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Synthetic biology education and pedagogy: a review of evolving practices in a growing discipline

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Synthetic biology is a growing field with an increasing number of successful applications. Yet, synthetic biology (SynBio) education initiatives are underreported and disconnected from each other. In this review we survey the literature on SynBio education and stratify this body of work into three categories: classroom activities, course designs, and program-level curricula-planning. For each category, we discuss the methods used to assess students' experiences and achievement of learning objectives. Throughout, we identify trends and opportunities for further development in SynBio education. We determined that the design of low-cost education kits is a growing opportunity to support student learning at the level of classroom activities. In support of that work, we present a mapping of published education kits onto Bloom's taxonomy, taking into account increasing accumulation of knowledge through continued experience. We further found that project-based learning is used widely and has proven effective in course designs. To facilitate such activities, we provide a high-level guide for the conversion of a didactic course into a project-based learning course. Further, we note that, currently, programs are delivered primarily at the graduate level, taking inspiration from traditional degree programs while incorporating interdisciplinary training. Finally, we find that design-based research may provide an effective framework for an iterative, mixed-method study design. To support such efforts, we provide a schematic overview of design-based research and its application to a learning progression for interdisciplinary skills. We conclude with a discussion of specific learning concepts that may be useful to SynBio educators and education researchers.

KEYWORDS

synthetic biology, education, pedagogy, curriculum, education kits, project-based learning, design-based research

1 Introduction

Physics and chemistry matured into core scientific disciplines throughout the 18th and 19th centuries. Throughout that process, the knowledge passed from one generation to the next became increasingly sophisticated. Innovations in research and technology were driven by a flow of learners acquiring the knowledge and skills needed to address the problems of the times. Since the mid-20th century, biology has matured dramatically and has spurred the development of new biotechnologies beginning to address major problems of our age: e.g., fossil-fuel dependency, antibiotic-resistant pathogens, unsustainable supply chains, and the pollution of ecosystems. In particular, the adoption of engineering principles into biology has given rise to the promising fields of biomedical engineering and synthetic biology (SynBio). Biomedical engineering education is supported by a wealth of pedagogical studies going back 50 years that seek a better understanding of how to train engineers focused on human health (Peura et al., 1975; Potvin et al., 1981; Blanchard and Hale, 1995; Dee et al., 2002; Harris et al., 2002; Allen et al., 2013; Linsenmeier and Saterbak, 2020). In comparison, education in SynBio has received less attention in the pedagogical literature, despite its success across several frontiers of innovation.

Synthetic biologists rely on the rich history of molecular biology (and related fields) to engineer cells and their components (Agapakis, 2014; Cameron et al., 2014; Meng and Ellis, 2020). In 2014, Agapakis identified three main research streams in SynBio: the synthesis of microbial genomes, the production of commodity chemicals and pharmaceuticals by engineered microbes, and the rational design of genetic logic circuits from modular DNA parts (Agapakis, 2014). Commercial products like plant-based burgers from Impossible Foods Inc., the diabetes drug Januvia®, and the biological nitrogen fertilizer PROVEN® are clear demonstrations of SynBio's utility (Voigt, 2020). These products are the result of inherently interdisciplinary activity. For example, the development of Januvia relied on computational protein design and directed evolution for the engineering of an enzyme that has enantioselective synthesis efficiency beyond what could be achieved by traditional organic synthesis methods (Savile et al., 2010). This new approach to thinking about biology presents challenges to pedagogical norms for training biology students and invites students in other disciplines to translate their seemingly unrelated knowledge (e.g., modelling, machine learning, process engineering, patent law, business) to a biological context. The process of translating biological research to commercial implementation is at the core of many modern SynBio endeavors, shaping SynBio to be inherently interdisciplinary.

Preparing learners for this challenging interdisciplinary environment is difficult. In an earlier study, we surveyed learners participating in Canadian SynBio design teams as part of the iGEM (international Genetically Engineered Machine) competition and identified gaps in the Canadian SynBio training pipeline, most notably the lack of collaborative and interdisciplinary training (Diep et al., 2021). Those findings parallel the conclusion of Agapakis (2014): "[…] collaborations offer engineers the opportunity to imagine new possibilities for how their work might be embedded into the human scale of everyday technology. Through design experiments and speculative prototyping, synthetic biologists can open up new directions for research, new questions, and new hypotheses, bridging the biological, the technological, and the social to communicate and question the potential benefits and risks of a new technology" (Agapakis, 2014). Learners in SynBio must not only master technical material (i.e., establish disciplinary grounding), but must also learn to identify problem areas in which their work would be most impactful and learn to effectively engage with experts grounded in other disciplines.

Interdisciplinary research and teaching is expanding across the globe, accompanied by a growing literature on the effectiveness of interdisciplinary teaching practices and program curricula (Jacob, 2015; You, 2017). Traditional engineering programs (e.g., chemical, mechanical, industrial) have recognized the demand to prepare their graduates to be productive members of interdisciplinary teams. This recognition has led to a growing number of studies and reviews describing effective pedagogical strategies (Jacob, 2015; Van den Beemt et al., 2020). Although SynBio educators can often translate these findings to the biological context, there is a paucity of literature specifically dedicated to education research and pedagogy for the interdisciplinary field of SynBio.

In this review, we survey and synthesize the current literature on SynBio education and stratify this body of work into three categories: (i) classroom activities, (ii) courses, and (iii) programs. This review is organized as follows. After a brief description of our methodology (Section 2), and a high-level description of summary statistics and the distribution of the body of literature we found (Section 3), we describe classroom activities and trends (Section 3.1), and their corresponding education research studies (Section 3.1.1). Next, we describe course designs and trends therein (Section 3.2), stratified by differing course lengths (Sections 3.2.1–3.2.4) and perspective pieces (Section 3.2.5 and 3.2.6), with a discussion of the corresponding education research studies (Section 3.2.7). Afterwards we describe program-level curriculum planning (Section 3.3), factors influencing programs (Section 3.3.1), and the corresponding education research studies (Section 3.3.2). We then proceed to describe learning concepts that may interface with SynBio education (Section 4), before concluding (Section 5).

2 Methods

To identify studies reporting on SynBio education we conducted a preliminary literature search through Google Scholar, PubMed and Web of Science using the search terms: *synthetic biology education*, *synthetic biology pedagogy*, *synthetic biology curriculum development*, and *synthetic biology training program*. This search was restricted to studies written in English, and published no later than July 2023. From this first set of publications, we then performed a vertical search on Web of Science by analyzing their bibliographies to identify additional relevant studies. We also performed a horizontal search with Web of Science search tools to find publications that had citation lists similar to the previously identified references. We included an additional three publications (Beason-Abmayr and Wilson, 2018; Johnson et al., 2022; Smith et al., 2022) suggested to us during the anonymous review process. Publications that did not report on at least one of the above categories were excluded, resulting in a finalized list of publications to be surveyed. We thus did not survey programs that were not reported on in a publication, systematic inclusion of which would have been challenging given the variability in publicly available information on education strategies.

3 Results and discussion

We surveyed 57 publications on the topic of SynBio education; summary statistics are shown in Figure 1. Most of these publications focused on the effectiveness of classroom activities for teaching specific SynBio concepts or on the effectiveness of course-specific curricula at helping students achieve learning objectives (Figure 1A, Classroom and Course, combined 68%). The majority (53%) were written by authors in the USA; the United Kingdom was the next most significant contributor (19%). This result may reflect the limitation of our search methodology to publications written in English, and that the USA and the UK have directed federal funding towards SynBio research over the past two decades (U.S. Trends in Synthetic Biology Research Funding, 2015; Kitney, 2021). With respect to student educational stage, most publications were focused on undergraduate students (60%), followed by high school students (20%) (Figure 1C). This distribution may reflect three factors: (1) that the main demographic of education research is high school and undergraduate students; (2) the difficulty of teaching SynBio before high school; and (3) that the increasing popularity of SynBio at the undergraduate and high school educational stages is driven by the international Genetically Engineered Machine (iGEM) competition's primary student demographic (high school and undergraduate students). Finally, according to our survey, the publication record began in 2009 (with a single publication found in 2003), consistent with the fact that the first SynBio research projects were carried out in the early 2000s, laying a foundation for undergraduate and graduate training (Figure 1D). Additionally, the increased rate of publication over time, particularly through the 2010s, may correlate with the growth in iGEM participation during these years (Jainarayanan et al., 2021), as well as with the steady increase in investments made in SynBio-based companies driving demand for practitioners with the relevant expertise (U.S. Trends in Synthetic Biology Research Funding, 2015; Kuiken, 2022).

Below, we separately analyze the surveyed publications after stratifying them into three categories: (i) classroom activities (Section 3.1), (ii) courses (Section 3.2), (iii) programs (Section 3.3). Within each section, we first summarize the literature and compare different

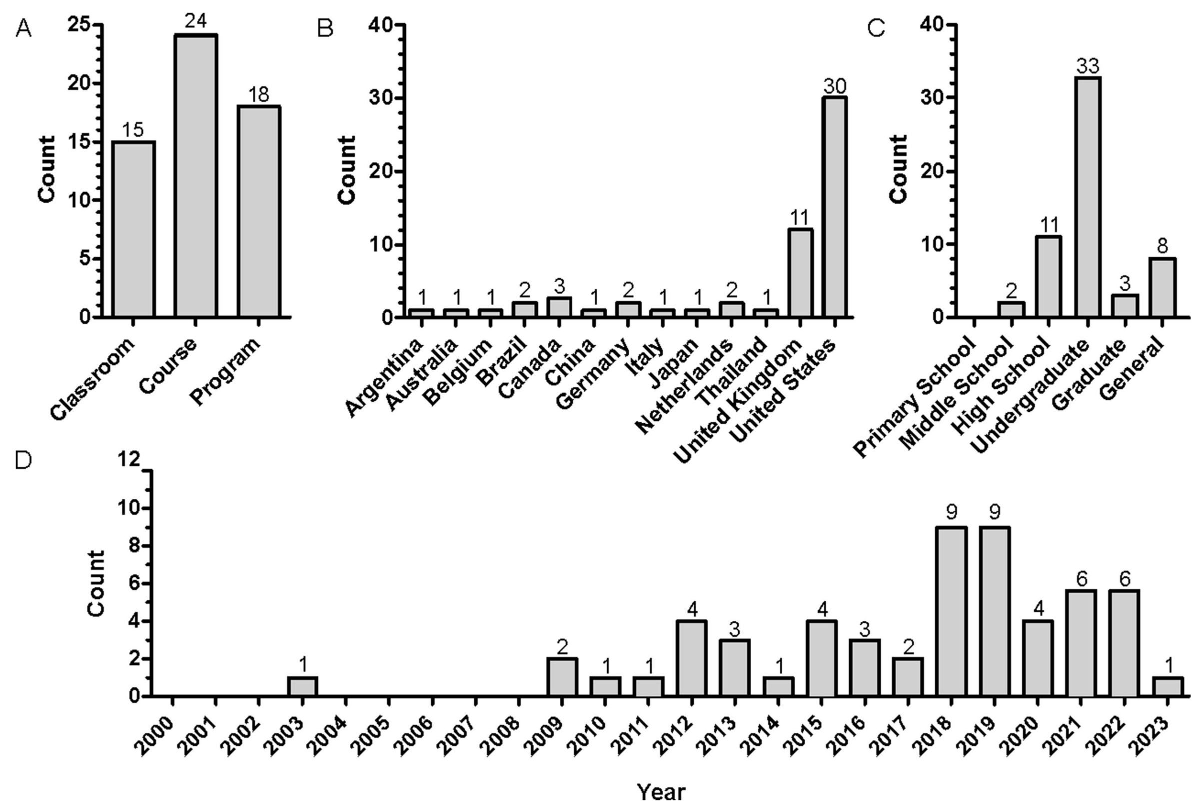


FIGURE 1
SynBio education papers reviewed. **(A)** Distribution by level: of classroom activities, courses, and programs. **(B)** National origin of publications. **(C)** Target student audience. **(D)** Distribution over time.

approaches educators have taken to achieve particular learning objectives (for classroom activities) or broader learning goals (for courses and programs). We then highlight the overall trends in each category and sketch the current landscape of SynBio education initiatives. To explore where the landscape may grow within each category, we discuss the publications that report research results and methodology (Table 1).

3.1 Classroom activities

We surveyed 15 publications in this category. These describe educational tools and interventions that could be deployed in a short timeframe (hours-to-days) to help students achieve modest learning objectives, such as understanding a specific concept or knowing how to perform a simplified molecular cloning protocol (Table 2). Most activities involved the use of affordable kits and devices that can bring molecular biology into the classroom without the need for expensive laboratory equipment. About half of these kits (7 of 15) provide cell-free, lyophilized ("just add water") reagents for introductory experiments (Huang et al., 2018; Stark et al., 2018, 2019; Collias et al., 2019; Huang, 2019; Williams et al., 2020; Rybnicky et al., 2022). Here, "cell-free" refers to cell-free synthetic biology, through which researchers use *ex vivo* preparations (i.e., outside of the cellular context) to recapitulate biological reactions typically performed in cells. To implement cell-free biomolecular activities, researchers have developed mixtures containing cellular lysate (i.e., the "innards" of cells), and added specific key components such as ribosomes, DNA, and enzymatic substrates depending on what kind of biological reactions is intended. These kits enable the experimental study of a range of biological phenomena: from protein expression and biosensing to applications of the genome editing tool called CRISPR-Cas9. Several of the described activities can be completed in just a few hours, allowing students to visually analyze their results the following day. The activities have lower chances of error because the components are prepared ahead of time in the correct quantities. Consequently, educators can confidently integrate this type of activity into a biology unit with minimal cost and preparation.

The design of these kits (including room-temperature storage) allows them to be relatively inexpensive and easy-to-use. However, more advanced audiences, who might benefit from exposure to experimental failure modes and the creative troubleshooting required to correct issues (Collias et al., 2019), may find their scope limited. For example, the application of CRISPR for genome editing requires troubleshooting when the Cas enzyme and guide RNA are suboptimal (Xu and Li, 2020). Additionally, these kits may offer limited modularity. Compared to the flexibility provided by electronic or chemistry hobby sets, these SynBio kits provide fewer opportunities for exploring behaviour beyond the specific procedures described by the manufacturer; users may be able to experiment with varying input concentrations of reagents (Huang et al., 2018), but investigating different promoters, RBSs, or CRISPR systems would require a completely different set of materials.

Of course, these limitations are only relevant to more advanced audiences; most of these kits are designed for junior audiences, or those less acquainted with molecular biology. In contrast, senior

TABLE 1 Summary of research-based studies ($N = 17$).

Study	Survey	Interview	Pre-/post-survey	Observation/ethnography	Content analysis	Skills assessment
Classroom interventions (*n* = 7)						
Betten et al. (2018)		X		X	X	
Campbell et al. (2014)			X			
Campbell and Eckdahl (2018)			X			
Kafai et al. (2017)		X				
Kuldell and Mitchell (2015)	X	X			X	
Walker (2021)		X		X	X	
Williams et al. (2020)			X			
Course (*n* = 5)						
Beach and Alvarez (2015)			X			X
Gill et al. (2022)						X
Johnson et al. (2022)	X					
Subsoontorn et al. (2018)	X			X		
Wolyniak et al. (2010)			X			
Program (*n* = 5)						
Dawson and Schibeci (2003)	X		X			
Diep et al. (2021)	X	X				
Dubé et al. (2017)	X					
Frow and Calvert (2013)				X		
Walker (2021)	X					

TABLE 2 Study characteristics of classroom intervention studies ($n = 15$).

Study	Target audience	Summary of intervention	Key findings
Betten et al. (2018)	Undergraduate	Students tasked with writing future scenarios imagining what the world might look like if their SynBio prototype was mass produced, including a moral vignette of the public's reactions.	Authors cite an increase in students' ability to anticipate barriers to product implementation, promotion of inclusion of non-expert audiences, reflexivity and moral awareness to others' concerns, and ability to change and improve their research product.
Campbell et al. (2014)	Undergraduate	pClone is an at-the-bench educational laboratory module for students to explore wet-lab techniques, focused on transcription and gene regulation.	Students working with pClone showed significant learning gains compared to a control group
Campbell and Eckdahl (2018)	Undergraduate	rClone Red, an RBS mutational analysis tool relying on golden-gate assembly, is cheap and easy-to-use by students.	Students in a genetics class had significant learning gains after a lab-based investigation into different strengths of RBSs using rClone Red.
Collias et al. (2019)	Undergraduate	A computational and two experimental (cell-free transcription-translation) modules to advance understanding of CRISPR-Cas9 genome editing technologies with minimal equipment and lab experience requirements.	The modules support CRISPR technology education by providing a quick and easy-to-use cell-free experimentation system.
Dy et al. (2019)	General	Compilation of six playlists of SynBio YouTube resources: SynBio overview, SynBio concepts, teaching or public lectures, research lectures, lab protocols, iGEM videos.	Playlists can complement classroom lectures and serve as a starting point for activities and projects.
Huang et al. (2018)	Secondary school, undergraduate	Freeze-dried cell-free "just add water" reactions for demos of fluorescence, enzyme-generated fragrances, and hydrogels; modular biosensing components to control gene expression are included.	Easy-to-implement hands-on biology demonstrations for STEM education
Huang (2019)	Secondary school	Expanded BioBits explorer kit with modules for ligation reactions, a SynBio breadboard, diagnostics, and CRISPR.	Kits are easy to set up and easy to use, enabling students to be involved in experiments.
Kafai et al. (2017)	Secondary school	Wetlab starter kit for transforming *E. coli* to produce a logo in a petri dish; contains an incubator, a spectrophotometer, capsules for cell distribution, and a media input / output outlet.	Participants experienced biology as a maker science.
Magaraci et al. (2016)	Undergraduate	Toolbox enabling students to explore modular tuning of genetic circuits, with robust performance at room temperature and automated time-lapse imaging.	A toolbox that can help students experiment with gene regulation and genetic circuits.
Porter et al. (2018)	Undergraduate	Introduces students to synthetic biology through a biosensor; describes a multi-course program that is essentially a curriculum-based intervention.	Highlights the importance of well-designed analytical tools in reinforcing learning methods for students who benefit from exposure to real-world applications.
Rybnicky et al. (2022)	Secondary school	Freeze-dried CRISPR-Cas12 *Wolbachia* DNA sensor to make diagnostic testing accessible and available to students.	A cell-free sensor that can support students in experimenting with applications of biology.
Stark et al. (2018)	Secondary school	Toolkit consisting of a 96-well plate with freeze-dried CFPS vectors containing fluorescence proteins, a mini-incubator to express the proteins, and an inexpensive spectrometer.	A room-temperature stable toolkit that is easy-to-use; experiment can be completed over a two-day period.
Stark et al. (2019)	Secondary school	Freeze dried, cell-free reactions kit. Activities to teach antibiotic resistance mechanisms and CRISPR-Cas9 gene editing, linking concepts to fluorescent readouts; results achieved in a one-hour class period, can be analyzed the next day.	Students reported significantly higher confidence in their understanding of the mechanisms of antibiotic resistance and CRISPR-Cas9 genome editing, and an increased self-identification as engineers.
Walker (2021)	Secondary school	Studio activity with three phases: assembly, where students modified yeast with a pre-designed kit of reagents and genetic material for vitamin A production; construction, wherein students created a food-grade silicon cake mold; imagination, wherein students were asked to speculate a SynBio-based food product that could be used in a health setting.	Activities resulted in high student participation, with students having ideas to improve their product or protocol and investing more time in imagining solutions.
Williams et al. (2020)	Undergraduate	Cell-free protein synthesis kit for transcription and translation, complete with reagents, laboratory manual, student worksheet, and augmented reality activity.	Students were more comfortable working with enzymes and with their laboratory skills after using the kit.

RBS, Ribosome Binding Site; SynBio, Synthetic Biology; iGEM, International Genetically Engineered Machine; STEM, Science, Technology, Engineering and Math; CFPS, Cell-Free Protein Synthesis.

undergraduate students would benefit more from laboratory exercises that simulate real-world practice. There appears to be significant untapped potential to use these cell-free systems in conjunction with other low-cost simplified components (e.g., gel electrophoresis set-ups, low-cost plate readers, Arduino-controlled elution columns) to increase the sophistication of the learning objectives associated with these kits (Gamale et al., 2021; Bergua et al., 2022; Diep et al., 2022; Thompson, 2022). Additionally, educators could incorporate digital media tutorials that have more advanced protocols and learning objectives to complement the prescribed kit activities. A repository of YouTube resources on SynBio concepts has been compiled (Dy et al., 2019) that could serve as inspiration for such tutorials, or be used *as is* for more advanced kits, such as those involving painting logos with pigment-transformed *E. coli* (Kafai et al., 2017), implementation of CRISPR-Cas12 for diagnostic sensing (Rybnicky et al., 2022), or tuning of genetic circuits in organisms (Magaraci et al., 2016).

3.1.1 Education research studies of classroom-based activities

Using pre-/post-test assessments, Campbell et al. found evidence that their pClone and rClone activity kits were able to significantly, and with large effect, improve students' knowledge of the relevant material (Campbell et al., 2014; Campbell and Eckdahl, 2018). Also, through a pre-/post-test assessment and a control group, (Williams et al., 2020) found that their Genetic Code Kit benefited students' learning about transcription and translation. They tested on an undergraduate audience, who may have been exposed to these concepts already. In contrast, the kit may provide a larger benefit to a secondary school audience, for whom transcription and translation might be unfamiliar. While quantitative methodologies such as pre-/post-tests can provide evidence for the effectiveness of an activity, they offer limited insight on *how* the students are learning, or *why* the activity is effective. Interviews and observational methodologies can reveal more detailed information (Cohen et al., 2017). For example, in other studies of SynBio classroom activities, students highlighted their sense of agency during project activities, and that activities contextualized their knowledge in real practice; these insights can help educators prioritize new activities that are effective for their students (Kafai et al., 2017; Betten et al., 2018; Walker and Kafai, 2021). For example, in Betten et al.'s (2018) scenario-based activity, interviews revealed that students found the writing process central to their learning.

Ideally, quantitative methods such as pre-/post-tests are paired with qualitative methods such as student interviews. Figure 2 provides a schematic for classifying cell-free expression kits for classroom activities, organized according to audience expectations and complexity of tasks. Ideally, such kits and equipment would be accompanied by "educational spec sheets," supported by empirical evidence reported in open access publications. These spec sheets could detail the kit's performance at helping students of different educational stages achieve specific learning objectives. In this manner, a Registry of SynBio Educational Kits could enable educators to easily find characterized SynBio education activities intended for specific audiences.

3.2 Course design

The 24 publications we reviewed in this category address the delivery of courses that require multiple classroom activities and education exercises to achieve their learning objectives (Table 3). The overarching trend we identified was widespread use of project-based learning (PBL), frequently integrated with activities associated with the iGEM competition. In PBL students work in groups or individually towards an "end product" such as a project proposal or iGEM competition deliverables. PBL has been found to significantly improve students' academic achievement (compared to teacher-led instruction), to foster participant motivation, to promote strong conceptual understanding, and to facilitate the development of collaboration and goal-setting skills (Kokotsaki et al., 2016; Chen and Yang, 2019; Virtue and Hinnant-Crawford, 2019). In Figure 3 we present a schematic overview of the process of converting a lecture-based course to a project-based learning course, including an overview of stakeholders that may offer useful perspectives for designing the projects. Our discussion of these publications, below, is organized by the length and nature of the courses: week-long, semester-long, year-long, and online. Additionally, we consider perspective pieces that comment both on how the iGEM competition can play an important role in shaping future practitioners in SynBio and on other dimensions of SynBio course design.

3.2.1 Week-long courses

The week-long courses described in the surveyed publications were summer camps for secondary school students with lecture-style presentations and group projects with mentors. Hendricks et al. (2015) developed a five-day summer camp for high school students, with a focus on bioengineering for global health. They introduced the participants to SynBio, to molecular biology, and to point-of-care diagnostics devices. They invited them to identify a pressing need in global health and then challenged them to design and present a bioengineering solution. The authors found that the camp provided statistically significant improvements in participants' knowledge of bioengineering. Subsoontorn et al. (2018) developed a five day "hackathon" for high school students that focused on biodigital, SynBio, and biomimicry topics. Each topic was supported by introductory lectures and activities, and ended with an open challenge. In small groups, participants proposed a biotechnology project, considered social implications, and discussed competing or traditional technologies. These works demonstrate how short project-based courses can provide valuable exposure to both the experimental and human practices dimensions of Synbio.

3.2.2 Semester-long courses

Cooper et al. (2012) reported on the *Build-a-Genome* course (Dymond, 2009) where students learned lab techniques such as PCR, cloning, and sequencing. The course also covered concepts central to SynBio, such as gene synthesis, recombinant DNA technologies, and genetic circuits. Situated learning (Cobb and Bowers, 1999) was deployed by treating the undergraduate students in this course as if they were graduate students or entry-level employees on an R&D team. The participants were provided initial training (eight guided sessions in a "molecular biology boot camp"), briefed on a course project (synthetic yeast genome), and then allowed to work relatively independently while providing updates at regular lab meetings. Students were also encouraged to develop their own "side-projects"; one such side-project was developed into a project for the first John Hopkins iGEM team.

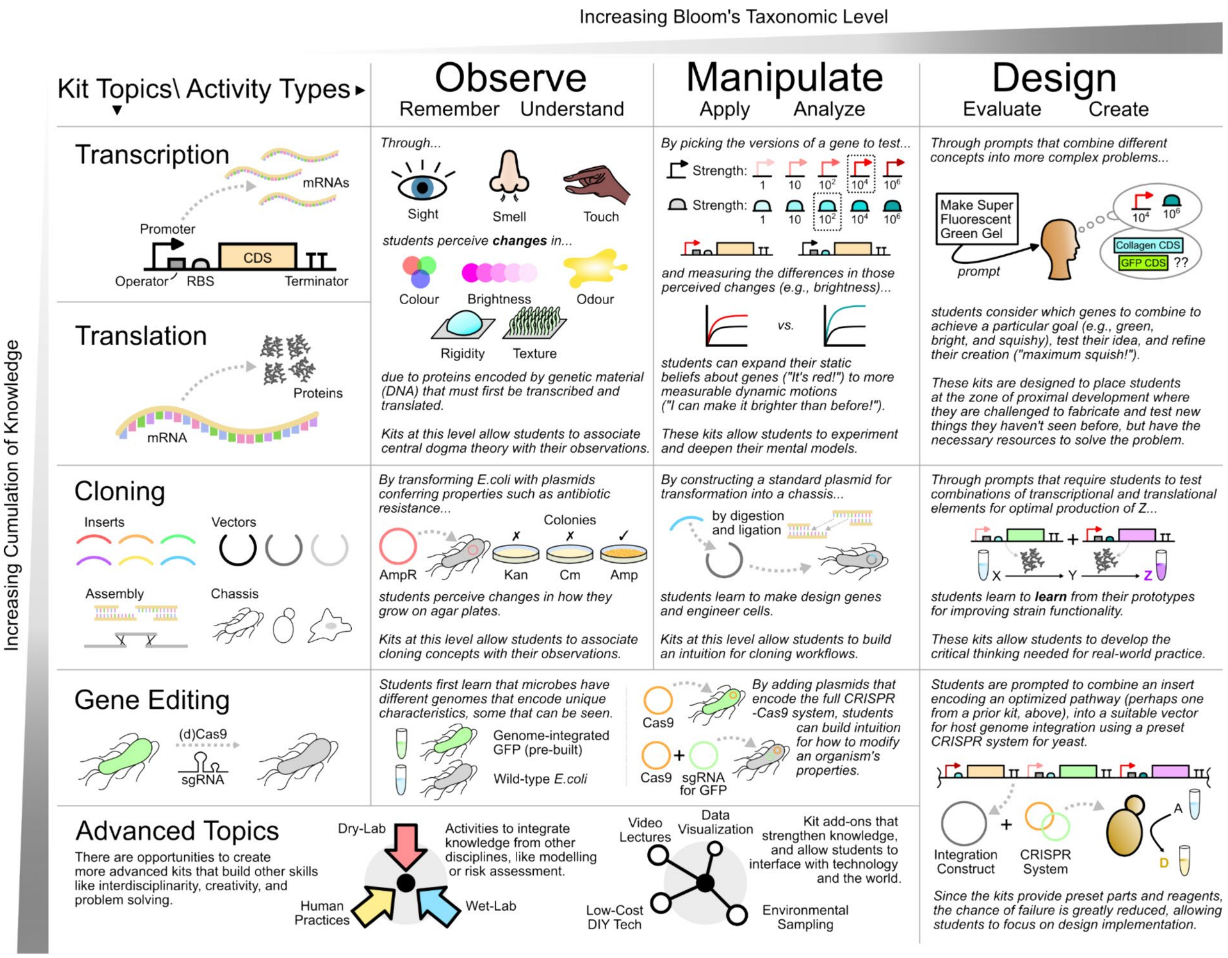


FIGURE 2
Overview of potential cell-free and cloning education (classroom activity) kits. Kit topics are listed in the far-left column in increasing cumulation of molecular biology knowledge. The activity types correspond to Bloom's taxonomic learning levels: Observe, where students recall theoretical knowledge and gain a deeper understanding of that knowledge by perceiving changes in some property (i.e., colour of solution) or outcome (e.g., colonies on a plate); Manipulate, where students can make choices about how to change the property or outcome and measure the extent of these changes; and Design, where students learn to make judgements about genetic parts and how to put them together to achieve a more complex property or outcome, thus empowering them with the agency required to practice in the SynBio space. The literature used to synthesize this figure is described in Section 3.1.

At some institutions, iGEM participation has been integrated into for-credit courses. Such PBL courses were seen as early as 2008 with MIT's *Introduction to Biological Engineering.* This PBL course, designed for first-year undergraduates, began with interactive lectures and moved into projects: students designed a biological solution to a problem of their choice (Kuldell and Mitchell, 2015). This approach has expanded to other schools. For example, Schmitt et al. (2021) developed an iGEM-based course focused on large student-led projects: with teams of nearly 20 members, students worked to establish sub-groups and write project proposals. Students also attended traditional lectures about pertinent topics in SynBio and xenobiology. For the remainder of the course, students were tasked with choosing their project, self-delegating experimental work and other tasks, preparing a presentation and online wiki page, then participating in the iGEM jamboree.

iGEM involvement, and large-scale research projects, are not the only ways to bring immersive SynBio education into a course. Smith et al. (2022) exemplify bringing interdisciplinary SynBio methods into a course in their PBL course. Students must both mathematically model, and experimentally construct a CRISPR-based toggle switch throughout the course, and provide a written report on their analyses and experiments. Johnson et al. (2022) report on a SynBio Course-based Undergraduate Research Experience (CURE) that effectively generates a SynBio learning environment through discussion of previous iGEM projects, and design and construction of a biosensor in small groups. Over 15 weeks, students work in groups to present on a number of previous iGEM team projects, familiarize themselves with the Registry of Standard Biological Parts, then work on biosensor projects. For their projects, teams must propose a design, build it using parts from the registry, characterize it, then deposit their work back into the registry for wider usage. This is similar to Beach and Alvarez's (2015) lab course where students are expected to explore and present on previous iGEM team projects, become familiar with the Registry, design a biosensor, then build one (albeit a different one from their design). These two courses exemplify ways of creating SynBio educational environments with individual and smaller group projects, rather than an iGEM team or a large-scale research project.

TABLE 3 Study characteristics of included course-based studies ($n = 24$).

Study	Target audience	Summary of intervention	Key findings
Adames et al. (2019)	Undergraduate	5-day law enforcement program incorporating lab work, site visits, and lectures to help students learn procedures such as PCR, Gibson assembly, gel analysis, and spectrophotometry.	In a student body consisting of 25+ year-olds, a more intimate approach to teaching was well received by the participants.
Anderson et al. (2019)	Undergraduate	Implementation of a massively online open course (MOOC) that combined underused platforms such as YouTube and online forums.	Integration of forums and open discussion platforms increased student retention and engagement, but despite the certification incentive, most students did not complete the course.
Balmer and Bulpin (2013)	Graduate	Investigated the effects of competition-driven learning and how it should be used to motivate student innovation. Draws on the Human Practices aspect of the iGEM competition.	Highlights the increasing inefficiencies of traditional life sciences programs in preparing undergraduate students for complex interdisciplinary fields of study such as SynBio.
Beach and Alvarez (2015)	Undergraduate	Constructs developed for a reporter gene and hybrid promoter using the iGEM Registry. Collaborative-only program that focused on team efforts to develop a novel sensory device.	By the end of the course, 90% of students were able to correctly attribute function to genetic elements and the construction of functional gene models.
Blount and Ellis (2018)	Undergraduate	A week-long course where practical experiments and their theoretical foundations were taught by experts in the field; included tutorials on relevant software.	Demonstrated the significance of emphasizing the practical application of the material; many students positively reinforced their own learning when they felt that the material being taught was of real-world significance.
Castro de Jesus and Cabral (2022)	Undergraduate	After surveying SynBio articles, students were asked to critically assess and consolidate the findings. Students tasked with breaking down the topics and designing a SynBio product.	Extremely effective method for raising overall critical thinking skills and abilities of participants.
Cooper et al. (2012)	Undergraduate	Fully synthesizing a 750 bp product through theoretical teaching and hands-on experiences. The focus was on showing the students how each step in a procedure works, as opposed to simply teaching them the relevant theory.	A lab course like this requires significant structure and guidance to operate well. This program allows students to achieve a sense of ownership of their success.
Gill et al. (2022)	Undergraduate	iGEM-inspired, student-centered, project-based learning program that matches student teams to challenges posed by faculty members, industry partners, or NGOs. The program has five phases: team-building, design, research, review, and completion.	Students reported improvements in leadership skills and personal development compared to traditional work-integrated learning.
Gervásio et al. (2022)	Undergraduate	14-week course with three modules: (1) leveling, where introductory molecular biology is taught; (2) introductory, where topics closely related to SynBio are introduced; (3) discussion, where 'deep dives' are done in groups, and iGEM projects can be proposed.	Group reading courses may be effective distance-learning courses, and iGEM team-building exercises.
Hendricks et al. (2015)	High school	Single-week program providing design challenges to groups of students to help them develop their critical thinking skills.	Program bolster the desire of the high school participants to attend college; interest in STEM careers also increased greatly.
Johnson et al. (2022)	Undergraduate	Semester-long SynBio CURE where in small teams students must design and build a small synthetic device to be expressed in *E. coli*, using parts from the iGEM Registry of Standard Biological Parts.	Using the LCAS and PITS survey frameworks, the authors found that students experienced collaboration on average between weekly and monthly, and that the CURE may reflect scientific practice more than traditional labs.
Kuldell and Mitchell (2015)	Undergraduate	Design a biotechnology that responds to a real-world need with hands-on activities, role-playing public opinion, and student-led design.	First-year students reported better understanding of the content in other courses, improved ability to read scientific articles and think critically about biology.
Lee et al. (2020)	Undergraduate	Synthetic biology and materials science course spanning 15 months. Introductory content covered for each discipline, then teams tasked with optimizing the production of a biomaterial with high tensile strength.	Pedagogical data not reported; the course was useful for obtaining more funding for other SynBio-related projects.

(Continued)

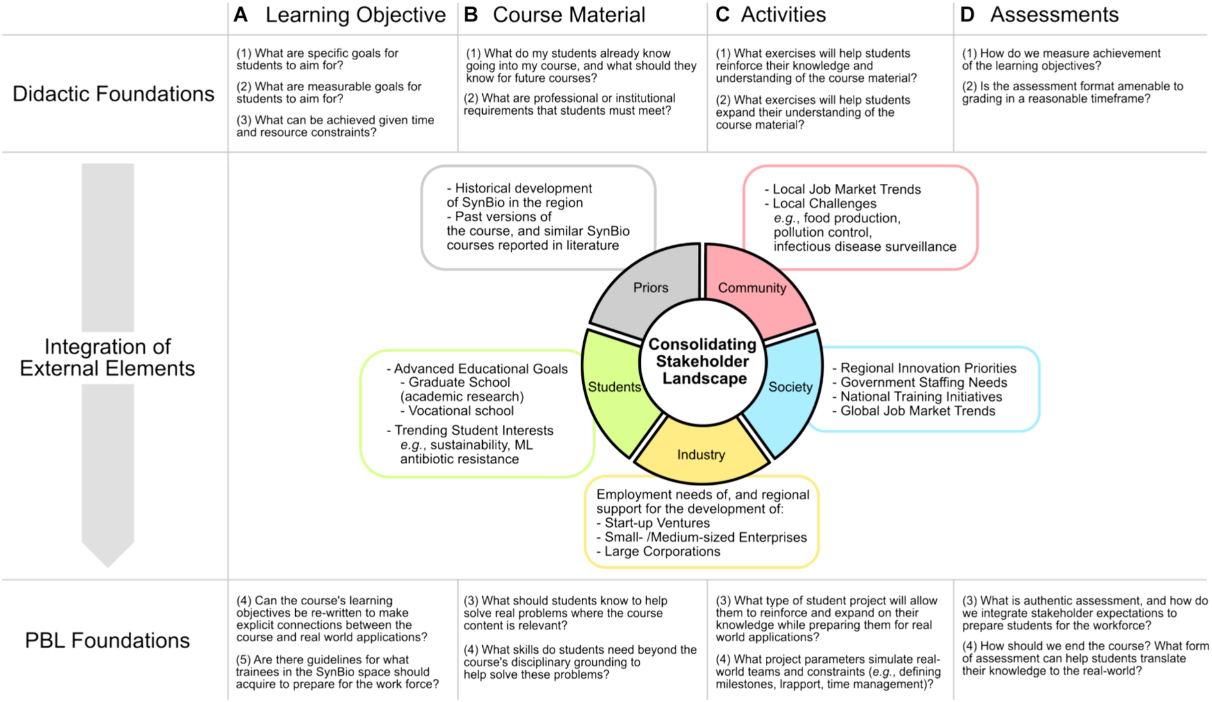
TABLE 3 (Continued)

Study	Target audience	Summary of intervention	Key findings
Mitchell et al. (2011)	Undergraduate	Program focused on developing a comprehensive survey to assess student experiences before and after the iGEM competition.	Most participants agreed that the iGEM competition helped them achieve learning outcomes through collaborative and independent work.
Muth et al. (2021)	General	A MOOC focused on Youtube playlists that cover the basics of SynBio focused training; makes use of social media, wet-lab simulations, and virtual labs as a future avenue for more digitally enhanced learning.	Addresses the increasing need for digital tools for the development of online and offline courses; instructors must be collaborative to improve the learning process.
Perry et al. (2022)	Undergraduate	Project-based distance learning course: each week included a synchronous lecture that is recorded, a design exercise, and remote experiments designed by students and executed either by: (1) robots (Opentrons), (2) cloud simulations, (3) a livestream of a TA, (4) the student in their home.	Students developed project prototypes remotely, with lab experiments done using community networks (e.g. institutions or makerspaces with automation equipment), through livestream, or through modular kits sent to learners.
Schmitt et al. (2021)	Undergraduate	Utilized an "evalsys" questionnaire to identify areas where a new course can be improved.	Describes an effective teaching method that uses many of the principles seen in iGEM related projects to better teach SynBio.
Smith et al. (2022)	Undergraduate	Interdisciplinary project-based learning course centered around modelling and constructing a CRISPR-based toggle switch.	Students reported they were satisfied with the course, and that the difficulty was "just right" –important given the interdisciplinary nature of the course.
Song and Wang (2021)	High school	Sequential mixed-methods study, with interviews, used to develop a metric for knowledge specifically related to SynBio	Highlights the importance of early-stage learning interventions. SynBio was better received by students who were introduced to some of the interdisciplinary philosophy behind SynBio earlier in their academic careers.
Steel et al. (2019)	Undergraduate	1-year long molecular techniques course with an independent student project and iGEM participation; summary of each of the 80 lectures, including assignments/ deadlines.	The course was popular, enrollment was expected to increase; the course successfully attracted students from a range of academic disciplines.
Subsoontorn et al. (2018)	High school	Week-long course focused on a modular teaching approach using digital teaching methods and tools.	Digital-based teaching methods and tools were effective at enhancing the engagement and understanding of SynBio material to students.
Thamamongood et al. (2013)	Undergraduate	Detailed explanation of the iGEM process directed at people new to iGEM.	Networking, self-monitored labs, and social impact evaluation assist student development and increase their overall comprehension of the SynBio material required to participate in the competition.
Verseux et al. (2016)	General	Focused on how to retain and gain attention, while improving the overall attitude towards SynBio	Conceptions of SynBio drive social and political outcomes of SynBio work; the acceptance of a SynBio technology is dependent on its end-use; interdisciplinary education may enable biologists to better communicate their work to non-experts.
Wolyniak et al. (2010)	Undergraduate	Through a diagnostic survey, instructors assessed student responses and share those findings with other instructors to build an improved pedagogical framework.	Found that thought experiments are sufficient to increase skill development in their students. Many students responded well to learning after an engineering goal was provided.

PCR, Polymerase Chain Reaction; iGEM, International Genetically Engineered Machine; SynBio, Synthetic Biology.

3.2.3 Year-long courses

The year-long courses we identified in our survey closely followed the iGEM competition cycle. Steel et al. (2019) described how, through 80 lectures spread over a year, they scaffolded the learning and project lifecycle of a US Air Force Academy iGEM team into a course (in which enrollment was a requirement for participating in their iGEM team). Lee et al. (2020) described an analogous course focused on the engineering of an organism to produce paper-like sheets of nanocellulose. Compared to Steel, Bates and Barnhart's course, offered to undergraduate-level air force cadets, the course described by Lee, Lux and DeCoste. was delivered to a cohort of professionals from materials science and biology, 82% of whom had more than 5 years of work experience, and 96% of whom had either a master's or PhD degree. Gill et al. (2022) used the iGEM cycle as a template for their work-integrated learning program alternative, where student teams worked on industry or community-partner defined research projects. These three courses serve as exemplars for creating courses with long-term learning goals and for up-skilling individuals with deeper expertise in related, specialized areas.



	A Learning Objective	B Course Material	C Activities	D Assessments
Didactic Foundations	(1) What are specific goals for students to aim for? (2) What are measurable goals for students to aim for? (3) What can be achieved given time and resource constraints?	(1) What do my students already know going into my course, and what should they know for future courses? (2) What are professional or institutional requirements that students must meet?	(1) What exercises will help students reinforce their knowledge and understanding of the course material? (2) What exercises will help students expand their understanding of the course material?	(1) How do we measure achievement of the learning objectives? (2) Is the assessment format amenable to grading in a reasonable timeframe?
PBL Foundations	(4) Can the course's learning objectives be re-written to make explicit connections between the course and real world applications? (5) Are there guidelines for what trainees in the SynBio space should acquire to prepare for the work force?	(3) What should students know to help solve real problems where the course content is relevant? (4) What skills do students need beyond the course's disciplinary grounding to help solve these problems?	(3) What type of student project will allow them to reinforce and expand on their knowledge while preparing them for real world applications? (4) What project parameters simulate real-world teams and constraints (*e.g.*, defining milestones, lrapport, time management)?	(3) What is authentic assessment, and how do we integrate stakeholder expectations to prepare students for the workforce? (4) How should we end the course? What form of assessment can help students translate their knowledge to the real-world?

FIGURE 3
Converting a didactic course to a project-based learning course in the context of SynBio. A course is divided into four parts: Learning Objective, Course Material, Activities, and Assessments. Aspects that the instructor will consider for designing a lecture-focused course (top row) can be informed by engagement with relevant stakeholders (middle row), resulting in questions to be considered when creating a Project-based Learning (PBL) course.

3.2.4 Online courses

As highlighted by the COVID-19 pandemic, sometimes in-person project-based courses are not feasible or desirable. We surveyed several examples of online SynBio courses. Anderson et al. (2019) published their Massive Open Online Course (MOOC) "Principles of Synthetic Biology" on the platform edX. This course focused on modeling and simulations, genetic circuits, and a project requiring students to design and model a system (Anderson et al., 2019). Castro de Jesus and Cabral (2022) reported an online PBL course where students worked in groups to design a genetic circuit to address an instructor-provided SynBio challenge. These projects involved students performing literature reviews, justifying their proposed circuit designs and their choices of chassis organism, plasmids, promoters, and cloning strategies. Elsewhere, BioSin was designed to be a course-like organization (akin to a study group or support group) for introducing SynBio to a wider audience: during the first 4 weeks, the group covered introductory molecular biology through peer-to-peer lectures; this was followed by 5 weeks of SynBio-specific topics such as genetic circuits and bioinformatic tools, where small groups broke off to study a topic, then presented to the whole group; and ended with another 5 weeks of discussions and individual student-led topic presentations (Gervásio et al., 2022). These three courses demonstrate an avenue for effectively teaching SynBio online without laboratory access. Perry et al. (2022) demonstrate a project-based distance learning course where automated equipment, or a teaching assistant livestreaming themselves, perform experiments students design; the authors suggest a vision for expanding SynBio education access through the use of interconnected community hubs students may access remotely, akin to a cloud computing network. To assist with the development and design of online SynBio courses, Muth et al. (2021) published a toolbox of digital resources and reviewed their strengths and weaknesses, while Sheets et al. (2023) published a module covering the basics of SynBio. These sources demonstrate that there are many ways to teach (or learn) SynBio concepts before stepping into the lab. We note that synergies between cell-free and cloning kits (as discussed above in Section 3.1) and online courses have not been described in the educational research literature: a clear path for further development.

3.2.5 iGEM-specific perspective pieces

In addition to course designs inspired by the iGEM competition, we found four reports that discussed the pedagogical value of the iGEM experience itself, which can be translated to SynBio course design. Mitchell et al. (2011) performed an extensive survey of all iGEM participants in 2007 and 2008, restricting their analysis to undergraduates. They found that participation in the iGEM competition enabled students to develop lab-related skills and essential research skills such as identifying relevant questions, integrating new data with old data, performing critical literature searches, and communicating scientific ideas. Complementing these findings from a different perspective, Thamamongood et al. (2013) described the experiences of two iGEM teams: the Tokyo Tech and HKUST undergraduate teams. They reported that the competition helped participants develop skills in proposing and managing projects, interdisciplinary teamwork, and leadership. Paralleling these findings, Kelwick et al. (2015) described how the iGEM competition enabled students to develop research skills, communication skills, and project management skills. In addition to technical, research, and soft skills, the overall iGEM experience has been discussed in the context of incentivizing collaboration and human practices for improved product design (Balmer and Bulpin, 2013). These reports give a taste of the impact that iGEM has on new SynBio practitioners, helping them develop technical and interpersonal skills, as well as practical skills in engineering product design.

3.2.6 Other relevant perspective pieces

Beyond these iGEM-specific reports, we surveyed two perspective pieces that focused on interdisciplinarity and misconceptions around SynBio. Using a sequential mixed-methods study design, Song and Wang (2021) found three interrelated factors contributing to interdisciplinary competence at the middle school level: disciplinary grounding, attitudes towards interdisciplinary approaches, and opportunities for interdisciplinary learning. These findings suggest that course design may be enhanced by choosing to emphasize these factors. In complementary work, Verseux et al. (2016) studied how public misconceptions of SynBio may affect interdisciplinary collaboration during a summer school course. They noted that biologists, like many STEM experts, are rarely trained in communicating to non-experts, and that context is important to non-biologist's reaction to a biotechnology. For example, the use of GMOs in agriculture was met with concerns, whereas GMOs used in manufacturing of medications or materials were seen much more positively.

3.2.7 Education research studies of SynBio courses

While the publications described in this section all report detailed course curricula, only some groups investigated the effectiveness of the course design in helping students achieve specified learning objectives. Subsoontorn et al. (2018) surveyed students participating in a week-long event called "Hack BioDesign." The authors remarked that students were able to learn concepts well enough to "discuss with their teams and staff about the redesigning of novel organisms" (Subsoontorn et al., 2018). During Beach and Alvarez's (2015) PBL lab course, students were challenged to develop a biosensor using parts from the iGEM Registry and by leveraging previous iGEM team's projects (Beach and Alvarez, 2015); the authors used a pre-/post-survey to assess whether students were meeting learning objectives (Table 4) through their PBL course, and further supported their study methodology by using students' weekly progress reports. They found their course significantly improved students' skills relative to five learning objectives. Moreover, comparing to a control consisting of responses from students who had not participated in their course, but had equivalent backgrounds to their participants, they found evidence that their course fostered a greater appreciation for interdisciplinary contributions, enabled students to imagine more application areas for SynBio, and that a majority of students preferred the project-based format over a traditional lecture format. Highlighting the utility of collecting qualitative feedback, a noteworthy response from a participant unhappy with the project-based format, was that they "got lost when the lab went on for too long" (Beach and Alvarez, 2015); responses such as this provide the course designer with clear options for refinement: e.g. reduce the lab length, or scaffold the lab activity more. Kuldell and Mitchell (2015) also surveyed and interviewed the students in their course. They found that the course helped students better understand content in their other courses, helped them gain skills in reading scientific literature, and helped them work better in groups. Through interviews, they found that central to students' learning were (i) having mentors providing feedback and occasional guidance, and (ii) the presence of a supportive environment in which mistakes and misconceptions could be addressed constructively (Kuldell and Mitchell, 2015). With extensive surveying and skills assessments, Gill et al. (2022) found evidence that their iGEM-inspired course improved students' leadership and collaboration skills, among others.

TABLE 4 Condensed learning objectives from those publications listed in Table 1.

Study	Condensed learning objectives
	Students will be able to...
Campbell et al. (2014); Beach and Alvarez (2015)	Apply standard molecular biology techniques to assemble BioBrick parts into devices and systems.
Beach and Alvarez (2015)	Analyze and evaluate data to draw conclusions about experimental results.
Beach and Alvarez (2015)	Design a functional synthetic device using BioBricks.
Beach and Alvarez (2015)	Use a SynBio device design to predict its function.
Beach and Alvarez (2015)	Define synthetic biology and its application to address biological problems.
Campbell and Eckdahl (2018)	Define standardization of parts and assembly in SynBio.
Campbell et al. (2014); Campbell and Eckdahl (2018)	Explain how Golden Gate Assembly works.
Campbell et al. (2014); Campbell and Eckdahl (2018)	Distinguish type II and type IIs restriction enzymes.
Campbell and Eckdahl (2018)	Interpret data from a reporter assay.
Campbell and Eckdahl (2018)	Design oligonucleotides for dsDNA.
Campbell and Eckdahl (2018)	Anneal oligonucleotides to build RBS.
Campbell and Eckdahl (2018)	Describe mutagenesis as an approach to understanding function.
Campbell and Eckdahl (2018)	Identify consensus sequences used in molecular biology.
Campbell and Eckdahl (2018)	Describe the role that ribosome binding sequences play in regulating gene expression.
Campbell and Eckdahl (2018); Williams et al. (2020)	Identify elements of translation and where it stops and starts.
Campbell and Eckdahl (2018)	Distinguish base pairing in RNA and DNA.
Campbell and Eckdahl (2018)	Recognize levels of abstraction in SynBio (DNA, parts, devices, systems).

These listed learning objectives are modified to combine overlapping or related learning objectives worded differently in different publications. The unmodified list of learning objectives is also available (Supplementary material). Campbell et al. (2014) is focused on transcription, and enabling students to investigate different promoters, while Campbell and Eckdahl (2018) is focused on translation, and enabling students to explore different RBSs. Williams et al. (2020) is focused on more basic ideas of transcription and translation, using a cell-free expression activity. Beach and Alvarez (2015) is a lab course focused on designing and building a biosensor using parts from the iGEM Registry. SynBio Synthetic Biology; dsDNA double-stranded DNA; RBS Ribosome Binding Site.

Together, these publications demonstrate how quantitative and qualitative methods can be combined to produce a holistic picture of students' learning experiences. SynBio education researchers can build on these foundations to investigate more dynamic factors such as the importance of assessing the improvement in effectiveness achieved through, e.g., clearer lecture slides, more realistic projects, or changes in assessment types. An important consideration for such studies is the Hawthorne effect, whereby students' awareness that they are being assessed in a research context causes them to perform better, thereby undermining assessment of whether improvement in learning can be specifically attributed to the intervention being studied (Cook, 1962). An iterative approach, as presented in Figure 4, may be appropriate; by using the first iteration of the course as a baseline, subsequent improvements (or lack thereof), can better reflect the real effects of interventions (see Section 4.2 for additional discussion).

It is important to consider the perspective of instructors throughout and after a course. Indeed, a 2010 teaching workshop consisting of faculty members from 15 different undergraduate institutions (Wolyniak et al., 2010) reported preliminary evidence that instructors may not have the tools or resources to effectively teach SynBio project courses to undergraduates. In a complementary report, Frow and Calvert (2013) published an ethnography of their 6 years as supervisors of the iGEM team at the University of Edinburgh. They provide a nuanced discussion of the issues that arise when students negotiate time constraints and the conflicting objectives of engineering and biological sciences. For example, the standardization of parts in mechanical engineering allows complex systems to be produced with relatively predictable behavior; in contrast, genetic parts and cellular chassis present an element of unpredictability. They found that students often did not discuss standardization in their day-to-day operations, despite iGEM's focus on standardization in submission of characterized BioBricks. Instead, students often focused on the science behind molecular cloning in attempts to finish constructs rather than the engineering of biological systems toward a specified function. Investigations of instructor experience and perspectives on SynBio education can reveal gaps in resources or challenges in integrating domain expertise. These can highlight opportunities for future work and provide a high-level perspective on the student's experience.

Another avenue for exploration is how a course's effectiveness depends on the demographics of the students. We did not find data on student demographics, prior education, or other identity factors in the SynBio education research space; these can be important considerations, especially for online courses intended to be accessible to a wider audience. Additionally, there are few published descriptions of PBL courses where the student audience comprises a "heterogeneous cohort," meaning the students are enrolled in distinct programs and so might otherwise not interact with one other in an academic setting. Such environments pose unique challenges: the students must demonstrate interdisciplinary skills as well as mastering technical knowledge to complete assignments and projects together. These challenges closely reflect real-world SynBio work environments (Tripp and Shortlidge, 2019; Diep et al., 2021).

3.3 Program-level curriculum planning

We surveyed 18 publications in this category related to the design and delivery of SynBio education programs – multiple courses, offered over extended periods of time, for a broad range of students (Table 5). Hall and Howe (2012) described how SynBio interfaces with a traditional chemical engineering undergraduate program. By drawing inspiration from published descriptions of SynBio courses (RAE, 2009; Cooper et al., 2012; Kuldell and Mitchell, 2015), they described three approaches to incorporation of SynBio: (1) integration of concepts into existing courses, (2) mixed teaching through courses offered from different departments, and (3) dedicated courses that explicitly cover SynBio with a high degree of research-led activity. After noting the merits of each approach, and the potential limitations imposed by an institution's circumstances, they highlight the advantages of an integrated-mixed approach—where students are exposed to SynBio concepts throughout their program's courses, but in which students with a keen interest could enroll in a mixed program with deeper immersion through more advanced upper-year courses. In a complementary report, Crowe (2009) discussed the disciplinary differences between biomedical engineering, systems biology, and SynBio, using these differences to highlight how SynBio could enable

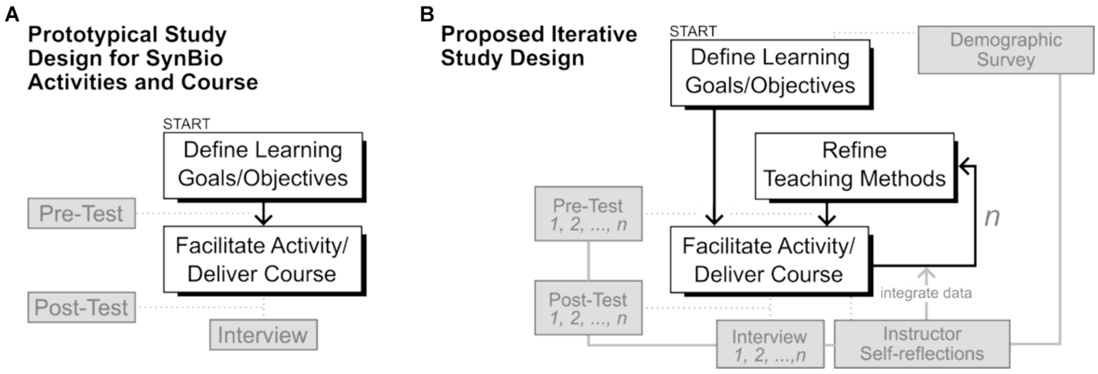


FIGURE 4
Study design for SynBio education research. **(A)** Prototypical study design to assess the effectiveness of SynBio activities and courses. A pre-/post-test (i.e., survey) is completed, after which interviews are performed. **(B)** Integration of an iterative "Refine Teaching Methods" step in which research data collected from one iteration informs the next, for a set number of cycles. Demographic survey data can also be collected prior to the study to assess the generality of the findings. The instructors' self-reflections are systematically incorporated.

TABLE 5 **Study characteristics of program-level studies (*n* = 18).**

Study	Target audience	Summary of intervention	Key findings
Cazimoglu et al. (2019)	Graduate	A 4-yr doctoral training program, outlines what students learn each week in the first two semesters, the rationale for how this material enables students to work on rotation projects; describes how student feedback influenced curriculum development.	Found that students formed connections between disciplines, demonstrated by knowledge of how to find information beyond their core discipline
Crowe (2009)	Undergraduate	Discussed the inter-relatedness of biomedical engineering, systems biology, and synthetic biology; introduction of synthetic biology in training of biomedical engineers is briefly described.	Suggests that the most viable approach to train biomedical engineers in SynBio is via masters' courses funded by both government and industry.
Dawson and Schibeci (2003)	Secondary school	Large survey (>900 students) to study the attitudes of Australian high school students towards biotechnology applications.	Found that students held many perspectives on biotechnology (e.g., engineering of bacteria/yeast vs. humans and embryo modifications). Concluded that biotech needs to be explicitly taught and suggests further instructor supports are required.
Delebecque and Philp (2019)	General	Focuses on industrial biotechnology (and the inherent requirements for workers to be more multi/interdisciplinary) and workplace skills gaps, and discusses approaches to training at different education levels.	Ends by asserting that adaptive and dynamic training programs will be the pioneers in training the future workforce.
Diep et al. (2021)	Undergraduate	Through surveying and interviewing Canadian iGEM teams, describes the landscape of SynBio education in Canada and supports from a student perspective.	The Framework for Transdisciplinary SynBio Education, outlining how to ground SynBio education in situated, project-based learning; and, recommendations for iGEM design teams and SynBio educators along five themes.
Dubé et al. (2017)	Secondary school	Describes the iGEM competition and the history of high school students' involvement, then highlights difficulties that high school teams face related to (i) training and project development, (ii) regional SynBio workshops, (iii) wiki and human practices, (iv) materials and equipment.	Small survey was conducted on a high school iGEM team found that the students had an overwhelmingly positive disposition towards SynBio, and that they planned to pursue careers in and related to SynBio.
Edwards and Kelle (2012)	Undergraduate	Focuses on dual-use education in the UK; describes where dual-use education should be integrated into SynBio training.	Found evidence of public education to connect researchers to the broader public community, but lack of impact on how researchers conduct themselves.
Farny (2018)	General	Discusses three important values that students in SynBio should be taught: (i) creativity (novice perspective), (ii) openness (open science), and (iii) interdisciplinarity and collaborativity.	Suggestions made for how to teach these values, such as course-based projects that are flexible and open to discovery and exploration.
Federici et al. (2013)	General	Starts with an in-depth discussion of what synthetic biology is, and its dimensions; continues with a brief discussion of learning and teaching.	Discusses how synthetic biology advances could be used to strengthen existing bioindustry.
Frow and Calvert (2013)	Undergraduate	Summary of the birth and growth of the iGEM competition, then provides an ethnographic account of an iGEM team's attempts to bring biology and engineering together through observations related to (i) standards, (ii) design, (iii) intellectual property, (iv) social dimensions.	Highlights the distinction between how iGEM portrays itself (as an engineering competition), and how iGEM teams work (driven by norms in the biosciences).
Gaisser et al. (2009)	General	Discusses a survey of SynBio researchers and stakeholders asked about what is needed to drive growth in the field.	Used their responses to create an interconnected roadmap that involves social contexts. Highlights the need for more funding.
Hall and Howe (2012)	Undergraduate	Focuses on discussion of what chemical engineering degrees generally look like and offers reasons how SynBio and ChE synergize; draws on literature describing successful examples of SynBio courses. Three approaches to bring SynBio into ChE curricula: (i) integration, (ii) mixed, (iii) dedicated.	Argues for a hybrid integration-mixed approach to cater to students' evolving interest in SynBio over an undergraduate program.

(Continued)

TABLE 5 (Continued)

Study	Target audience	Summary of intervention	Key findings
Hallinan et al. (2019)	Graduate	Provides a discussion of tools and resources, then the importance of RRI; highlights four fundamental issues with teaching SynBio: (i) interdisciplinarity, (ii) standards and consistent language, (iii) computation and automation, and (iv) incorporation of RRI.	Concludes by describing a masters in SynBio program, highlighting. Specifically, highlighting ways SynBio is taught to a heterogenous cohort.
Kelwick et al. (2015)	Undergraduate	Discusses the merits of iGEM for teaching students synthetic biology and microbiology; describes what teams must do to show how much work is required.	Argues that the iGEM competition provides wide-ranging training and educational experiences in SynBio for students.
McCarthy (2016)	Undergraduate	A description of the WISB and their common activities. Provides a description of a short SynBio module given to third-year students, as well as iGEM team support.	Institutional support facilitates SynBio education.
Nadra et al. (2020)	Undergraduate	Historical account of how a regional synthetic biology community developed over time in a "meandering way" because of government budget cuts.	By providing a description of how a regional SynBio community evolved over time, they suggest future teams facing similar issues could benefit from the lessons they described.
Sheets et al. (2023)	Undergraduate	In response to lack of comprehensive engineering biology content in widely used textbooks, and multiple requests from educators, EBRC developed a module that can act as a course unit, or as a framework for broader curricula planning. The module covers: what is SynBio, DBTL cycles, core tools, and applications.	Engineering biology concepts, tools, and applications are not comprehensively represented in widely used textbooks, and educators are requesting resources.
Walker (2021)	Middle school	Small survey for an American cohort of middle school students.	Found students held many perspectives on biotechnology; concludes by discussing how related perspectives form early in adolescence.

SynBio, Synthetic Biology; iGEM, International Genetically Engineered Machine; ChE, Chemical Engineering; RRI, Responsible Research and Innovation; WISB, Warwick Integrative Synthetic Biology Centre.

biomedical engineers to operate at molecular scales to achieve desired physiological effect, in contrast to the cellular and tissue-level focus of many current practitioners in the field.

At the Master's level, Hallinan et al. (2019) described barriers associated with interdisciplinary fields in SynBio and provided rationale for development of a 1-year Master's program in SynBio at Newcastle University. They began by highlighting important tools and resources for working in the field, then described the program: through a series of multidisciplinary lectures, computational and experimental assignments, group projects, seminars, and involvement with iGEM, students gained the ability to work with existing technologies and were encouraged to work with, and develop, new technologies in the field. In a complementary report focusing on the doctoral level, Cazimoglu et al. (2019) described the Synthetic Biology Centre for Doctoral Training (SynBioCDT), a collaboration between the Universities of Oxford, Bristol, and Warwick. The program is focused on interdisciplinary training of doctoral students. In the first year, all students learn both experimental and computational skills. The authors found that, as students progressed through their programs, they were able to recognize interdisciplinary links because of their common first-year studies. Importantly, the authors describe integration of student feedback to improve the program (Cazimoglu et al., 2019). Dedicated programs like these can be complemented with additional means of meeting educational goals, such as the establishment of dedicated SynBio centers (as could be outlined in national strategies). For example, the Warwick Integrative Synthetic Biology Centre brings together researchers from different disciplines and incorporates an educational component to connect learners' studies to the latest advances in research (McCarthy, 2016).

3.3.1 Factors influencing program-level curricula

Competing values, priorities, and community needs can influence the design of a curriculum. Farny (2018) argued the importance of open science, of having new perspectives to propel creativity in the field, and of having diverse teams to drive collaborative discovery and interdisciplinarity. On the other hand, expanding the biotechnology industry relies on commercialization and protecting intellectual property—both of which may run counter to the values of an open, accessible science and which require skills not generally covered by a traditional STEM program. Focusing on these skill gaps, Delebecque and Philp (2019) emphasized the importance of interdisciplinary training at various education stages. Additionally, Edwards and Kelle (2012) argued training should include the ability to assess risks posed by the dual-use nature of SynBio innovations. Expositions like these serve as launch points for institutional leaders to reflect on the values and priorities of a nation's SynBio community, and how those values make their way into curricula.

National training strategies are developed to gather consensus, to summarize the community's values, and to suggest how to build training pipelines or how to direct investment. As part of a European Commission programme, Gaisser et al. (2009) surveyed 176 stakeholders within the EU SynBio community, and generated a roadmap. The community priorities reflected in this roadmap were intended to inform discussions by policy-makers, funding agencies, and research organizations on how to strategically invest in, and regulate the development of, this emerging field. In this roadmap, the authors specifically argued for immediate funding to maintain European competitiveness. The United Kingdom (UK) Synthetic Biology Roadmap Coordination Group later provided a clear demonstration of how a national strategy could be drafted through stakeholder feedback. Their national SynBio roadmap in 2012 (UK Synthetic Biology Roadmap Coordination Group, 2012) emphasized the issue of training: "the next generation synthetic biology community needs to [be comprised of] researchers with (a) depth within core disciplines and the ability to work in cross-disciplinary collaboration; and (b) high-level, broad interdisciplinary synthetic biology expertise." From this roadmap, several UK groups have published work describing the development and outcomes of SynBio programs at the undergraduate and graduate level (Hall and Howe, 2012; McCarthy, 2016; Cazimoglu et al., 2019; Hallinan et al., 2019). Specifically, Kitney (2021) provided a comprehensive review of outcomes from the 2012 UK roadmap, including establishment of research centres, biofoundries, and innovation funds, as well as policy changes. An important step in creating a national training strategy for SynBio, then, is to ground it in the values of the existing community.

Knowledge of the historical development of successful research communities can be used to foster the growth of new communities. Federici et al. (2013) provided a history of SynBio in detail, then delineated how advances in the field could improve Chile's existing bioindustry. Addressing Latin America more broadly, Nadra et al. (2020) described the pivotal moments that defined that region's SynBio community of practice, which could be used to ground national training strategies catering to the specific needs of students, academia, and industry. Such comprehensive surveys of regional SynBio stakeholders can build community consensus and identify priorities for national training pipelines.

We did not find other examples of literature that addressed national SynBio strategies supported by government agencies. This gap may highlight community disconnect. Based on the literature, national training strategies can help determine what are the most important values and skills to transmit to students, how to identify and build on the local SynBio community's successes, and how to guide the development of programs at all post-secondary levels to produce a diverse workforce. National training strategies should be living expositions that change with new demographic and pedagogical data. The resulting training strategies can effectively meet the needs of a broad range of students, promoting a stronger workforce.

3.3.2 Education research studies for program-level curricula

While national training strategies may summarize the perspectives of numerous stakeholders in SynBio education, students are the ones experiencing that education first hand. We found several publications that report results of surveying students at the middle school and high school level. Dawson and Schibeci (2003) surveyed 905 students (15–16 year olds) in Australia to understand their attitudes towards biotechnology. They found that at this early age, these students had already formed opinions about which biotechnologies were more acceptable than others (i.e., bacterial/yeast engineering were mostly acceptable, while human embryo technologies were some of the least acceptable). More recently, Walker (2021) adapted the survey used by Dawson and Schibeci to evaluate American middle school (11–14 year old) students' perceptions of biotechnology, and noticed similar trends in attitudes towards biotechnologies derived from bacterial/yeast cells versus human-derived cells. These works indicate that understanding the initial attitudes of students should influence how curricula can be designed to appeal to, and introduce biology to, younger students. After discussing high school iGEM teams, Dubé et al. (2017) present the results of surveying the Lethbridge High School iGEM team (24 respondents), finding that iGEM was able to engage students in science, support students learning of science and scientific experimentation, and support the learning goals of the broader Alberta science curriculum. By surveying and interviewing undergraduate students on Canadian iGEM teams, Diep et al. (2021) found the students reported needing additional support, resources, and training from their institutions to reach their SynBio goals. Treating the iGEM experience as a proxy for SynBio education, the findings of Dubé et al. (2017) suggest that teaching SynBio can be consistent with broader STEM curriculum requirements, while the findings of Diep et al. (2021) suggest that students can describe gaps that their current institutions could fill to provide a more successful SynBio education.

4 Bridging learning concepts with SynBio education research

In the previous sections we summarized and identified trends in the SynBio education research literature after stratifying relevant publications into (i) classroom activities, (ii) course design, and (iii) program-level curriculum planning. We considered publications that used quantitative, qualitative, and mixed methodologies to assess students' experiences and their achievement of learning goals and objectives. In this section, we build on those discussions by gathering three important learning concepts that SynBio educators and education researchers may find applicable to their courses and programs (Figure 5) and highlight a few selected course-based publications.

4.1 Learning progressions

Learning progressions are structured course sequences that outline the expected stages of knowledge and skill development in specific subject areas (Scott et al., 2019). These progressions help educators and curriculum designers understand how students typically advance in their understanding and abilities over time (Figure 5A). Learning progressions provide a roadmap for crafting instructional strategies and assessments that are developmentally appropriate and aligned with learners' needs and that successfully guide them toward more advanced concepts and competencies as they progress through their education. National training strategies and other expositions by stakeholders can highlight what skills students should develop and master in a SynBio program; these insights can align SynBio learning progressions with national priorities.

We can consider interdisciplinary collaboration as an example of a learning progression: in the previous section, we discussed how disciplinary grounding, attitudes toward interdisciplinarity, and

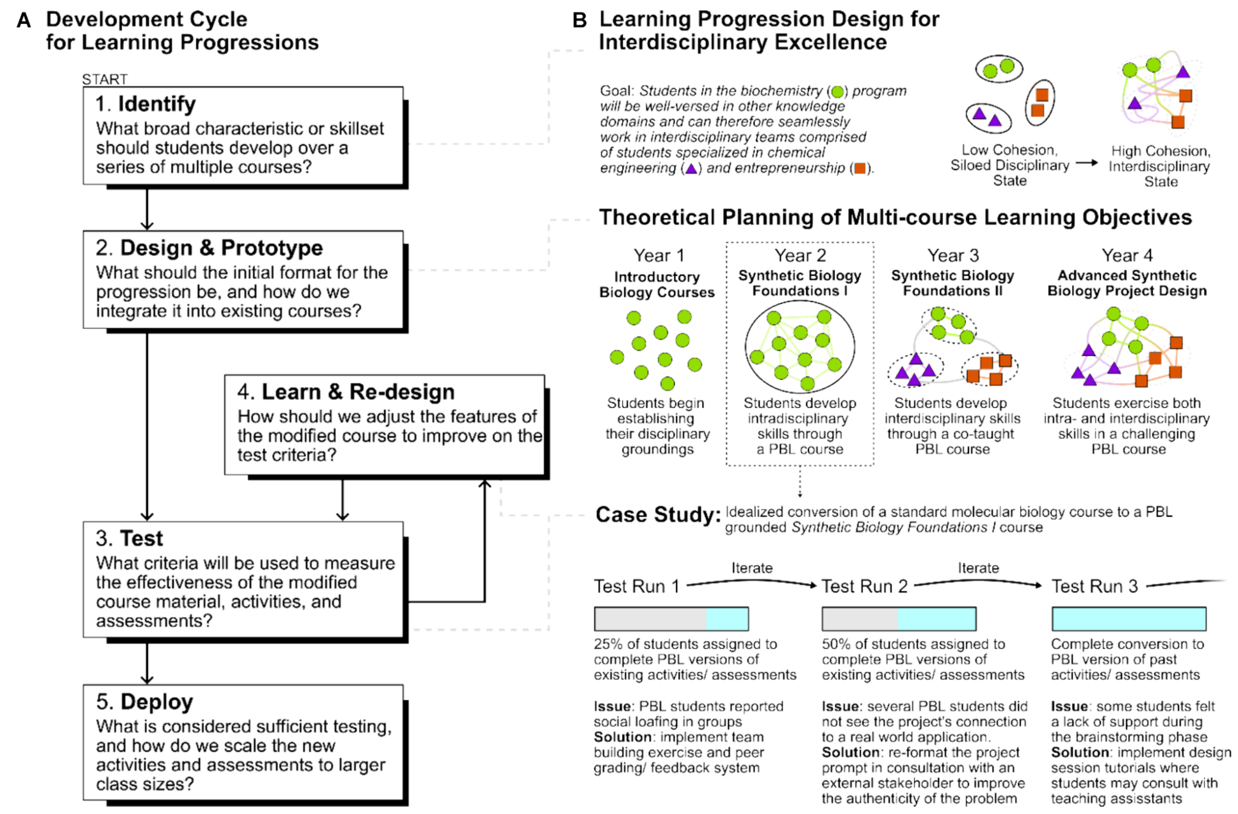


FIGURE 5
Learning progressions and design-based research. **(A)** Iterative design and implementation of learning progressions. Each of the five stages is characterized by an overarching question. Stages 3 and 4 are iterated until specific criteria for teaching effectiveness are met. **(B)** Implementation of a learning progression for interdisciplinary competence, with focus on biochemistry students (green circles). A four-year course series is proposed in which biochemistry students develop disciplinary grounding in Year 1, then build intradisciplinary skills (e.g., conflict management, time management, teamwork, communication) in group projects in Year 2. Throughout Year 3 and 4, these biochemistry students work with students from chemical engineering and business programs who have completed their own disciplinary Year 1 and 2 courses designed for entry into the SynBio space. Case study: Year 2's "Synthetic Biology Foundations I" course that began as a standard molecular biology course for biochemistry students and was transformed through an iterative design-based research process.

opportunities for interdisciplinary collaboration are interrelated factors contributing to interdisciplinary competence (Figure 5B). A learning progression that leverages those factors and PBL could consist of a second-year project-based course offered to students in a particular degree or program (practicing intra-disciplinary collaboration and solidifying disciplinary grounding) followed first by a third-year project-based course taken by students with distinct backgrounds (such as the course described by MacLeod and van der Veen, (2020)), and then by a fourth-year capstone project with teams composed of students from very different backgrounds, in the flavour of an iGEM team (Figure 5).

As discussed in Diep et al. (2021), learning progressions would ideally be prototyped and tested using iterative mixed-method study designs (Figure 5). Prototyping a course element that contributes to an interdisciplinary aptitude learning progression may involve cross-course collaboration. As an example, consider a project shared across two courses, where students in each course learn different, but related, content, and collaborate on the project. Designing a sufficiently complex project that challenges the students from each course to develop an interdisciplinary response would involve an analysis of each course's syllabus and rely on collaboration between the instructors. Testing could involve allowing students to opt into either the project shared across courses or a final assessment independent of the other course. Pre-/post-assessments and interviews could be conducted over multiple iterations to determine whether students are developing more interdisciplinary aptitude, how to modify the shared assessment(s), or whether there should be more or less shared content. Figure 5 provides a graphical overview of this process.

As described, cross-course collaboration offers a method to route students from different specializations to collaboration on a project relevant to each of their specializations. The work of MacLeod and van der Veen (2020) is one such example. Bringing second-year undergraduate students from applied mathematics, civil engineering, and industrial & engineering management together to collaborate on a project, MacLeod and van der Veen found that students find the course and project meaningful (albeit with differences across disciplines) and that students found working with partners from disparate disciplines one of the most valuable aspects of the course. Even before students begin collaborating, cross-campus collaboration between a course organizer and a writing centre can prepare students to be stronger communicators. Beason-Abmayr and Wilson (2018) describe a course where students learn to provide better journal presentations through a required writing centre workshop. The authors report that student presentations qualitatively improved and that average scores across the presentation rubric were higher than previous offerings that lacked a writing centre workshop.

Examples like these suggest that reaching across the university may provide students with effective and meaningful learning experiences.

4.2 Design-based research

Design-based research (DBR) seeks to improve educational practices (e.g., classroom activities and courses) by integrating research, design, and implementation (Scott et al., 2020). It involves creating and refining instructional strategies, interventions, or educational technologies within real-world educational settings. DBR emphasizes collaboration between researchers and practitioners to address specific educational challenges and enhance learning outcomes. This iterative process mirrors the design-build-test-learn cycle familiar to SynBio practitioners (Figure 4B; Figure 5A). DBR has been used in biology education. For example, Zagallo et al. (2016) reported the three-year development of an activity for molecular and cellular biology majors to practice connecting scientific models with empirical data. By analyzing students' written work and small-group audio recordings, Zagallo et al. determined strategies that students used to identify and interpret patterns in data. Such results can directly inform subsequent course design. In another report on DBR, Scott et al. (2020) reported the use of two course iterations to guide the development and understanding of their physiology course. From the first offering, the authors learned to broaden their assessments to other physiological systems to ensure students had context to generalize the principle of flux. They refined their learning progression with both written and interview data. These examples illustrate how DBR formalizes measurement of changes in student learning (e.g., through pre-/post-test assessment) and also determines (through qualitative methods) the mechanisms driving those changes leading to practical changes in the course. Indeed, Scott et al. noted "DBR invites the use of mixed methods to understand student learning." Through DBR, SynBio educators can effectively and precisely improve the practical outcomes of classroom activities and course designs, all while better understanding the student's experience.

4.3 Concept inventories

Concept inventories are an assessment tool used to measure student understanding of essential concepts within a subject domain. In physics education research, Concept Inventories were first introduced for measuring conceptual understanding of force, motion, and Newtonian physics (Hestenes et al., 1992). More recently, concept inventories were introduced to biology faculty and next steps were discussed, specifically the need to agree on introductory concepts (D'Avanzo, 2008). With evolutionary biology in mind, Furrow and Hsu (2019) surveyed concept inventories for evolution, and described how they may be used. In the same year, Cary et al. (2019) described four biology core concept instruments they developed, inspired by concept inventories. Their instruments are intended to be a method of measuring student understanding of the five core concepts outlined in the *Vision and change* report (American Association for the Advancement of Science, 2011). Of the publications we surveyed, most of the literature reported on the evaluation of a method or on education research by using a survey as an assessment tool; some performed observational reporting or interviews with their participants (Table 1). Of those that used a survey, only some performed pre- and post-test assessments to estimate the impacts of their activity, course, or program; fewer had follow-up interviews to investigate *how* or *why* a particular result was observed (Table 1). Concept inventories could provide a standardized measure of student understanding of core SynBio concepts, although this would require a consensus on what concepts are core to SynBio.

To our knowledge, there is no literature explicitly outlining the development, testing, and refining of concept inventories for SynBio. Here, we propose a 4-step guideline for the process of creating them, using molecular cloning (i.e., DNA assembly, or genetic engineering) at the undergraduate levels as a concrete example. (1) *Anchoring*. A high-level concept should be defined in a way that explains what the student should know and be capable of doing if they have excellent comprehension of it. This could be linked to learning progressions (Section 4.1). In our example, a student should understand the methods used to manipulate DNA to create genes, or networks of genes, that impart some biological reaction or function. (2) *Decomposition*. The high-level concept should then be broken down into separate ideas with enough simplification (or abstraction) that one approaches a reasonably reduced form. In this fashion, a fundamental grasp of the concept at its "first principles" can be achieved. In our example, DNA manipulation could be broadly understood as cutting, copying, and pasting of nucleic acids. "Cutting" DNA could involve restriction enzymes and CRISPR-Cas9; all of which could be further reduced to hydrolysis of the phosphodiester backbone of DNA, with specificity imparted through the nature of the enzyme. "Copying" DNA would involve PCR-amplification, which could be further reduced to understanding how double-stranded DNA come together through base-pair matching. "Pasting" DNA would again involve base-pair matching, as well as ligation of the phosphodiester backbone in a condensation reaction. The product of this reductionist approach is a knowledge tree where the starting high-level concept is sub-branched up to a threshold that educators (experts in the field) define. In our example, that threshold is organic chemistry, which we would consider sufficient since the next level of reduction (quantum chemistry and chemical physics) is not required for molecular cloning. (3) *Inventorying*. The sub-branches can then be converted into tangible learning goals by creating an inventory of assessment tools (i.e., questions, problems, scenarios, tasks) that challenge students' understanding. For Cutting DNA, a series of knowledge questions about how restriction enzymes work (i.e., DNA recognition, binding, catalysis), and standardized problems (i.e., designing molecular cloning sites, predicting fragment sizes, matching overhangs to their complementary overhangs) could be developed. (4) *Iterative Testing*. Finally, the educator could perform DBR to understand and improve the effectiveness of their teaching. Other concept inventories include genetic circuits, flux balance analysis, biosensing, and more. Future discussion and research should be directed at defining appropriate concept inventories for synthetic biology where efforts can overlap with development of learning progressions by engaging with relevant stakeholders that employ synthetic biologists.

4.4 Starting points for planning a SynBio course

A number of publications we reviewed provide excellent starting points for designing and planning related SynBio courses.

In their publication describing a SynBio device design lab course, Johnson et al. (2022) provide a comprehensive amount of material for planning a similar course. They included faculty training videos and interviews, clear learning objectives, a week-by-week description of what students should be doing, and, in their supplementary material, they included assignment examples, rubrics, and representative student assignment submissions. For an 8-week course balanced between modelling and building a CRISPRi toggle switch, Smith et al. (2022) provide a week-by-week overview of their course, and a GitLab repository[1] containing assignments, course schedule, and python notebooks for running code. For a course devoted to modelling in SynBio, *Principles of Synthetic Biology* is archived on edX[2] complete with a course syllabus, schedule, recorded lectures, and problem sets (Anderson et al., 2019).

5 Conclusions and outlook

In our survey of the SynBio education research literature, several noteworthy trends emerged. First, it was evident that cell-free SynBio kits are a popular area of study, with several paths to enhance their educational outcomes by incorporation of low-cost technologies and online courses. Second, in the realm of course-level education research for PBL iGEM-inspired courses, diverse methodologies have been employed. However, there remains room for improvement, particularly regarding the incorporation of iterative DBR, exploration of instructor perspectives, and the consideration of demographic factors. Third, the assessment of program effectiveness has primarily relied on student surveys. While such surveys provide valuable insights, there is an opportunity to broaden the scope of stakeholders (e.g., employment needs of start-ups, SMEs, and corporations; public sector needs of policy-makers) from whom input is solicited. Several valuable learning concepts have yet to be widely adopted by SynBio education researchers. These include the prototyping and testing of learning progressions, the incorporation of DBR principles into course design, and the standardization of concept inventories tailored to the field's unique requirements. Ultimately, the SynBio community must engage in critical self-examination regarding the definition of SynBio itself, addressing what proficiencies are required of trainees in the field. Over time, the integration of education science methodologies into the field is anticipated to play a pivotal role in advancing the training and preparation of future SynBio practitioners.

Author contributions

JM: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. PD: Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. FS: Formal analysis, Methodology, Visualization, Writing – original draft. AE: Formal analysis, Methodology, Writing – original draft. CD: Writing – review & editing. VS: Writing – review & editing. AA: Data curation, Formal analysis, Writing – original draft. EB: Data curation, Formal analysis, Writing – original draft. AB: Data curation, Formal analysis, Writing – original draft. SC: Data curation, Formal analysis, Writing – original draft. JD: Data curation, Formal analysis, Writing – original draft. CE: Data curation, Formal analysis, Writing – original draft. TL: Data curation, Formal analysis, Writing – original draft. IM: Data curation, Formal analysis, Writing – original draft. LM: Data curation, Formal analysis, Writing – original draft. DS: Data curation, Formal analysis, Writing – original draft. AS: Data curation, Formal analysis, Writing – original draft. SS: Formal analysis, Writing – original draft, Data curation. BI: Funding acquisition, Supervision, Writing – review & editing.

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SC was employed by Phyx44 Labs Pvt Ltd. JD was employed by Rapid Novor, Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2024.1441720/full#supplementary-material

SUPPLEMENTARY TABLE 1
Additional publications suggested during anonymous review. Plus, un-condensed learning objectives for selected publications, and a short list of graduate programs in SynBio.

SUPPLEMENTARY TABLE 2
List of publications found and reviewed, plus our early summaries of them. This file also includes the data used for Figure 1.

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[1] https://gitlab.com/wurssb/systems-and-synthetic-biology/

[2] https://www.edx.org/learn/synthetic-biology/massachusetts-institute-of-technology-principles-of-synthetic-biology?irgwc=1

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