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Exploring mRNA vaccines: an immunology case-study approach that leverages team-based learning in an integrated intermediate-level biology course

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The American Association for the Advancement of Science (AAAS)'s call to action outlined a vision for the future of undergraduate biology education which included core concepts and inquiry-based skills to engage students in understanding the natural world. The report highlighted the need to connect the classroom to the real world to promote science literacy. Immunology is a field that connects AAAS-identified core concepts to the real world, however there has been a lack of emphasis on immunology education, contributing to low levels of immune literacy in the general public and subsequent vaccine hesitancy. The undergraduate course Genes, Molecules, and Cells (BIO211) at Hamilton College seeks to fill this gap by preparing students early in their undergraduate education with the necessary foundations in biochemistry, cell biology, molecular biology and genetics for studying immunology in the context of the SARS-CoV2 pandemic and subsequent mRNA vaccine development. Importantly, the course deviates from the traditional pathway of teaching the central dogma, beginning instead with translation and following the story of mRNA delivery to cells and production of the spike protein. The lecture includes traditional lecture-style teaching, combined with case studies and team-based learning to enhance student learning and engagement with the material. The lecture and its associated laboratory successfully address all six core competencies of the ImmunoSkills Guide. Pairing partners for a final poster presentation on debunking vaccine misinformation or a novel use of mRNA technology helps students make the connection between science and society while working collaboratively to communicate scientific concepts to a broad audience. After four semesters of this course, students consistently showed statistically significant improvement on the Molecular Biology Capstone Assessment. Students reported that iterative, low-stakes team questions were highly effective tools for learning, leading to high levels of self-reported participation and engagement, but were less enthusiastic about the benefits of the collaborative group format. On the end-of-semester poster project students reported high enthusiasm and effectiveness. Future goals of the course include more closely tying the relevance of laboratory modules to lecture case studies and improving the experience of team-based lecture questions.

KEYWORDS

immunology, cell biology, biochemistry, genetics, molecular biology, biology education, COVID-19, mRNA vaccines

1 Introduction

Immunology is an interdisciplinary scientific field crucial for understanding the human immune system, especially in the context of global health challenges such as pandemics, emerging infectious diseases, vaccine development, and innovative immunotherapies. Despite the increasing significance of immunology, systematic pedagogical approaches for teaching the subject have been limited, with a lack of scholarly literature addressing evidence-based methods for immunology curriculum design, instructional strategies, and assessment. Fewer pedagogical resources and instructional resources have been developed for undergraduate immunology educators (Bruns et al., 2019) compared to other fields such as genetics (Massingham et al., 2022), biochemistry (Bell et al., 2019) and cell biology (Tanner and Allen, 2002). Additionally, immunology at the undergraduate level is less developed than other fields in regards to a consensus of core concepts. Other disciplines such as genetics (Massingham et al., 2022), biochemistry (Bell et al., 2019), physiology (Michael and McFarland, 2011), microbiology (Paustian et al., 2017), and neuroscience (Kerchner et al., 2012) have defined core competencies and tools to assess student learning. Recent studies have sought to address this gap in immunology by surveying immunology educators on common topics and concepts as well as assessing the priority of these topics and skills (Bruns et al., 2021). An undergraduate immunology education taskforce has identified fundamental concepts in immunology that align with the American Association for the Advancement of Science (AAAS) report "Vision and Change in Undergraduate Biology Education: A Call to Action" and solicited feedback to achieve consensus on these concepts (Justement et al., 2020). Surveys, focus groups, and interviews have yielded the development of an ImmunoSkills Guide with an immunology-specific hierarchical learning framework with six core competencies and 20 associated illustrative skills and associated student learning outcomes (Pandey et al., 2024). The six core competencies include: (1) ability to apply the process of science, (2) ability to understand the relationship between science and society, (3) ability to communicate and collaborate with others, (4) ability to use quantitative reasoning, (5) ability to perform basic lab procedures, and (6) ability to explain and/or perform laboratory methodology to address an immunology-based research question (Pandey et al., 2024).

While immunology is a critical field for training future scientists as well as informed citizens, it is often taught as an advanced upper level course (Justement and Bruns, 2020). The curricular structure of most higher education in biology delays the introduction of immunology until later in the coursework, reducing the access of immunology-focused content for introductory-level students. Limited access to immunology education represents a missed opportunity to adequately prepare students for careers in healthcare, biomedical research, and public health policy. Additionally, this shortfall contributes significantly to low levels of immune literacy among the general public, limiting informed decision-making and heightening vulnerability to misinformation, particularly regarding vaccination and health policies (Mixter et al., 2023; Sanchez et al., 2024; Lorini et al., 2017; Castro-Sánchez et al., 2016). Despite this important need to teach immunology, much of its core content is predicated on student understanding of basic concepts in cell biology, biochemistry, molecular biology and genetics, thus its positioning later in curricular structures. Recognizing these educational hurdles, we have developed a new intermediate-level course, BIO211: Genes, Molecules, and Cells, designed to merge the need to teach immunology at an earlier stage in undergraduate education while providing students with a solid foundation in a broad range of molecular biology fields.

The BIO211 course leverages the context of the COVID-19 pandemic and subsequent mRNA vaccine development to provide students with an integrated understanding of fundamental biological concepts, serving as an introduction to molecular biology, cellular biology, biochemistry, and genetics, while exposing students to immunology at an early stage in their training. Hamilton College is a private four-year liberal arts institution located in Central New York. Enrollment for the 2024–2025 academic year was 2,046 students. Students enrolled in BIO211 are typically second-semester freshman and sophomores who have completed a pre-requisite introductory biology course (BIO100 Explorations in Biology). Each introductory biology lecture section is designed around its own unique theme resulting in differential emphases across subdisciplines of biology. Continuing with the theme-based approach, BIO211 provides all continuing students with a strong foundation in cellular and molecular biology in preparation for upper level courses. While the majority of enrollees are intended biology, neuroscience, or biochemistry/molecular biology majors, or pre-health students outside of these majors, this course is not restricted to any specific program of study.

Studies on STEM education have consistently emphasized the importance of using integrative and interdisciplinary approaches to improve student understanding of complex scientific concepts, highlighted in particular by the AAAS Vision and Change Report [National Research Council (NRC), 2012; Freeman et al., 2014; AAAS, 2011]. These studies underscore that interdisciplinary courses enhance cognitive integration, foster deeper conceptual learning, and encourage the development of critical thinking and analytical skills among students (Handelsman et al., 2004; Redish and Cooke, 2013; Hoskinson et al., 2017). BIO211 is built around a molecular story of mRNA vaccines; by following the mRNA vaccines, from their composition, to their mechanism of action within cells, the immune signaling response and larger social context of vaccination and immunity, students are able to navigate and integrate a wealth of biology topics and their interactions with society. Through the design of this course and its associated laboratory, we implemented all of the six core competencies outlined in the ImmunoSkills Guide, as well as multiple illustrative skills. Within the course, students read immunology primary literature articles focused on SARS-CoV2, use quantitative reasoning to interpret data, and learn and perform lab procedures relevant to immunology research. BIO211 culminates in a final public poster presentation where students collaboratively investigate and present on either future applications of lipid nanoparticle (LNP) or mRNA technology, or address a public misconception about vaccines. The course educational goals include fostering intellectual curiosity, analytical discernment, disciplinary practice, effective communication, and ethical citizenship. Through rigorous scientific inquiry, hands-on laboratory experience, and interdisciplinary discussions that utilize a team-based learning approach, students gain a holistic understanding of molecular biology and its profound implications for society. BIO211 thus represents a model for interdisciplinary curriculum development, enhancing scientific literacy and societal awareness among undergraduate students.

2 Pedagogical frameworks

2.1 BIO211: lecture structure, content and learning objectives

BIO211 employs a storytelling approach to introduce core concepts in molecular biology, cellular biology, biochemistry, and genetics (Figure 1), centered around the COVID-19 pandemic. As an intermediate-level course bridging introductory biology (BIO100 in our curriculum) and more advanced subjects, the first few weeks begin with a review of biomolecules and an introduction to the molecular mechanisms of protein translation. The synthesis of the major histocompatibility complex (MHC) molecules is used as an example to explain the secretory pathway and the roles of organelles involved in endomembrane homeostasis. Antigen presentation via MHC molecules introduces key topics such as cellular interactions, communication, and signal transduction, leading to in-depth exploration of transcriptional regulation, cellular movement, and energy production. The final quarter of the course focuses on DNA replication, mitosis and meiosis, and concludes with Mendelian and population genetics. There, we return to the question of why different human populations may be more susceptible to SARS-CoV-2 infection and explore the possible molecular mechanisms underlying this susceptibility, using data from primary research articles (Al-Youha et al., 2021; Wu et al., 2023). For a full list of content and core concepts (see Table 1). Description of the immunology-related case-studies associated with these core concepts are discussed further below in section 2.3.

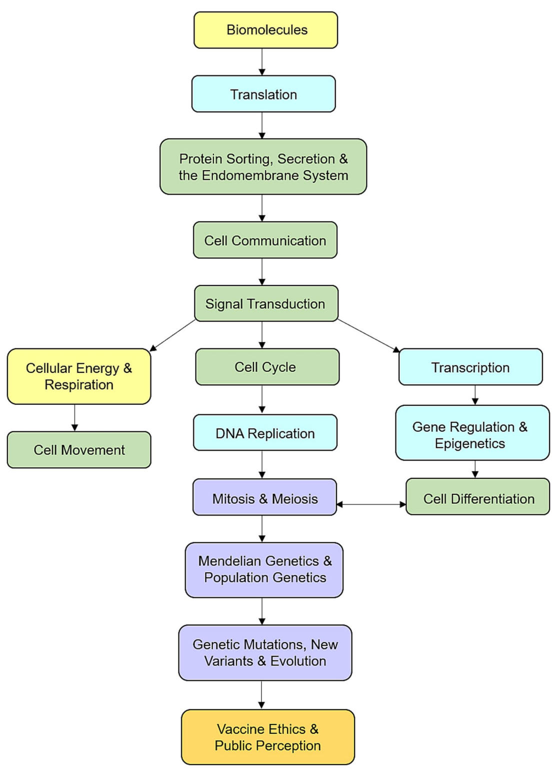

FIGURE 1
Flow chart of core concepts in BIO211: Genes, Molecules and Cells. Concepts in biochemistry are highlighted in yellow, cell biology in green, molecular biology in blue, genetics in purple, and ethics in orange.

One of the unique features of this course structure is the disruption of the traditional progression through the central dogma of molecular biology (Figure 1). The central dogma is the biological flow of information that begins with DNA, which is copied in replication, converted into RNA messages during transcription and then translated into protein. This linear description often obscures the complexity of gene regulation and genotype–phenotype relationships, limiting student comprehension of the process (Reinagel and Bray Speth, 2016). In the design of BIO211, we intentionally broke up the components and processes of the central dogma. We began with translation, following the story of mRNA delivery to cells and production of the spike protein. Students later returned to the central dogma to separately learn transcription in the context of gene regulation related to the immune response to spike proteins and replication in the context of dividing and differentiating blood cell types. Similar efforts to teach students the central dogma through concept maps that break each process into a discrete unit helped reveal student misconceptions (Briggs et al., 2016). One example of common observed misconception is the belief that replication must occur within a cell before transcription and translation; students mistakenly think that downstream processes cannot occur without being immediately preceded by the upstream event.

We found that students were often resistant to learning the central dogma in this reverse order as it countered their prior experiences in introductory biology course (BIO100) and high school (AP Biology, if taken), but ultimately pushed them to identify and correct their misconceptions when each process was taught in a novel order. Student resistance was based in misconception of temporal and causal relationships (for example, transcription must occur immediately before translation), and usage of the mRNA vaccine case study facilitated breaking these assumptions and overcoming resistance. With a concrete example of translation occurring without being immediately preceded by transcription, students were more willing and able to embrace the non-traditional learning approach, and ultimately the non-linearity of the central dogma. Our pre- and post-course Molecular Biology Capstone Assessment revealed the success of this approach, specifically by comparing performance questions covering Core Concepts #4 and #5 (as defined in Couch et al., 2015). These core concepts focus on the discrete processes of gene expression (#4 focused on transcription and #5 focused on translation). By evaluating the specific Assessment questions that target these concepts, we found that students increased their Concept #4 (transcription) scores by 8.6% and Concept #5 (translation) scores by 9.3%, both above the average improvement of 4.3% across all questions on the Assessment.

To help develop students' ability to comprehend scientific articles and interpret data, we also incorporated several review and primary research papers into our discussion sessions. These included a review of the principles of mRNA vaccines (Chaudhary et al., 2021), an article on the components of lipid nanoparticles used in mRNA vaccine delivery (Cross, 2021), studies on ACE2 expression (Bunyavanich et al., 2020; Silva et al., 2022), and literature related to COVID-19 screening. Finally, the discussion and debates on vaccination ethics and policies were guided by two review articles (Giubilini, 2020; Stuart, 2021). For a full listing of the readings and resources (see Table 1).

TABLE 1 Table of core concepts in BIO211 color-coded by discipline: biochemistry (yellow), molecular biology (blue), cell biology (green), genetics (purple), and ethics (orange).

Category	Core concept	Immunology case study	Resources and readings
Biochemistry	Biomolecules: nucleic acids, proteins, lipids, carbs	Lipid nanoparticle, mRNA vaccine composition	Cross (2021) and Stuart (2021)
Molecular biology	Translation	Spike protein translation	Chaudhary et al. (2021)
Cell biology	Endomembrane system	Spike protein trafficking	Chaudhary et al. (2021)
	Cell communication	Immune system: cytokines and MHCs	Buszko et al. (2021)
	Signal transduction	B and T cell signaling, antibody production	Dutcher et al. (2024) and Mandavilli (2023)
Biochemistry	Cellular energy and respiration	Glycolysis, glucose levels and COVID risk	Codo et al. (2020)
Cell biology	Cell movement	Macrophage and neutrophil movement	Fritz-Laylin et al. (2017)
Molecular biology	Transcription	ACE2 expression	Bunyavanich et al. (2020) and Silva et al. (2022)
	Gene Regulation	ACE2 regulation and aging	Bunyavanich et al. (2020) and Silva et al. (2022)
Cell biology	Cell differentiation	Blood and Immune cell lineage	Laurenti and Gottgens (2018)
	Cell cycle	Hematopoietic stem cell transplantation	PDQ Adult Treatment Editorial Board (2002)
Molecular biology	DNA Replication	Division of hematopoietic stem cells	Laurenti and Gottgens (2018)
Genetics	Mitosis and meiosis	Chromosome segregation activity	Hubbs et al. (2017)
	Mendelian and population genetics	ABO blood type and COVID risk	Almadhi et al. (2021), Al-Youha et al. (2021), and Wu et al. (2023)
	Mutation and evolution	SARS CoV2 mutation and new variants	Fan et al. (2022)
Ethics	Vaccination ethics	COVD-19 vaccine mandates	Giubilini (2020) and Stuart (2021)

Concepts are listed in chronological order of the course progression. Each core concept had an associated immunology case study related to mRNA vaccines, SARS-CoV2 infection, or health related to COVID-19 pandemic.

2.2 BIO211: lab competencies and learning objectives

The lab component of BIO211 roughly follows the progression of the lecture, with lab modules testing for biomolecules, exploring enzymes and factors that affect the rate of enzymatic reactions, bacterial transformation with the pGLO plasmid and subsequent isolation and quantitation of the Green Fluorescent Protein (GFP), testing for the SARS-CoV2 virus using both Enzyme-Linked Immunosorbent Assay (ELISA) and reverse transcription polymerase chain reaction (rtPCR) and genotyping for the PTC (phenylthiocarbamide) tasting allele followed by pedigree construction and Hardy–Weinberg analysis. Details on learning objectives, lab techniques, and analytical skills from each of the five modules are outlined in Table 2. The overarching learning objectives of the lab portion of the course are an understanding and application of experimental design, designing hypotheses and predicting experimental outcomes, collecting and interpreting data and analyzing experimental results. Basic lab techniques include serial dilutions and constructing and utilizing standard curves, which are used throughout the course. More advanced lab techniques, such as conventional and reverse transcription PCR, gel electrophoresis, restriction fragment length polymorphism (RFLP) analysis and ELISA are utilized later in the semester as student skills and knowledge expand. Data analysis skills include calculating descriptive statistics, performing T-tests and chi-squared tests, as well as graphing results. Allele and genotype frequencies are calculated using the Hardy–Weinberg equation and students construct a familial pedigree.

2.3 Case studies and core concepts

Case-based pedagogical approaches have been widely used in biology to help students understand the connection between biological concepts and real-world applications (Knight et al., 2008; Cleveland et al., 2017). Case studies have been shown to increase student motivation in group settings (Flynn and Klein, 2001) and increase their positive perception of the coursework (Murray-Nseula, 2011). In our BIO211 course, we sought to provide students with a large foundational base in the molecular biosciences with concepts in biochemistry, molecular biology, cell biology and genetics. The significant amount of content in this course could prove to be overwhelming for students, so we utilized a storytelling approach following the example of mRNA vaccines for SARS-CoV2. Within this immunology story framework, we were able to identify and use specific case studies and examples that connected to the core concepts. Table 1 outlines major core concepts covered in the course and their associated case study.

Throughout the course, students follow the story of mRNA vaccines, their mechanism of action through translation and trafficking, immune cell response, communication, movement and life cycle, and inheritance of blood type and associated viral

TABLE 2 Table of lab learning objectives and associated wet-lab techniques and analytical skills.

Module	Learning objectives	Lab techniques	Analytical skills
Module 1: Biomolecules	Test for proteins, simple sugars, starch, and lipids	Biuret test for proteins	Calculate and perform a serial dilution
	Apply tests for biomolecules to unknown samples	Benedict's test for reducing sugars	Construct and interpret a standard curve
	Design an experiment	Iodine test for starch	Differentiate qualitative from quantitative data
	Predict the results of biomolecule tests for various milk and milk products	Emulsion test for lipids	
	Test hypotheses	Sudan III test for lipids	
Module 2: Enzymes	Understand the function of enzymes	Measure the rate of an enzymatic reaction	Calculating descriptive statistics: mean, standard deviation, standard error
	Explore the variables that impact the activity of enzymes		Performing dilutions
	Predict the impact of changing environmental factors on the rate of reactions		Performing a T-test
	Identify independent versus dependent variables		Interpreting a p-value
			Constructing a bar graph of means with error bars
Module 3: pGLO transformation	Perform a bacterial transformation	Bacterial transformation	Quantify protein concentration
	Perform protein chromatography and subsequent quantitation	Inoculation	Calculate and perform a serial dilution
		Bradford assay	Construct and interpret a standard curve
		UV–Vis spectroscopy	
		Protein chromatography	
		Protein quantitation	
Module 4: COVID-19 screening	Describe rtPCR and its uses	rtPCR	Design primers using bioinformatic tools
	Describe a primer and understand its use	Gel electrophoresis	
	Differentiate rtPCR from conventional PCR	ELISA	
		Primer design	
Module 5: Phenylthiocarbamide (PTC) tasting	Perform DNA extraction and purification	Extract and purify DNA	Perform a chi-squared test
	Perform PCR	PCR	Calculate variables using the Hardy–Weinberg equation
	Perform restriction digest and subsequent gel electrophoresis	Perform a restriction digest	Design primers using bioinformatic tools
	Differentiate genotype from phenotype	Gel electrophoresis	Calculate the length of amplicons and restriction fragments using bioinformatic tools
	Differentiation allele from genotype frequencies.		
	Design a pedigree		

In the most recent semester (Spring 2025), the lab contained five total modules averaging 1–3 weeks, covering a total of 13 weeks over the course of the semester.

susceptibilities. Beginning with mRNA vaccine composition, students were able to learn nucleic acid structure, chemical and physiological properties of lipids, and appreciate the breakthroughs in ionizable lipids that helped lipid nanoparticle technology become safe and effective (Cross, 2021; Chaudhary et al., 2021). Pulling significantly from the Chaudhary et al. (2021) review of mRNA vaccines, particularly the pathway of spike protein translation, trafficking, antigen presentation, and stimulation of the immune system, students were able to connect concepts of translation, the endomembrane system and cell communication to the real-life application of this type of vaccination.

After learning about signal transduction through MHC receptors in B and T-cells, concepts split into three branches (Figure 1). The first branch followed cellular energy and respiration, which we linked to SARS-CoV2's known impacts on metabolism, followed by cellular movement taught using videos of macrophage navigating the bloodstream. The branch following transcription allowed students to explore the immune and inflammatory response genes and their regulation, including the specific case of NFkB and IKK gene regulation. The third branch followed the cellular life cycle through DNA replication and division, ultimately linking to the transcription branch by following the case of hematopoietic stem cells. Students continued through the case study of red blood cells with ABO blood type, learning Mendelian and population genetics and analyzing data from studies linking blood type and COVID severity (Al-Youha et al., 2021; Almadhi et al., 2021). Lastly, students learned the core concepts of mutation and evolution through the study of SARS-CoV2 mutation using new variant spreading through the online tool Our World in Data with variant data supplied by GISAID (Global Initiative on Sharing All Influenza Data) and figures by Fan et al. (2022) on the spread of the omicron variant. We concluded our semester with a final project tying together science and society, specifically focused on new vaccine technologies and vaccine myths (Giubilini, 2020; more specifics on the final project can be found in section 3.3). To facilitate the case study approach, we use published resources and readings outlined in Table 1. Students do not always read the entire primary literature article, but instead are asked to interpret a graph, dissect a figure, or explain and apply a major concept from the article both during lecture, with their teams (further discussed in section 2.4), and in their problem sets.

Throughout the four semesters of BIO211, instructors have noted student enthusiasm for the immunology-based case study approach. Students often comment on the real-world application and the personal connection to their own experiences with receiving mRNA vaccines, seeing vaccine hesitancy in their community, and experiencing SARS-CoV2 illness either in themselves or in friends and family members. As we discuss further in the Results section, students have reported that they found the case-study approach to be both effective and engaging, the connection to the core concepts was clear, and assessments show effectiveness of learning through this approach.

2.4 Team-based learning strategies

Team-based learning has demonstrated successes on student retention in STEM and gains in student learning (Metoyer et al., 2014) as well as content retention and classroom performance (Swanson et al., 2019). Team-based learning encourages students to take ownership and initiative of their learning, as well as creating a more engaging, inclusive and supportive learning environment (Hewitt et al., 2024). Studies have shown that team-based learning in inclusive settings improves student learning outcomes, knowledge retention and enhances understanding (Forslund Frykedal and Hammar Chiriac, 2017; Cagliesi and Ghanei, 2022; Fatmi et al., 2013). When designing BIO211, we sought to use a team-based approach in addition to the immunology case-study approach. The format of the classroom learning was largely lecture based as described in section 3.1, however a significant portion of class time was dedicated to team-based problem solving. These breakout sessions involved 1–3 team questions to be worked on in groups of 4–6 students. Students were assigned to these groups by the instructors, and group membership was switched every 2 weeks. With the 15 min of dedicated class time, the students were able to begin answering these questions, but completed the work outside of class time. These questions were due before the following class, and grading was based on completion rather than accuracy. The goal of frequent, low stakes assessments was to provide iterative attempts and quick feedback on student learning, but also build community within the class as well as create learning communities that students could leverage outside of class. Some examples of team questions are listed in Table 3. As described in the Results section, students thought the team-based questions were effective in their learning (8.4/10), but found the team-work less enjoyable (6.6/10). However, attempts to create a welcoming learning environment were effective as students scored the classroom environment as highly welcoming and supportive (9.1/10). Students also reported high enjoyment and effectiveness of the final project, which was a semester-long team-based project (Section 3.3), suggesting perhaps that students found longer-term connections with peers useful and enjoyable as compared to relatively short group work sessions within class time. We are considering implementation of a similar model with the team questions, placing students in groups that are maintained throughout the system to facilitate stronger relationships. An additional possibility is to give students choice in the make up of the teams.

3 Learning environment

3.1 Classroom learning environment

The BIO211 course debuted in the fall of 2023 and has been taught for four semesters (fall 2023, spring 2024, fall 2024, and spring 2025), enrolling a total of 159 students. Given that the course is designed to be a bridge course between introductory and upper-level biology courses, it primarily enrolls second semester freshmen and sophomores, with occasional juniors. The course was developed and is taught by a team of faculty, with a single lecture instructor and 1–2 lab instructors each semester. The faculty team rotates coverage of the lecture and lab depending on the semester. The course enrolls approximately 40 students per semester, but multiple sections have been offered allowing for higher enrollments.

The main format of the course is lecture-style, but every class session incorporates team learning and case study-based active learning. When taught as a 75 min class twice a week, the last 15 min of each class session is dedicated to in-class problem solving in teams. Instructors use the case study topic at the beginning of lecture to introduce the core concept, then continue the main lecture content using the case study as a story that is followed throughout the lecture to reinforce and highlight the application of the concept. In the final 15 min of the class, students break into their teams to work through a problem based on the lecture material. These team questions are often tied to the case study. For example, in the biochemistry section on biomolecules, students learn the case study of lipid nanoparticle composition (Table 1) and are asked to explain two reasons that the development of cationic ionizable lipids contributed to function and safety of LNP-based vaccines (Table 3).

Students are encouraged to discuss and complete each problem, and submit answers prior to the following class session. The quality of the answers - rather than their accuracy - is the sole grading criterion for this assignment. These problems and their solutions are discussed in the following lecture where students are able to ask questions or for clarification. To encourage teamwork, peer learning, and class participation, team rosters are randomly reassigned every 3–4 weeks. Grading in the lecture is based on three midterm exams, one final exam, several take-home assignments, and completeness of the team discussion questions. Lecture is worth 60% of the students' final grade in the course. Each class section has two TAs that hold office hours, study sections, and help with grading.

3.2 Laboratory learning environment

The lab portion of the course is generally taught to 20 students at a time, split into five lab groups of four students each. Each lab period is allotted 3 h, and labs have taken anywhere from 90 min to the full 3 h. The lab utilizes introductory concept lectures followed by hands-on lab experiments and techniques, and subsequent data collection and analysis. There are five lab modules that run between 1 and 3 weeks each (Table 2). Most weeks there is a pre-lab quiz, designed to ensure that students have read over the lab introduction materials and protocol for the week and have copied the protocol into their lab notebooks. Over the semester students write two lab reports, one on the "mystery milk" lab, where students use their knowledge of biomolecule tests to distinguish between four types of milk and milk products. The second lab report is based on the SARS-CoV2 testing module, comparing the results of an ELISA test to an rtPCR test for Covid-19 on three patients. Throughout the semester there are various other post-lab assignments on the remaining three modules, which are focused on data analysis, graphical representation of data, performing statistical tests and discussing results. Lab is 30% of the students' final grade in the course.

The first iterations of the lab had basic, one period long laboratory modules to focus on beginner lab skills and concepts for the first half of the semester. Feedback from some students indicated that these labs were redundant with either AP Biology courses, if previously taken, or the prerequisite introductory biology course (BIO 100) required before enrolling in BIO 211. Feedback on the lab was contradictory in the first two semesters, with a large proportion of the students finding it redundant, and/or not intellectually stimulating, while a similar proportion of students gave positive feedback stating that the lab was engaging and thought provoking, with many commenting on its strong connection to the lecture material. For this reason, only minor changes were made in the lab content between the first iteration in the fall of 2023 and the spring semester of 2024. In the fall of 2024, a larger bioinformatics component was added, connecting with both the SARS-CoV2 and PTC tasting modules. The major focus of the bioinformatics portion was on primer design for PCR and its importance in detecting newSARS-CoV2 variants while avoiding false negatives. Further changes were made in spring 2025 with the consolidation of introductory concepts and techniques into fewer weeks, and the introduction of a new module. The new module focused on transformation of the pGLO plasmid into *Escherichia coli* cells and quantification of Green Fluorescent Protein (GFP) expression. These changes and additions to the laboratory content were the result of student feedback and better synergies with introductory biology (BIO100) labs.

TABLE 3 Table of example team questions.

Discipline	Core concept	Question
Biochemistry	Biomolecules: lipids	What are two reasons cationic ionizable lipids are helpful lipid nanoparticle function? How does their function make them safe for usage in human therapies?
	Biomolecules: proteins	What specific amino acids do think make up the transmembrane anchor domain within the spike protein? What would happen if they were switched to arginines and glutamines?
Cell biology	Cell movement	We have discussed many types of cellular work this semester. Can you describe a specific example of each of the three types of work: mechanical, transport, and chemical work?
	Endomembrane system	Draw a diagram of the route that the mRNA vaccine translated spike protein/ antigen follows through the endomembrane system to reach the surface of the cell
Molecular biology	Transcription	Where is the gene (open reading frame) located in this DNA sequence? What amino acid sequence will it produce? CTACGCTACAGTTTAAGCCAGGATAGCAGACGGCATATAAATTACGG
	Gene regulation	Why do you think antibody production requires activation through both B cells' BCR and T-cells' TCR? What advantage or protection does it confer?
Genetics	Mendelian genetics	A person with blood type O and a person with what appears to be blood type O have a child with blood type A. They confirm that the child is genetically their offspring. How is this possible? Use the genotypes and diagrams below to help you hypothesize a reason for this inheritance pattern
	Population genetics	Using the allele frequency table provided in class, calculate the frequency of blood type A in the European population.
Ethics	Vaccination ethics	What are some social issues that arose during the COVID-19 pandemic related to vaccination? Use the four bioethical principles to explain why these are ethical issues and who they impact in society.

Questions are color-coded by discipline category and linked to their core concept.

3.3 Final project: posters on vaccine myths and vaccine technologies

Students work in pairs throughout the semester on an end-of-semester poster presentation. Students are paired based on interest in either: (1) addressing a public concern or myth about vaccines (or /82) novel applications of lipid nanoparticles (LNPs) or mRNA technology. For vaccine misinformation, students explain the misinformation, debunk it by citing primary literature and provide a science-based alternative, while discussing the social impacts of the misinformation (ex. Increases in vaccine hesitancy). If the topic chosen is a novel use of LNPs or mRNA they explain the illness or condition being treated, currently available treatment options, the application of the new technology and why it is a preferred alternative treatment. They conclude with the current status of the new treatment and potential social impacts. Early in the semester research librarians give presentations during the lab period focused on finding and properly citing peer-reviewed scientific literature, as well as on poster design, color, and imagery. The project culminates in a poster session at the end of the semester where each member of the pair separately presents their poster with a 3–5 min oral presentation. Their final grade on the poster project is 10% of their final grade in the course. As discussed below in Results, students found the final poster project to be highly effective in developing their science communication skills as well as deeply engaging on a topic they are passionate about. The poster session is open to the campus and the broader community, and students often invite their friends and faculty members from outside of scientific disciplines. The broad range of attendees provides students with the opportunity to explain scientific concepts in an accessible manner that is audience dependent.

4 Results/assessment

Our BIO211 course used two major pedagogical approaches: (1) case study-based learning using immunology examples such as mRNA vaccines and SARS-CoV2 and (2) team-based learning with frequent, low-stakes group problems. To assess the success of these approaches, we used both an assessment of student learning and a survey of student experiences and perceptions. The Molecular Biology Capstone Assessment is a multiple-true/false concept assessment developed to evaluate biology curricula focused on molecular biology (Couch et al., 2015). The assessment is intended for students completing their undergraduate studies, and thus serves as a reflection on their full undergraduate training. We implemented this assessment to help measure growth within a single semester, administering the assessment at the beginning and end of the semester. Couch et al. (2015) found that graduating biology students scored an average of 67% on the assessment. BIO211 students are freshmen and sophomores, thus scores were expected to be lower than those measured by Couch et al. (2015). Across all semesters, students consistently scored an average of 56.1% on the pre-course assessment, and 60.5% on the post-course assessment (Figure 2). In each of the semesters, students improved their scores by an average of 4.4%, and this improvement was statistically significant ($p < 0.05$ in each pre- and post-assessment comparison). These results demonstrate successful learning of core molecular concepts, and suggest that our methods of immunology case-study and team-based learning are effective.

In addition to assessment of student learning through the Molecular Biology Capstone Assessment, we surveyed students on their experiences in BIO211. A survey was developed with 18 questions and administered through Qualtrics (Appendix 1). Five questions were demographic and the remaining questions asked students about their perception of the immunology case studies, team questions, lab modules, and the final project. Students were also asked about their level of participation in the course and the degree to which they felt welcomed in the class. No identifying information was collected, all responses were anonymous, and the survey was found to be exempt from full IRB review (S25-024, Appendix 1). The survey was sent to all former BIO211 students, with a total of 49 respondents (28.5% response rate) Previous studies based on data from the National Survey of Student Engagement (NSSE) found that response rates of 20–25% for sample sizes <500 students provide confident estimates of the population (Fosnacht et al., 2017). The majority of respondents indicated they were interested in pursuing a career in STEM (92%), and identified as having extensive high school preparation for collegiate biology coursework (68%).

Students were asked a series of questions on a 1–10 scale to assess their experiences in the course, with 10 as the highest score. Students found the immunology case study effective with an average score of 8.3/10, and a similar score for reported enjoyment (Figure 3). Similarly, students found the final poster project to be both effective and enjoyable. Students reported an average of 7.9/10 for effectiveness of the final project in helping them develop science communication skills, and 8.0/10 for how engaging they found the project (Figure 3). Interestingly, there was a difference between student perceptions of the team questions. Students found these team questions to be effective (8.5/10), and yet scored them as less enjoyable (6.7/10). When asked about their level of participation in the class, including working with their teams and engaging in discussion, students reported that their participation level was high (8.3/10).

The survey also asked students about the clarity of the case studies and their connection to biological concepts (Figure 4). Students reported high clarity and connection of the case studies to lecture concepts (8.3/10), but reported a lower connection to lab skills (6.6/10). The lab modules changed substantially over the course of the four semesters, and we continue to iterate on the modules to strike a balance between providing foundational skills and teaching immunology-related wet lab skills. One of the major goals of the BIO211 course was to create a welcoming learning environment where students are comfortable asking questions in and out of class, discussing concepts with their peers, and receiving support from their instructors. Students reported an average score of 9.0/10 for how welcomed and supported they felt in the class.

5 Discussion

In this study, we present the design, implementation, and evaluation of an interdisciplinary intermediate-level biology course, BIO211: Genes, Molecules and Cells. This course integrates immunology case studies and team-based learning to enhance student engagement, conceptual understanding, and scientific literacy. Given

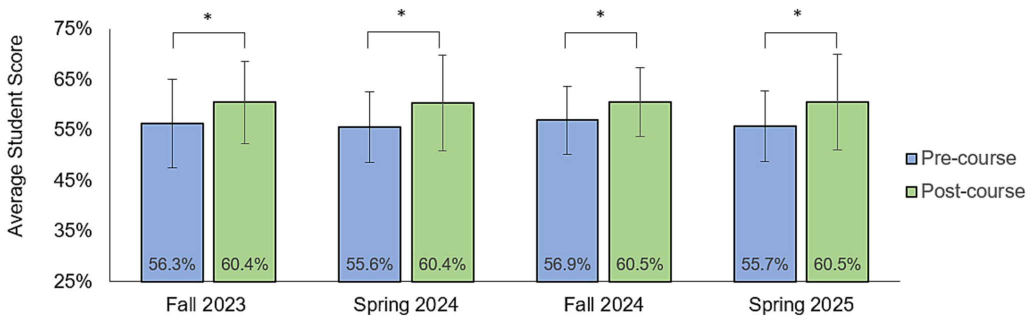

FIGURE 2
Average student scores on the Molecular Biology Capstone Assessment (Couch et al., 2015); each student was assessed before and after completion of BIO211. Post-course scores were statistically higher in each semester. *p <0.05.

the broad range of core concepts (Table 1), we sought to use a case study storytelling approach to motivate students with direct application to immunology. By embedding immunology examples within our framework and using narrative structure centered around mRNA vaccines, the course challenges traditional curricular sequences and expands access to immunology earlier in students' academic experiences. Our findings suggest that this method not only enhances student learning gains but also fosters engagement, scientific literacy, and communication skills. In their final project for the course, students were able to engage with societal questions of viruses, pandemics, and vaccinations, providing the opportunity to investigate vaccine technologies, vaccine hesitancy, and vaccine myths, and ultimately to communicate their findings with the broader public.

The case-study and team-based learning approaches have proven successful with a positive impact on student learning outcomes. Students demonstrated statistically significant gains on the Molecular Biology Capstone Assessment (Couch et al., 2015), despite being in earlier stages of their academic careers (Figure 2). These results align with previous research that shows even complex molecular concepts can be successfully introduced to beginning-level students when effectively scaffolded (Freeman et al., 2014; Offerdahl et al., 2017). Importantly, these gains occurred within a single semester of BIO211, highlighting the potential of integrated, case study-based learning to accelerate student conceptual development.

A major strength of BIO211 lies in its narrative, storytelling nature centered on mRNA vaccines that allows it to avoid the traditional linear teaching of certain concepts. By beginning with translation of the mRNA into spike protein, then later returning to transcription and replication (Figure 1 and Table 1), students are challenged to learn the material from a new perspective. Previous studies have shown that concept-mapping strategies in which students must identify and define the relationships between core concepts, such as the relationship and information flow between transcription and translation, yield significant increases in understanding of the central dogma and correction of misconceptions (Briggs et al., 2016). Similarly, asking students to define the relationships between two molecules, then integrating these individual relationships into a network that leads to systems-level thinking has yield improved understanding (Reinagel and Bray Speth, 2016). In our approach, students were similarly challenged to think of each molecule in isolation, then define the relationships between them using a non-traditional learning sequence. Non-linear and non-traditional learning sequences have been shown to support cognitive flexibility, deeper understand, and the ability to integrate new information (Spiro et al., 1991). Our results show student learning gains and engagement with this non-linear approach to the central dogma. Students reported that the case study approach was effective (Figure 3), and clearly connected to broader course concepts (Figure 4). Within the lab section of the course, students learned an extensive range of foundational molecular biology techniques, as well as specific application of immunology lab skills in Module 4: Testing for COVID-19 (Table 2). Students reported more difficulty connecting lab skills to the case studies (Figure 4), but it is important to note that the lab modules changed significantly over the semesters as we continue to iterate and improve the connection between lecture and lab. Ultimately our findings show that students found the case-study approach effective, clear, and enjoyable (Figures 3, 4) as well as statistically positive on their learning gains (Figure 2). Our results align with a growing body of research that shows students are highly motivated to engage with material that connects to socially relevant content and global challenges (Cleveland et al., 2017; Murray-Nseula, 2011; Siani et al., 2024).

Team-based learning also played a significant role in the course structure, including team questions and a final project conducted with team member(s). Students reported that iterative, low-stakes team questions were highly effective tools for learning (8.3/10, Figure 3) leading to high levels of self-reported participation and engagement (8.3/10, Figure 4), although they were less enthusiastic about the benefits of the collaborative group format (6.7/10). This pattern mirrors previous findings that while team-based learning improves learning outcomes, it can also challenge students' comfort with group dynamics (Fatmi et al., 2013; Forslund Frykedal and Hammar Chiriac, 2017). Interestingly, while BIO211 students reported higher enthusiasm for the final project (Figure 3), which involved a longer and more significant time investment with partner pairs. It is possible that longer-term projects give students the opportunity to form meaningful and impactful relationships. The final project was also successful in reinforcing the societal relevance of biology and immunology specifically as students publicly presented posters on vaccine technologies and misinformation. Students valued this opportunity to investigate a topic of their choosing and communicate their findings to a public audience, which they reported as effective in their science literacy and communication skills and has been proven in scientific training (Figure 3; Brownell et al., 2013). The final project also gave students the opportunity to explore novel

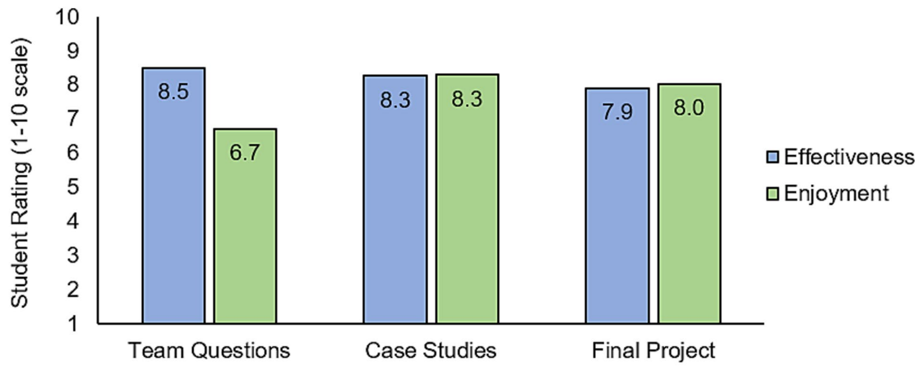

FIGURE 3
Average scores on survey questions sent to former BIO211 students. Questions asked on a 1–10 scale with 10 being the highest for effectiveness (blue) or enjoyment (green) of the team questions, case studies, and final project.

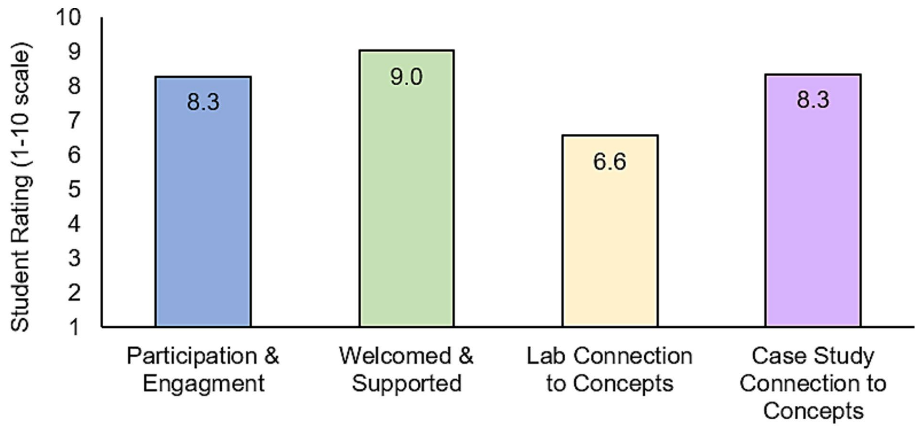

FIGURE 4
Average scores on survey questions sent to former BIO211 students. Questions asked on a 1–10 scale with 10 being the highest score. Students were asked to report their level of participation and engagement in the course (blue), the degree to which they felt welcomed and supported in the class (green), the clarity of the connection between lab and the course concepts (yellow), and the clarity of the connection between the case studies and the course concepts (purple).

applications of both lipid nanoparticle (LNP) technology and mRNA vaccines following their use to end the SARS-Cov2 pandemic. A plethora of mRNA vaccines have been developed, including many to treat various cancers, following the Covid pandemic (Chandra et al., 2024). In future iterations of the course these new vaccines present a potential focus for instruction in both lab and lecture.

The BIO211 course successfully aligned with recommendations laid out in the AAAS Vision and Change report on undergraduate science education as well as covering all six core competencies outlined in the ImmunoSkills Guide (Pandey et al., 2024). Both the AAAS report and the ImmunoSkills Guide emphasized the importance of the process of science and inquiry-based learning, science literacy and communication, quantitative reasoning, collaboration, and societal engagement. Through the case-study and team-based learning approaches, as well as the lab associated inquiry-based learning and investigative final project, BIO211 effectively teaches these competencies. Our outcomes demonstrate the feasibility and effectiveness of introducing immunology at the intermediate undergraduate level. This model supports both the learning of core biological concepts (Table 1). Future directions for the BIO211 course include enhancing the connection and clarity between lab modules and lecture case studies, improving the experience of group-based team questions, and exploring additional immunology case studies involving COVID-19 and mRNA vaccines that intersect with core concepts and societal issues. The course is also highly adaptable, and the storyline of the course could be easily shifted to another virus to both avoid COVID fatigue and highlight a newly emerging disease. The overall structure of the course could remain constant with updates to the case studies and team questions. BIO211 is an innovative model with quantitative results supporting its success; this course model offers a structural road map for other instructors seeking to reimagine their undergraduate immunology education.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Institutional Review Board at Hamilton College. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

NN: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. W-JC: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. RD: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. NM: Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. IB: Conceptualization, Writing – review & editing, Project administration, Supervision. NR: Conceptualization, Project administration, Supervision, Writing – review & editing, Funding acquisition, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft.

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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.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1639899/full#supplementary-material

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