (69.2%; Table 3).

Other Disciplines

CUREs within the category designated as "other" are those CUREs that had few representatives within their respective STEM disciplines. This includes such diverse disciplines as

TABLE 4. Percentage of published CUREs in the biological sciences that include the five primary CURE components and the specific science practices, grouped by subdisciplines of biology and course level[a]

	Genetics (n = 48)	Microbiology (n = 28)	Molecular biology (n = 24)	Introductory biology (n = 18)	Ecology (n = 17)	Introductory level (n = 65)	Advanced level (n = 99)
General science practices	100% (48)	100% (28)	100% (24)	100% (18)	100% (17)	100% (65)	100% (99)
Specific science practice: Student-selected hypothesis	45.8% (22)	67.9% (19)	83.3% (20)	83.3% (15)	82.4% (14)	72.3% (47)	70.7% (70)
Specific science practice: Student-designed methodology	50% (24)	57.1% (16)	75% (18)	77.8% (14)	70.6% (12)	60% (39)	67.7% (67)
Specific science practice: Student review of primary literature	81.3% (39)	78.6% (22)	83.3% (20)	88.9% (16)	88.2% (15)	80% (52)	88.9% (88)
Specific science practice: Student dissemina-tion	60.4% (29)	60.7% (17)	37.5% (9)	55.6% (10)	76.5% (13)	58.5% (38)	57.6% (57)
Discovery	100% (48)	100% (28)	95.8% (23)	100% (18)	100% (48)	98.5% (64)	100% (99)
Relevance	100% (48)	100% (28)	100% (24)	100% (18)	100% (48)	100% (65)	100% (99)
Collaboration	91.67% (44)	100% (28)	100% (24)	100% (18)	91.7% (44)	95.4% (62)	99% (98)
Iteration	100% (48) a	85.7% (24) ab	91.7% (22) b	100% (18) ab	100% (48) a	92.3% (60)	97% (96)

[a]Only those subdisciplines with more than 15 representatives were included in this analysis. Percentage is reported first with total number of CUREs in our sample that include the component listed in parentheses. Significant differences between disciplines for each component are indicated by different letters. There were no significant differences between course level (introductory and advanced) for the any of CURE components. Significance was calculated using Mann-Whitney *U*-tests with significance level set at 0.05.

engineering, food sciences, geosciences, nutrition, and public health (Appendix A in the Supplemental Material). Due to the small number of CUREs in each of these disciplines, we combined them into one category to determine whether there were any specific trends of note. These CUREs followed the same distribution of components as the other disciplines. For the five primary components, we found that these CUREs included science practices, discovery, relevance, collaboration, and iteration more than 94% of the time. Similar to CUREs in other STEM disciplines, the CUREs in these fields featured the specific science practices less often, with dissemination used as an element in only 44.4% and student-selected hypotheses in only 66.7% of these CUREs.

DISCUSSION

This paper provides the most recent and comprehensive systematic review of CUREs in the published literature. One of the most critical components of this review is that we were able to analyze each CURE to determine whether it included the five primary components of CUREs as well as the specific science practices associated with scientific reasoning. We identified 242 individual CUREs in 220 articles across all STEM fields and recorded the discipline, course level, and science practices used in each CURE. We also tracked the number of CUREs over time to determine how CURE implementation has changed in recent years, and we provide a summary of these CUREs (Appendix A in the Supplemental Material).

Current Status of CUREs

The number of CUREs has increased dramatically over the time frame of this review (2000–2020). This increase in the number of CUREs was likely in response to the call for a move away from traditional lab experiences to more active learning in laboratory classrooms (Handelsman *et al.*, 2004). There has been a further call to increase research opportunities for students (Lopatto, 2010), as such opportunities can increase retention in STEM (Ward *et al.*, 2002; Zydney *et al.*, 2002; Seymour *et al.*, 2004; Russell *et al.*, 2007; Laursen *et al.*, 2010). CUREs have been identified as a mechanism to allow larger numbers of students to participate in research experiences (Auchincloss *et al.*, 2014) and increase access to research opportunities for students, especially those from historically minoritized groups (Bangera and Brownell, 2014), so it is not surprising that they have become increasingly common at many institutions.

As we saw this increase in CUREs, we also saw that CUREs were implemented across STEM disciplines, including biology, chemistry, biochemistry, engineering, physics, nutrition, computer science, geosciences, astronomy, and public health and bridging multiple disciplines. Our findings highlight the applicability of CUREs in diverse fields and their inclusion in new

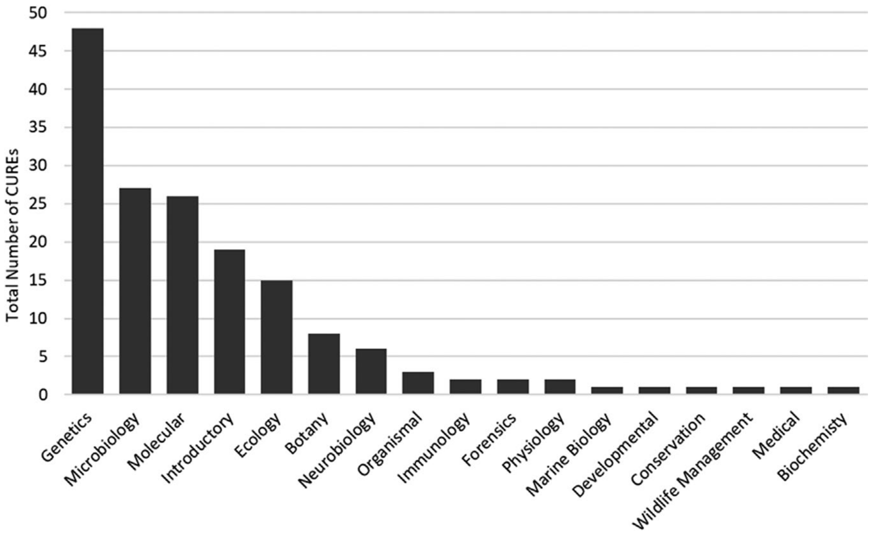

FIGURE 6. Total number of CUREs published within the years 2000 through 2020, grouped by subdiscipline of biology.

areas of study. The larger number of CUREs in the biological sciences is not surprising, as CUREs were first developed for biology courses, and the definition of a CURE was originally published in the biology education literature (Auchincloss *et al.*, 2014). Furthermore, due to the high number of biology majors, there are often more students than available research mentors, thus limiting research opportunities for these students. This has resulted in increased pressure to provide research opportunities in the classroom. Additionally, many health professional schools require students to participate in research during their undergraduate education, making CUREs a more common aspect of biology classrooms. There has also been substantial support for the development of CUREs in the biological sciences. Research Coordination Networks have been funded to continue to develop and apply CUREs in undergraduate classrooms (Dolan, 2016), and there has been an increase the body of literature examining the benefits of CUREs primarily in biology (Brownell *et al.*, 2012, 2015; Alkaher and Dolan, 2014; Shaffer *et al.*, 2014; Hanauer *et al.*, 2016; Olimpo *et al.*, 2016; Rodenbusch *et al.*, 2016; Shanle *et al.*, 2016). Furthermore, more publication options for dissemination of CURE curricula have been added, with the development of the CUREnet repository (https://serc.carleton.edu/curenet/index.html) and the journal *CourseSource*, which focuses on publishing teaching resources for biological science courses.

In addition to the overall increase in the number and diversity of CUREs, there were changes in the course levels at which CUREs were offered. CUREs were initially created for advanced-level courses, and while we continue to see an expansion in the number of these CUREs, we also see an increase in CUREs for introductory-level courses. The initial development of CUREs in advanced-level courses is likely because these courses are smaller in size and have students with a stronger science background, thus making research experiences less challenging to implement. However, development of CUREs in introductory-level courses affords research opportunities to a larger number of students, and it is therefore important to develop CUREs at this level. This increase in the number of CUREs in introductory classrooms provides an excellent opportunity for further implementation of introductory-level CUREs as well as elucidation of outcomes that may be unique to students in these courses.

Inclusion of CURE Components and Specific Science Practices

A goal of our work was to analyze each CURE based on its inclusion of the CURE components defined by Auchincloss and colleagues (2014) as well as our own specific science practices. This allowed us to create a summary (Appendix A in the Supplemental Material) of what was included in each CURE, which allowed for rigorous testing of logic models put forth by Corwin *et al.* (2015). As we reviewed the CUREs in our sample, we saw that all five of the primary components of CUREs were commonly included across all STEM disciplines and biology subdisciplines. This is not surprising, as these components were clearly identified as critical elements to include in a CURE in 2014, and most of the CUREs in our sample were published after that time. If we examine the primary components individually, we do see some interesting patterns in their implementation. Science practices, as defined by Auchincloss and colleagues (2014), include asking questions, building and evaluating models, proposing hypotheses, designing studies, selecting methods, using the tools of science, gathering and analyzing data, identifying meaningful variation, navigating the messiness of real-world data, developing and critiquing interpretations and arguments, and communicating findings. As this definition of science practices is quite broad, it is not surprising that they are very commonly found in CUREs. In fact, 99.6% of all CUREs in our sample included science practices. This is encouraging, because the model proposed by Corwin *et al.* (2015) indicates that student participation in science practices should lead to increases in analytical, communication, and technical skills, which in turn lead to increased self-efficacy and eventual enhancement of science identity, and thus the majority of students in CUREs will have the potential to gain these benefits.

Discovery, or the generation of new knowledge, is another primary CURE component commonly included in STEM CUREs. Discovery requires students to produce novel results or ask novel questions, which makes it a key aspect of research (Spell *et al.*, 2014). The CURE model (Corwin *et al.*, 2015) indicates that discovery in a CURE should lead to increased project ownership, which would then lead to longer-term outcomes, including increasing tolerance for obstacles, self-efficacy, science identity, motivation, and persistence in science. Discovery also adds to student's perception that the research is authentic (Goodwin *et al.*, 2021). When the result of an experiment is unknown, students must interpret their own data to draw inferences about how to proceed and what conclusions may be reached (Auchincloss *et al.*, 2014), which is a critical science practice. Discovery is a key component of research, and it was a design element in the vast majority (97.9%) of CUREs in our sample. However, we did find that interdisciplinary CUREs used discovery as a component less than biology CUREs ($U = 990.5$, $p = 0.02$). We argue that discovery is at the core of the research process and to best highlight the true nature of scientific research, discovery needs to be included as a component in all CUREs.

Another primary component included in the definition of a CURE is broadly relevant work (Auchincloss *et al.*, 2014). Relevance can have many different connotations, but Auchincloss and colleagues (2014) refer to relevance as work that fits into a broader scientific context and therefore has meaning beyond the particular course. For our project, we defined relevance as student work that has an impact outside the classroom (Table 2). Brownell and Kloser (2015) note that relevance is important to show students the value of scientific research, and Linn and colleagues (2015) further state that participation in relevant research experiences helps students make sense of science. Research has indicated that students who understand the relevance of the project to their course work appreciate the opportunity to do real-world research (Kinner and Lord, 2018) and that an understanding of the relevance of their research is something that students can gain from participating in a CURE (Kappler *et al.*, 2017). Although not all authors agree that relevance has a significant impact on student outcomes (Ballen *et al.*, 2018), many argue that relevance should be a key component in CUREs (Auchincloss *et al.*, 2014; Corwin *et al.*, 2015, 2018b; Linn *et al.*, 2015; Cooper *et al.*, 2019; Beardslee, 2021). We found that all CUREs in our sample included relevance, indicating that CURE designers and instructors recognized the significance of this component in a research experience regardless of discipline or course level.

Collaboration is considered another critical component of CUREs, and in the model proposed by Corwin and colleagues (2015), collaboration is linked to short-term outcomes, such as an increased sense of belonging, and long-term outcomes, such as increased tolerance for obstacles, enhanced science identity, and persistence in science. Researchers have noted that students in CUREs report higher levels of collaboration than students in inquiry-based laboratory experiences and that this collaboration positively predicts both cognitive and emotional ownership (Corwin *et al.*, 2018b). In addition, collaboration helps students verbalize their thinking and requires them to practice communicating biological ideas and interpretations to others (Smith *et al.*, 2011; Auchincloss *et al.*, 2014). In general, collaboration is a key component of science reasoning, because scientists construct knowledge in collaborative groups (Chinn and Malhotra, 2002) and lab courses that involve students in collaboration are likely to foster student understanding of the nature and practices of science (Corwin *et al.*, 2018b). Consistent with these findings of the importance of collaboration, we found that collaboration was a common component of the CUREs in our sample, with 96.7% of all CUREs implementing collaboration as part of their curricula. We argue that all CURE instructors and designers in those courses should consider including collaboration in their CUREs.

The final primary component of CUREs is iteration, which Auchincloss and colleagues (2014) note is critical to include in CUREs, because it reflects the process of science, where new knowledge builds on existing knowledge. In fact, students who participate in CUREs that include iteration demonstrate a better understanding of the nature of science (Brownell *et al.*, 2015; Corwin *et al.*, 2018b; Gin *et al.*, 2018) and show an increased tolerance for obstacles (Gin *et al.*, 2018), a valuable and necessary skill in science (Chinn and Malhotra, 2002; Laursen *et al.*, 2010). As students learn to deal with problems in their experiments, they engage more deeply with their projects, which then increases their sense of commitment and ownership of their work (Gin *et al.*, 2018). Although iteration is a key component of the process of science, students often have misconceptions about its importance (Brownell *et al.*, 2014); it is therefore important to include iteration as a design component of a CURE. However, iteration was not included in all CUREs in our sample, although a strong majority (94.6%) did include repetition of work by students. Our work found that students in molecular and microbiology CUREs practiced iteration less often than students in genetics CUREs, which may be due to the complexity of the methods used leaving less time for iteration. As iteration is critical for students to understand the true nature of science, we would recommend that CURE instructors devise strategies for its inclusion. This is especially important for introductory courses, as introductory students have more misconceptions about the importance of iteration compared with advanced students (Brownell *et al.*, 2014).

Inclusion of Specific Science Practices

The first specific science practice that we examined was student selection of the hypothesis, which along with the determination of a research question serves as an essential part of the practice of science (Chinn and Malhotra, 2002; Chin and Chia, 2004). In our sample of CUREs, we found that student-selected hypotheses were employed by 71.1% of all CUREs, which was lower than expected, considering this practice's benefits for students. It is important that students be given the freedom to select a hypothesis or ask a scientific question, as this leads them to derive an increased sense of motivation toward the work they will undertake (Neber and Anton, 2008; Herranen and Aksela, 2019) and causes them to be more engaged with the course material (Herranen and Aksela, 2019). Further, the process of students developing a scientific question supports interpersonal discussion and helps to improve reasoning and knowledge acquisition, as students can explore potential answers to these questions (Chin and Chia, 2004). When we examined CURE components by course level, we found that allowing students to select or develop their own hypotheses was a common practice in introductory courses and slightly less common in advanced courses, although the difference was not statistically significant. We posit that content of CUREs in advanced courses may be aligned with the research interests of the instructor, and therefore the hypotheses are predetermined based on previous work of that instructor.

The second specific science practice examined in this review was student design of methodology for their experiments. We found that this practice was only used in 67.8% of CUREs across all disciplines and was also rare in the subdisciplines. For example, only 50% of CUREs in genetics and 57.1% of CUREs in microbiology incorporated this science practice. When considering science practices across course level, we found that student design of methodology was significantly less common in introductory CUREs, likely because students at this level lacked the scientific knowledge to develop their own methods to answer a research question. However, we feel that this practice is a key component of CUREs, because in any part of science reasoning, researchers must consider how best to go about answering their research questions (Chinn and Malhotra, 2002). Corwin and colleagues (2015) hypothesize that having students design the data-collection methodology will increase project ownership, motivation in science, and tolerance for obstacles, as well as self-efficacy. Other researchers have noted that, because the development of experimental methods often requires creativity and deeper understanding of the course material, students gain self-efficacy and a better understanding of steps involved in the research process (Winkelmann *et al.*, 2014; Kusnadi *et al.*, 2017). In addition, the mere act of designing a study leads to greater gains in ability than simply being told how to design a study (Brownell *et al.*, 2014), and students often take on more responsibility for the outcome of the project (Winkelmann *et al.*, 2014).

Another critical science practice is the review of primary literature by students, which Corwin and colleagues (2015) predict will lead to increased content knowledge along with increases in self-efficacy, motivation, science identity, and eventual persistence in science. An understanding of the literature is important to the process of science, as new knowledge expands upon on existing knowledge (Auchincloss *et al.*, 2014). Science reasoning is based on the social construction of knowledge, which builds on the work of multiple scientists (Chinn and Malhotra, 2002); however, this facet of research is often lacking in simple inquiry. When we examined CUREs by discipline, we found that review of primary of primary literature was widely used as an element in CUREs across all STEM disciplines, biology subdisciplines and all course levels. Although this practice was commonly implemented, we argue that all CUREs should include it, as it will help students to become better acquainted with the process of science. There are multiple ways to incorporate primary literature into the classroom, such as the C.R.E.A.T.E. (Consider, Read, Elucidate hypotheses, Analyze and interpret data, Think of the next Experiment) method (Hoskins *et al*., 2011) and modifications of that method (Beck, 2019), as well as the Figure Facts method (Round and Campbell, 2013), and we encourage CURE authors to investigate these techniques for examples of how review of primary literature may be incorporated into their CUREs.

The final specific science practice examined in this review was student dissemination of their results outside the classroom. Sharing the results of a scientific study is the ultimate goal for scientists, and students who disseminated their research were more motivated to engage with scientific content and to feel confident in their abilities as scientists (Wiley and Stover, 2014). In addition, student dissemination is beneficial to researchers in general, as student results expand the state of knowledge of a subject. However, this was the specific science practice found least often in CUREs, with only 55% of all CUREs requiring students to disseminate their results. We argue that the CURE designers should include student dissemination as an integral part of any CURE.

Next Steps

Based on the results of our systematic review, we have recommendations for the future of CUREs and CURE research. The first recommendation is increased implementation of CUREs in the classroom. We hope that the CURE summary (see Appendix A in the Supplemental Material) generated from this systematic review will provide educators with a resource to consult as they consider adding a CURE to their courses. The information in Appendix A will allow instructors to determine which CUREs already exist in their fields and then select a CURE based on the desired timeline, discipline, and course level. This should decrease some of the common barriers to CURE implementation, such as determining logistics, finding a research topic, and the time investment involved in developing a CURE (Shortlidge *et al.*, 2016). Additionally, the list of CUREs in Appendix A includes whether each CURE includes the primary CURE components and specific science practices, therefore allowing instructors to choose a CURE that better aligns with their course objectives.

We encourage not only increased implementation of CUREs, but also creation new CUREs, especially in those disciplines in which CUREs are uncommon. The majority of published CUREs are designed for classes in the biological sciences, which may be due to the support for the creation and publication of CUREs that exists in this field. We would like to see similar support for CUREs in other disciplines, including increased grant opportunities for CURE development, Research Coordination Networks for CURE designers and instructors, and increased publication opportunities for CURE curricula across all STEM disciplines. In particular, engineering, mathematics, physics, and geosciences are underrepresented among STEM disciplines in CURE implementation and are disciplines where CUREs could be added. However, there is no need to limit CUREs to STEM disciplines. CUREs have already been developed in music education (Dvorak *et al.*, 2019), anthropology (Miller, 2021), and psychology (Perlman and McCann, 2005). We feel that providing more CUREs across the entire undergraduate curriculum will provide the opportunity for students to engage in research, which allows students to develop valuable skills for their future careers.

As more CUREs are created, we encourage instructors to disseminate their CURE curricula. In the span of 20 years, we were able to find 242 total CUREs. It is likely that more exist, but instructors have not published their CURE curricula in peer-reviewed formats. Therefore, we urge CURE authors to publish their curricula in widely accessible journals. We also encourage CURE authors to include detailed curricula with clear description of the science practices their CUREs include. This will allow other instructors to gain a better appreciation of what is incorporated in a CURE to allow them to better assess the CURE for implementation in their own classrooms. In addition, we argue for the development of a comprehensive database for CUREs of all disciplines. CUREnet (https://serc.carleton.edu/curenet/index.html) serves as a database of CUREs primarily in biology, and we encourage CURE authors to consider submitting their CUREs to CUREnet so that other instructors may have access to their curricula.

Our final recommendation is that education researchers use our summary of CUREs to test the components of the models put forth by Auchincloss *et al.* (2014) and Corwin and colleagues (2015) to better understand which outcomes are associated with various CURE components. The short-, medium-, and long-term outcomes hypothesized by Corwin *et al.* (2015) can be examined by finding CUREs that include components of interest, such as collaboration or iteration, and then measuring student outcomes. We feel that our summary of CUREs can be used as a resource for education researchers to compare the impacts of CUREs more broadly, with the caveat that our summary is limited by our specific definitions of science practices. We argue that comparisons of different CUREs that include the same components are vital to the field of CURE research so that general conclusions can be drawn about the impacts of CUREs.

In summary, there is evidence that students who participate in CUREs show an increase in the motivation and self-efficacy and are more likely to persist in their fields of study (Rodenbusch *et al.*, 2016; Hanauer *et al.*, 2017). Furthermore, student content knowledge and analytical skills increase following participation in a CURE (Bascom-Slack *et al.*, 2012; Hanauer *et al.*, 2012; Jordan *et al.*, 2014). Overall, research into the impact of specific CUREs has indicated positive trends, yet we have the opportunity to go deeper in our understanding of which aspects of CUREs lead to these outcomes. We encourage researchers to examine each component of a CURE and assess it for desired outcomes, thus providing information on which CURE components and specific science practices are critical for CURE inclusion to achieve specific student outcomes.

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