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# Integrating mathematical modeling into synthetic biology education: a comprehensive approach through webinars and syllabus development

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Mathematical modeling is a fundamental aspect of synthetic biology, enabling precise design and analysis of biological systems. To enhance students' understanding of this critical topic, we developed a series of webinars aimed at teaching mathematical modeling to iGEM teams. These webinars were initially created to maintain student engagement during a period of restricted lab access but quickly demonstrated their value as an effective educational tool. The success of these webinars highlighted the suitability of mathematical modeling as a topic well-suited to both onsite and online learning environments. Recognizing this, we expanded the content into a comprehensive syllabus for undergraduate courses in synthetic biology at the Universitat Politècnica de Valencia in Spain and Universidad de las Fuerzas Armadas—ESPE in Ecuador. The course now serves as a core component of synthetic biology education, offering students a robust framework for understanding and applying mathematical models. It includes a series of lectures, practical exercises, and case studies, all designed to deepen students' knowledge and skills in this essential area. To support educators and students, we have also developed a deck of slides and example scripts that provide practical examples and reinforce the concepts taught in the course. This manuscript presents the development, implementation, and impact of these educational initiatives, demonstrating how mathematical modeling can be effectively integrated into synthetic biology curricula to prepare students for real-world challenges in the field.

KEYWORDS

**iGEM, mathematical modeling for biology, webinar education, synthetic biology education, DBTL**

## 1 Introduction

Synthetic biology, an interdisciplinary field at the intersection of biology, engineering, and computational sciences, is revolutionizing how we design and manipulate biological systems. By applying engineering principles to biology, synthetic biology enables the construction of novel biological systems and the re-design of existing ones for useful purposes, ranging from medical applications to environmental sustainability (Cameron et al., 2014; Khalil and Collins, 2010). Central to the success of these endeavors is the use of mathematical modeling, which allows scientists to predict the behavior of biological systems before they are constructed, thereby reducing trial-and-error experiments and enhancing the reliability of outcomes (Elowitz and Leibler, 2000).

Mathematical modeling is indispensable in synthetic biology because it provides a framework for understanding complex biological processes, such as gene regulation, metabolic pathways, and signal transduction networks (Kitano, 2002; Marchisio, 2018). These models are essential for designing genetic circuits that can perform specific functions, such as oscillators, toggle switches, and biosensors (Gardner et al., 2000). However, the abstract and interdisciplinary nature of mathematical modeling presents unique challenges in education. Unlike traditional engineering disciplines, where physical components like wires and resistors can be directly manipulated, synthetic biology deals with molecular-scale processes that are often represented as theoretical constructs. This complexity requires a deep understanding of both biological principles and mathematical techniques, making it difficult for students to grasp the importance of modeling in predicting the behavior of engineered biological systems (Purnick and Weiss, 2009).

The COVID-19 pandemic further exacerbated these educational challenges by restricting access to laboratory environments, which are typically essential for reinforcing theoretical learning through hands-on experience. In response to these challenges, we developed a series of webinars aimed at teaching mathematical modeling to iGEM teams and other students engaged in synthetic biology. These webinars, initially conceived as a means to maintain student engagement during the pandemic, quickly demonstrated their value as a powerful educational tool that could transcend the limitations of physical classrooms (Brooks and Alper, 2021).

The webinar series focused on core aspects of mathematical modeling relevant to synthetic biology, covering topics such as dynamic modeling, reaction kinetics, and the use of ordinary differential equations (ODEs) to describe biological processes. The positive reception of these webinars highlighted the suitability of mathematical modeling as a topic well-suited to online learning environments, which can offer flexibility and accessibility while maintaining rigorous educational standards (Muth et al., 2021). Encouraged by this success, we expanded the content into a comprehensive syllabus for undergraduate courses in synthetic biology at the Universitat Politècnica de Valencia (UPV) and Universidad de las Fuerzas Armadas—ESPE, Ecuador.

Incorporating synthetic biology into educational programs poses unique challenges and opportunities. This initiative fits well within the current educational paths by providing students with applied experiences that traditional coursework might lack. At the Universitat Politècnica de Valencia (UPV) and Universidad de las Fuerzas Armadas—ESPE, the synthetic biology course supplemented existing theoretical classes with practical applications, such as genetic circuit design and mathematical modeling. By doing so, students not only learn the theory but also acquire hands-on skills in modeling biological systems—essential in synthetic biology. This initiative also aligns with efforts to incorporate interdisciplinary approaches in STEM education, particularly in fields such as bioengineering, where students must integrate knowledge from mathematics, biology, and computational sciences to succeed.

Moreover, the novelty of this initiative lies in its online format and the focus on mathematical modeling—a critical but often underrepresented component in synthetic biology education. By providing this material through webinars, we not only reach a broader audience but also create an accessible framework that can be incorporated into diverse curricula, helping bridge gaps between biological theory and computational practice. This work contributes to ongoing discussions about how to effectively teach synthetic biology, especially in light of the growing need for remote learning tools.

This manuscript presents the development, implementation, and impact of these educational initiatives. It demonstrates how mathematical modeling can be effectively integrated into synthetic biology curricula, providing students with the necessary tools to tackle real-world challenges in the field. We offer a robust educational framework that bridges the gap between theoretical knowledge and practical application, ensuring that students are well-prepared for the complexities of synthetic biology (Diep et al., 2021; El Karoui et al., 2019; Boada et al., 2021; Picó et al., 2021).

## 2 Webinar series design and content

The *Mathematical Modeling in Synthetic Biology* webinar series was meticulously designed to provide a comprehensive introduction to the essential concepts and techniques of mathematical modeling as applied to synthetic biology. The structure of the webinars was carefully crafted to build a solid foundation in modeling biological systems, progressively guiding participants from fundamental principles to advanced applications. Each session focused on a specific aspect of mathematical modeling, ensuring that participants gained both theoretical knowledge and practical skills. The webinars were particularly targeted at members of iGEM teams and undergraduate students, offering them invaluable resources to enhance their understanding and application of modeling techniques in synthetic biology projects. The webinar series covered essential topics in mathematical modeling for synthetic biology are detailed in Table 1.

These topics were selected to provide a comprehensive introduction to mathematical modeling, ensuring that students developed a solid foundation in this critical area. Special considerations were given to make the content accessible to a biology-oriented audience, bridging the gap between biological concepts and mathematical techniques. A comprehensive deck of slides that may be used for teaching modeling for synthetic biology together with the scripts both in Matlab and Python can be found on the GitHub repository https://github.com/sb2cl/SynBio_Modeling_Webinars.

### 2.1 Promotion, outreach, and audience accessibility

#### 2.1.1 Promotion and recruitment

To maximize participation, the webinar series was promoted through the iGEM newsletter and website. Direct communication

TABLE 1 Webinars on mathematical modeling for synthetic biology: topics, scope, title, links, publication dates, and views on iGEM universe and YouTube.

| | | | |
|---|---|---|---|
| **Webinar topic: Introduction to mathematical modeling in biology** | | | |
| **Scope**: The first webinar introduced the basic principles of mathematical modeling in biology. Participants were introduced to the concept of modeling as a tool for simplifying and understanding complex biological processes. The session covered how to define and structure a model, the importance of assumptions and simplifications in making models computationally feasible. | | | |
| **Webinar title and link** | **Publish time** | **iGEM universe** | **YouTube** |
| Introduction to modeling for synthetic biology—iGEM 2020 Opening Weekend Festival | 9-Jun-20 | 25 views | 1,349 views |
| **Webinar topic: Mathematical modeling and ODEs** | | | |
| **Scope**: This session focused on the use of ordinary differential equations (ODEs) to describe the dynamic behavior of biological systems over time. Key topics included the formulation of ODEs based on biological principles, solving these equations using analytical and numerical methods, and practical applications such as modeling population dynamics and gene expression. | | | |
| **Webinar title and link** | **Publish time** | **iGEM universe** | **YouTube** |
| Week #2A: Modeling Part 1/3—ODEs—iGEM 2020 Measurement Webinars | 25-Jun-20 | 169 views | 1,617 views |
| **Webinar topic: Modeling reactions and law of mass action kinetics** | | | |
| **Scope**: This webinar delved into the principles of reaction kinetics, particularly the law of mass action, which is fundamental in modeling biochemical reactions. Participants learned how to derive kinetic equations and apply them to model processes such as enzymatic reactions and metabolic pathways. | | | |
| **Webinar title and link** | **Publish time** | **iGEM universe** | **YouTube** |
| Week #2A: Modeling Part 2/3—Introduction to Hill Functions—iGEM 2020 Measurement Webinars | 25-Jun-20 | 93 views | 1,525 views |
| **Webinar topic: Constitutive expression and induced promoters** | | | |
| **Scope**: This session explored the mechanisms of gene expression, focusing on constitutive expression and the role of inducible promoters. The webinar introduced the Hill equation, which is used to model the interaction between molecules and promoters, influencing gene expression levels. It provides insights into both constant gene expression and regulated gene expression through inducible promoters. | | | |
| **Webinar title and link** | **Publish time** | **iGEM universe** | **Youtube** |
| Week #2A: Modeling Part 3/3—Examples of Hill Functions—iGEM 2020 Measurement Webinars | 25-Jun-20 | 55 views | 583 views |
| **Webinar topic: Using experimental data with models** | | | |
| **Scope**: This webinar emphasized the integration of experimental data into mathematical models to validate and refine them. Participants learned techniques for calibrating models using data such as fluorescence measurements and optical density readings, which are critical for ensuring that models accurately represent biological systems. | | | |
| **Webinar title and link** | **Publish time** | **iGEM universe** | **YouTube** |
| Week #3A: Modeling Part 1/3—Composing Circuit Models from Hill Functions—iGEM 2020 Measurement | 2-Jul-20 | 103 views | 948 views |
| **Webinar topic: Designing genetic circuits using models** | | | |
| **Scope**: In this session, the application of mathematical models in designing and predicting the behavior of genetic circuits was explored. Participants used models to simulate genetic circuits, optimizing designs before laboratory implementation. The session covered the use of differential equations and kinetic models to predict the outputs of circuits such as toggle switches and oscillators. | | | |
| **Webinar title and link** | **Publish time** | **iGEM universe** | **YouTube** |
| Week #3A: Modeling Part 2/3—Relating parameters and data—iGEM 2020 Measurement Webinars | 2-Jul-20 | 30 views | 305 views |
| **Webinar topic: Advanced modeling techniques: incoherent feed-forward loops** | | | |
| **Scope**: This advanced webinar introduced more complex genetic circuits, such as incoherent feed-forward loops (IFFLs), which are crucial in synthetic biology for filtering signals and creating pulse responses. The session provided detailed instruction on modeling these circuits using differential equations and predicting their behavior under various conditions. | | | |
| **Webinar title and link** | **Publish time** | **iGEM universe** | **YouTube** |
| Week #3A: Modeling Part 3/3—Example: Incoherent Feed-Forward Loop—iGEM 2020 Measurement Webinar | 2-Jul-20 | 33 views | 592 views |
| **Webinar topic: Introduction to ODEs and hill functions** | | | |
| **Scope**: This webinar revisited the basics of ODEs and introduced Hill functions, which are critical for modeling gene expression regulation. Participants explored how Hill functions describe the interaction between transcription factors and DNA, an essential component for understanding the non-linear dynamics of gene regulatory networks. | | | |
| **Webinar title and link** | **Publish time** | **iGEM universe** | **YouTube** |
| Modeling I: ODEs and Hill Functions—2021 iGEM Engineering Webinars | 30-May-21 | 1,100 views | 206 views |
| **Webinar topic: Modeling circuits with ODEs and experimental data** | | | |
| **Scope**: This session combined the use of ODEs with experimental data to model and simulate genetic circuits. The focus was on integrating experimental results into models to improve their accuracy and make reliable predictions, particularly in real-world synthetic biology projects. | | | |

*(Continued)*

TABLE 1 (Continued)

| Webinar title and link | Publish time | iGEM universe | YouTube |
|---|---|---|---|
| Modeling II: Modeling Circuits with ODEs and Experimental Data—2021 iGEM Engineering Webinars | 30-May-21 | 498 views | 118 views |
| **Webinar topic: From ODEs to gene expression** | | | |
| **Scope**: This final webinar connected ODEs directly to gene expression models. Participants learned how to translate the mathematical formulations of ODEs into predictions about gene expression levels under various conditions, covering advanced topics such as stochastic modeling and the impact of noise on gene expression. | | | |
| **Webinar title and link** | **Publish time** | **iGEM universe** | **YouTube** |
| Modeling for SynBio: from ODEs to Gene Expression | 14-Jul-22 | 300 views | 1,174 views |
| Total views | | 2,406 | 8,561 |

channels, including email updates and announcements, were employed to inform iGEM teams about the upcoming webinars and provide clear instructions on registration and participation. This outreach strategy aimed to establish a direct connection with potential participants and create awareness within the iGEM community.

### 2.1.2 Target audience

The webinars were designed for second to fourth-year undergraduates participating in iGEM, with a focus on making complex mathematical concepts accessible to students with a biology background from diverse disciplines such as biotechnology, bioengineering, and biology. Efforts were made to simplify the content and engage a broader audience, ensuring inclusivity and comprehensibility. The target audience was particularly those with a limited background in mathematics, providing them with the necessary skills to apply modeling techniques in their synthetic biology projects.

### 2.1.3 Accessibility measures

The courses were designed to accommodate students with different learning preferences and backgrounds. Resources such as the deck of slides used, videos of the recorded webinars sessions, and the code used in the webinars both in Matlab and Python were provided to enhance accessibility and comprehension. Additionally, the syllabus was carefully structured to gradually build up complexity, starting from fundamental concepts to more advanced applications of mathematical modeling in synthetic biology.

## 2.2 Post-view statistics on YouTube and the iGEM video universe

The video recordings of the webinars were made available on YouTube and the iGEM Video Universe, allowing for continued engagement beyond the live sessions. Post-view statistics, detailed for each webinar in Table 1, provided additional insights into the reach and impact of the series:

- **YouTube views:** Each session garnered significant view counts, with the "Modeling" session reaching the highest numbers. In particular, on the YouTube platform, where 62 related videos are available, four of the modeling webinars are prominently featured among the top 15 most viewed, amassing a total of more than 5,540 views.
- **iGEM Video universe:** The platform also showed substantial engagement, with numerous views and interactions from the iGEM community. Notably, among the 89 webinar-related videos hosted on the iGEM Video platform, the modeling-focused videos rank among the top seven most viewed. The two most popular videos, Modeling I and Modeling II, have collectively garnered over 1,600 views.

# 3 Syllabus development at university teaching level

The success of the webinars led to the development of a comprehensive syllabus for undergraduate courses in synthetic biology, including mathematical modeling. This syllabus was implemented at both the Universitat Politècnica de Valencia and Universidad de las Fuerzas Armadas—ESPE, aiming to provide a robust educational framework. The mathematical modeling part of the courses included a blend of theoretical lectures, practical exercises, and case studies designed to give students a practical understanding of designing and analyzing biological systems through mathematical models. The aims is to provide a structured and detailed introduction to mathematical modeling for synthetic biology, ensuring continuity and expansion of the educational initiative.

## 3.1 Case: Universitat Politècnica de València, Spain

The course *Synthetic Biology—11166* at Universitat Politècnica de València (UPV) is a critical component of the Biotechnology degree, designed to equip students with the foundational knowledge and practical skills necessary to excel in the interdisciplinary field of synthetic biology. This course emphasizes the integration of engineering principles with biological sciences, aiming to transform biological organisms into efficient platforms for various industrial applications. It covers the entire synthetic biology cycle, including design, construction, analysis, and learning, providing a comprehensive framework for understanding and manipulating biological systems.

Throughout the course, students engage in both theoretical and practical learning, where they design, build, and test genetic circuits using computational tools and laboratory experiments. This hands-on approach ensures that students not only grasp the theoretical concepts but also acquire the practical skills to apply these concepts in real-world scenarios. The course also emphasizes the standardization of biological processes and the use of *in silico* modeling to predict and simulate outcomes, thereby enhancing the reliability and efficiency of genetic circuit design.

#### 3.1.1 Integration of mathematical modeling into the syllabus

One of the core components in the development of the *Synthetic Biology—11166* course at UPV is the integration of mathematical modeling. This section of the course provides students with a deep understanding of how mathematical models can be applied to predict the behavior of synthetic biological systems, which is crucial for the design and analysis of genetic circuits.

The key topics covered in mathematical modeling section of the course are as follows:

- **Dynamic models in biology**: The course begins with an introduction to dynamic models, emphasizing their importance in understanding and predicting biological processes. Students learn to develop and analyze models using ordinary differential equations (ODEs), which are essential for modeling dynamic biological systems such as gene expression and population dynamics.
- **Genetic circuit modeling**: A significant portion of the course is dedicated to the modeling of genetic circuits. This includes the application of the law of mass action to model biochemical reactions, the use of Hill functions for modeling gene regulation, and the implementation of the Quasi-Steady-State Approximation (QSSA) for simplifying complex biological systems. Students gain practical experience by using simulation software like MATLAB to model and analyze genetic circuits.
- **Software tools for simulation**: Students are introduced to various computational tools used for modeling in synthetic biology. The course includes practical sessions where students use MATLAB, Python, and other simulation tools to implement and analyze the models discussed in lectures. This hands-on approach ensures that students are proficient in using these tools to simulate genetic circuits and predict their behavior in the laboratory.
- **Examples and case studies**: The course integrates several case studies and examples to provide students with practical applications of mathematical modeling. These include the logistic growth model, predator-prey dynamics, and pandemic models, which help students understand the real-world implications of the mathematical concepts they are learning.
- **Experimental data calibration**: To bridge the gap between theory and practice, the course includes a section on calibrating mathematical models with experimental data. Students learn techniques for calibrating models using fluorescence measurements and optical density data, which are critical for validating their models against experimental results.

### 3.2 Case: Universidad de las Fuerzas Armadas—ESPE, Ecuador

The "Synthetic Biology and Genetic Editing" course offered at ESPE, Ecuador, provides students with a comprehensive understanding of the foundational principles and cutting-edge techniques within the rapidly evolving field of synthetic biology and is thought to students of Biotechnology Engineering degree on their 4th year. The syllabus is meticulously designed to cover a broad spectrum of topics, beginning with an introduction to synthetic biology, the history and development of genetically modified organisms (GMOs), and the essential processes of gene expression and biodiscovery. The course progresses to advanced topics such as DNA synthesis and assembly, as well as methods for gene expression measurement. A critical component of this curriculum is the integration of mathematical modeling, which plays a vital role in the design, analysis, and prediction of synthetic biological systems. Through dedicated lectures and practical sessions, students explore dynamic models, genetic circuit modeling, and the application of key mathematical concepts, such as the Hill function and Quasi-Steady-State Approximation (QSSA). This rigorous approach ensures that students not only grasp the theoretical aspects of synthetic biology but also acquire the practical skills necessary to apply mathematical modeling in real-world scenarios, thus bridging the gap between conceptual understanding and practical application in the field of synthetic biology. *In-class* application of mathematical modeling is supplemented with webinars to enhance understanding of the topic. The detailed syllabus of the mathematical modeling part is as follows:

- **Dynamic models**: Emphasizes the importance of dynamic models in understanding and predicting the behavior of synthetic biological systems.
- **Practical applications**: Application of mathematical modeling to their own synthetic biology projects to provide students with practical applications of mathematical modeling.
- **Genetic circuit modeling**: Focus on modeling gene expression using constitutive and regulated models, including the derivation of the Hill function and application of the Quasi-Steady-State Approximation (QSSA).
- **Software and tools**: Hands-on experience mainly with MATLAB, but also with other simulation tools to model and analyze genetic circuits.

### 3.3 Survey for student feedback and learning outcomes

After the implementation of the syllabus including the mathematical modeling section at UPV and ESPE, a survey was conducted to evaluate its effectiveness. The survey aimed to gather students' feedback on various aspects of the course, including the clarity of mathematical modeling concepts, the usefulness of case studies and practical exercises, and the overall impact on their understanding of synthetic biology. The survey and the results report can be found in the Github repository https://github.com/sb2cl/SynBio_Modeling_Webinars.

### 3.3.1 Methodology

The survey, available at the repository, consisted of a series of quantitative and qualitative questions. Students were asked to rate their understanding of mathematical modeling before and after the course, the helpfulness of teaching materials, and their interest in synthetic biology as a career path. Open-ended questions were also included to gather detailed feedback on what students found most beneficial and areas where they felt improvements could be made.

### 3.3.2 Preliminary findings

The survey, which garnered responses from 40 students, primarily from Ecuador (80%), with the remainder from Spain, provides valuable insights into the effectiveness of the mathematical modeling course. The majority of respondents were in their fourth year of study (62.5%), with a significant proportion (27.5%) also in their third year. Biotechnology was the predominant field of study (75%), although students from biomedical engineering, biology, and biomedicine also participated. Notably, confidence in understanding modeling principles varied significantly by field of study: **students from biomedical engineering (90%) and biomedicine (85%) reported the highest levels of confidence**, whereas students from biotechnology (60%) and biology (55%) expressed more moderate confidence. However, despite lower initial confidence, **students from biotechnology and biology showed a greater increase in interest** in mathematical modeling after completing the webinars (Figure 1A). Over 82.1% of the respondents agreed that the course materials significantly aided their understanding of mathematical modeling, while 87.2% found the mathematical modeling component of the course to be highly interesting. Furthermore, over 79.5% of students rated the webinars as very or extremely engaging, indicating a strong connection between the interactive materials and the students' sustained interest in the subject matter.

When asked which topics they found most challenging, a significant portion of the students (59%) indicated that "Mathematical modeling and ODEs" was particularly difficult, followed closely by **"Advanced topics in modeling" (59%)** (Figure 1B). Despite these challenges, 79.5% of participants rated the webinars' explanations as either "Very good" or "Excellent" (Figure 1C), demonstrating that the course materials and instruction were effective in overcoming these difficulties. A similar percentage expressed high satisfaction with the overall experience, with **85.6% reporting that they were "Very satisfied" or "Extremely satisfied"** with the course (Figure 1D). Moreover, 61.5% of the students reported that they had applied the learned techniques to other projects, with an additional 23.1% indicating that they might have done so (Figure 1E). Furthermore, 92.3% of the students stated they would strongly recommend this course to other students, reflecting the course's broader applicability and perceived value. The survey also highlighted the importance of providing more **hands-on, practical examples**, as reflected in the word cloud of suggested improvements (Figure 1F). These findings underscore the positive impact of the webinars on students' understanding and application of mathematical modeling in synthetic biology, while also pointing to areas for future enhancement, such as the need for more practical, real-world examples to solidify student learning.

Finally, when we asked *"What did you like most about the mathematical modeling part of the course?"* the students highlighted the two following key takeaways:

- **Clarity and practical application** were the most appreciated aspects of the course, with students repeatedly emphasizing the importance of clear explanations, useful examples, and the ability to apply theoretical concepts to real biological problems.
- **The use of MATLAB and Python** and the application of ODEs were specifically highlighted as valuable tools for learning and applying mathematical modeling in synthetic biology.

The results of this survey are being used to continuously refine the syllabus further, ensuring that it remains responsive to student needs and continues to evolve with advancements in the field of synthetic biology. In the GitHub repository https://github.com/sb2cl/SynBio_Modeling_Webinars readers can find the survey and use it to assess their own mathematical modeling teaching effectiveness.

## 4 Discussion

The integration of mathematical modeling into synthetic biology education, as facilitated by the webinar series and subsequent syllabus development, represents a significant advancement in the pedagogical approach to this interdisciplinary field. The success of the webinars underscores the potential of online learning platforms to deliver complex, technical content effectively, especially in situations where traditional, laboratory-based education is not feasible.

Survey results from students at both UPV and ESPE indicate a marked improvement in their understanding and confidence in applying mathematical models to synthetic biology problems. The majority of respondents reported that the webinars and course materials effectively bridged the gap between theoretical knowledge and practical application, particularly through the use of case studies and hands-on exercises.

However, the survey also highlighted areas for improvement. Some students indicated a desire for more interactive and hands-on components, particularly in the online format, to further enhance their learning experience. This feedback is invaluable as it points to the need for continued refinement of the educational content, with a focus on increasing student engagement and providing more opportunities for practical application.

The expansion of the webinar content into a formal syllabus at UPV and ESPE ensures that the impact of this educational initiative extends beyond the initial online sessions. The inclusion

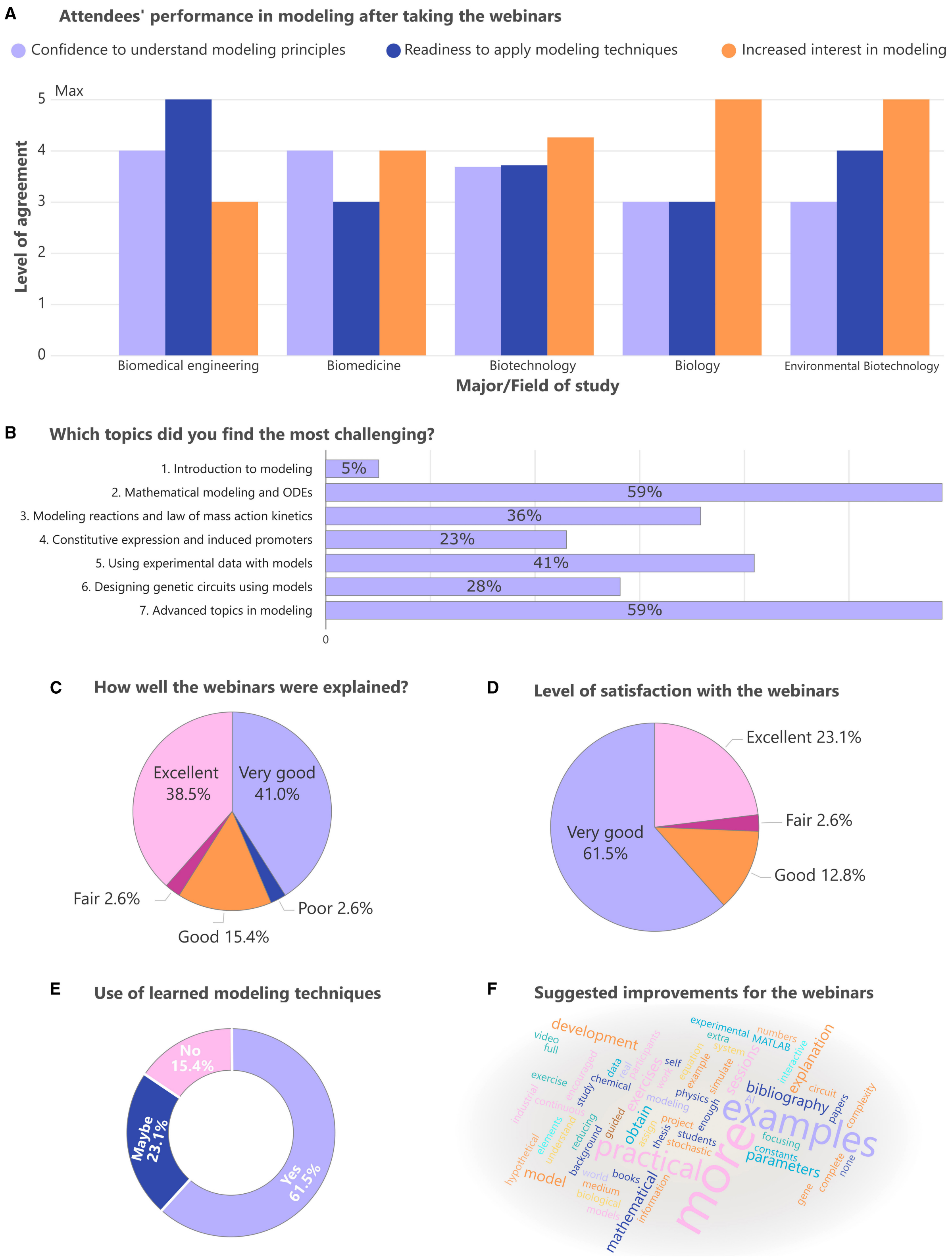


FIGURE 1
Survey results on the impact and effectiveness of the mathematical modeling webinars. **(A)** Attendees' performance in modeling after taking the webinars across different fields of study. **(B)** Distribution of responses regarding which topics were found to be the most challenging during the webinars. **(C)** Attendees' evaluation of how well the webinars were explained. **(D)** Overall satisfaction level with the webinars. **(E)** The percentage of participants who have applied the learned modeling techniques to other projects or coursework. **(F)** Word cloud representing the most common suggestions for improvements, with "more examples" being the most frequently mentioned improvement.

of mathematical modeling as a core component of the synthetic biology curriculum at these institutions reflects the growing recognition of its importance in the field. By providing students with a comprehensive understanding of how to design, simulate, and analyze biological systems through mathematical models, we are equipping the next generation of synthetic biologists with the tools they need to succeed in both academic and industrial settings.

In addition to technical knowledge, this initiative provided a unique opportunity for students to develop essential soft skills. By working in teams—whether in person or remotely—students honed their communication, problem-solving, and collaboration abilities. These skills are vital in synthetic biology, where projects often require cross-disciplinary teamwork and collective problem-solving to design functional biological systems. Moreover, by exposing students to real-world problems through practical assignments, the course helped them cultivate a researcher's mindset, encouraging critical thinking and a deep engagement with the subject matter.

Moreover, the success of this initiative highlights the broader applicability of online learning in STEM education, particularly for complex, interdisciplinary subjects like synthetic biology. The positive reception and significant engagement metrics from the webinars demonstrate that online platforms can effectively complement traditional education methods, providing accessible and flexible learning opportunities for students worldwide.

As synthetic biology grows in educational importance, initiatives like this one become increasingly relevant. While many biology and bioengineering programs include modules on molecular biology, few offer hands-on experiences in synthetic biology or computational modeling. This initiative demonstrates the value of integrating synthetic biology projects into standard educational programs, and highlights the potential for further development in the area of mathematical modeling. While this program successfully introduces students to essential concepts, additional support—such as labs, internships, or further computational coursework—could ensure even deeper engagement with synthetic biology. Thus, programs like this are a promising first step in promoting synthetic biology in education but should be expanded upon to fully meet the growing needs of the field.

In conclusion, the integration of mathematical modeling into synthetic biology education through webinars and structured courses represents a significant step forward in the field. The combination of theoretical instruction, practical exercises, and online accessibility has proven to be an effective approach in preparing students for the challenges of synthetic biology. As the field continues to evolve, it will be essential to build on these educational foundations, incorporating new technologies and methodologies to ensure that synthetic biology education remains at the forefront of scientific and technological innovation.

All in all, this initiative demonstrates the critical role that mathematical modeling can play in synthetic biology education. The program not only helped students grasp complex concepts but also provided them with the practical tools to apply this knowledge in real-world contexts. Going forward, integrating more computational and hands-on lab work into standard curricula will be essential to fully leverage the benefits of synthetic biology education. Moreover, the focus on team-based learning and problem-solving will prepare students for the interdisciplinary, collaborative nature of the field. Open challenges remain in how to scale such programs and ensure they are widely adopted across educational institutions, but this work provides a strong foundation for future growth.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

YB: Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Methodology, Supervision, Validation, Visualization. FF: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Project administration. AV: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project administration, Resources, Software, Writing – original draft, Writing – review & editing, Supervision.

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## Conflict of interest

The 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.

## Publisher's note

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