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Strengthening immunology literacy: an adaptable curricular framework for enhancing undergraduate immunology education

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The rapidly expanding knowledge base in immunology and its increasing significance in multiple research areas and healthcare underscore the need for more comprehensive undergraduate curricula that allow students to engage deeply with immunology-based content. A robust immunology curriculum will provide undergraduate students a solid foundation for successful careers in research and healthcare. Unfortunately, there are few undergraduate programs in the United States that focus on core Immunology principles. This translates to deficits in Immunology education for medical students, graduate students, career scientists, and healthcare professionals. The Immunology and Medical Microbiology (IMMB) Bachelor of Science program at West Virginia University offers undergraduate students a comprehensive education in immunology and associated disorders. In pursuit of this degree, undergraduate students are required to take at least two laboratory-based and three lecture-based immunology courses. Although there is a need to enhance Immunology education and literacy, we recognize that doing this presents challenges in most undergraduate institutions and curricula. Therefore, we wanted to identify the most salient immunology topics from our three lecture-based immunology courses – Principles of Immunobiology, Cellular Immunobiology, and Molecular Immunobiology — that are most useful for professionals in both the research and healthcare sectors. Based on survey responses from IMMB alumni and current IMMB seniors, we provide a curricular framework that can be highly adaptable and serve as a model for institutions looking to enhance immunology education within their respective degree programs.

KEYWORDS

immunology, undergraduate, curriculum, immune literacy, education

1 Introduction

Immunology enhances our understanding of cancer, metabolic disorders, neurodegenerative diseases, and pathogenic infections. In order to effectively communicate with different populations about how immune dysfunction can lead to chronic conditions, foundational knowledge of immune function is essential.

Although there is evidence of inducing immunity to smallpox dating back to the 1500s (Needham, 1974; World Health Organization, 2025), the first documented modern innovation in immunology was in 1845 when Elias Metchnikoff made the groundbreaking discovery of phagocytic cells (Kaufmann, 2019), which catalyzed rapid advancements in the field. In 1913, The American Association of Immunologists (AAI) was founded, and Immunology was

formally recognized as a distinct medical specialty (American Association of Immunologists, 2025a). Subsequently, immunology advanced so quickly that researchers struggled to keep pace with its developments. In 1996, AAI established the first intensive short course in immunology at Lake Forest College (American Association of Immunologists, 2025b). AAI currently offers both introductory and advanced immunology courses annually, addressing the critical need to educate practicing scientists and medical professionals on emerging discoveries, including the rapid development of immunology-based therapies (Chatanaka et al., 2022). For many participants, these AAI courses are often the first formal instruction dedicated solely to immunology in which they have had the opportunity to participate.

Immunology curricula at the undergraduate level has failed to keep pace with the rapid progression of the field, leading to insufficient foundational immunology training at the professional level. A 2019 analysis of undergraduate programs revealed that only 10 institutions in the United States offered a dedicated immunology major, with just three requiring more than three immunology courses (Bruns et al., 2019). Many undergraduate curricula only include immunology topics as part of microbiology, physiology, or introductory biology courses. Further, there is variable consensus on which topics to include beyond fundamental concepts when immunology is offered as a stand-alone course. In 2021, a survey of instructors who have taught an undergraduate immunology course suggested general agreement on the major topics to prioritize, which included adaptive and innate immunity, host-pathogen interactions, and molecular mechanisms of immunological responses. However, there was significant variability on which subtopics and emerging areas to include (Bruns et al., 2021).

Inadequate immunology education can result in decreased immune literacy among biomedical scientists and healthcare providers, which can then negatively impact the health literacy of their respective patient populations. Immune literacy, defined by Mixter et al. as "an individual's ability to hear, learn, read, write, explain and discuss immunological content with diverse audiences," empowers healthcare providers and biomedical scientists to better communicate with their patient population about how certain diseases can be managed by immunotherapies, vaccinations, or nutritional choices (Mixter et al., 2023). Deficiencies in undergraduate immunology education can lead to underprepared medical students as well (Bansal, 1997). Medical school curricula require their students to master the dynamic nature of immunology, including the diverse cell types, complex signaling networks, and finely regulated responses encompassed within the mammalian immune system. Immunology knowledge deficiencies are exemplified by a 2019 study where a clinician stated, "of all the science topics covered in medical school, immunology was one of the hardest to wrap my head around" (Haidaris and Frelinger, 2019). This is particularly concerning given the fact that 6–11% of the questions on the United States Medical Licensing Examination Step 1 pertain to immunology (Reynolds et al., 2022).

A comprehensive understanding of immunology requires knowledge across multiple scientific disciplines including anatomy, cellular and molecular biology, microbiology, chemistry, and biochemistry. Additionally, immunology introduces unique concepts—such as antigen processing and presentation, antigen-specific B and T cell responses, immunological tolerance, transplant rejection, and immunological memory—that are not typically covered in other bioscience courses. Thus, while an immunology-focused curriculum naturally integrates a wide range of scientific fields, a biology-based curriculum that excludes immunology leaves a significant gap in a biomedical education.

The rapidly expanding knowledge base in immunology coupled with the limited number of immunology-focused undergraduate programs underscore the need for curricula that encourage students to engage more deeply with immunology-based content. An undergraduate curriculum enriched with immunology will not only equip students for success in immunology-focused research but also provide a robust educational foundation in the broader biomedical sciences and healthcare fields, thereby improving immune and health-literacy.

The West Virginia University Immunology and Medical Microbiology (IMMB) Bachelor of Science Degree was created in 2014 to prepare students for careers in biomedical research, healthcare and biotechnology. Students are admitted to the IMMB program as first-time-freshman or transferees and are required to complete biology and chemistry courses that are considered standard for admission into medical school or graduate biomedical sciences programs (Table 1). Throughout the program, IMMB students complete three lecture-based courses (*Principles of Immunobiology*, *Cellular Immunobiology*, and *Molecular Immunobiology*) and three lab-focused courses (*Immunology Colloquium I*, *Immunology Colloquium II*, and *Molecular Immunobiology Lab*), all of which emphasize the coordination of the immune system to facilitate detection and elimination of pathogens, tumor cells, and transplanted cells (Table 1). In December 2023, the *Immunology Learning Framework*, created in response to a 2010 AAAS Vision and Change report on undergraduate science education (Porter et al., 2021), identified five key concepts and six key competencies to help focus immunology education. Despite being created several years prior to the *Immunology Learning Framework*, our curriculum maps to each of the key concepts, which underscores the relevance of our tailored courses (Table 1).

Students begin taking IMMB specific courses as early as their freshman year (i.e., *Microbiology Colloquium I*), and they begin their immunology-specific course progression their sophomore year and continue through to their senior year. The lecture-based courses all have an oral presentation component and are designed to complement the laboratory-focused colloquia courses, which emphasize common immunology laboratory techniques (e.g., tissue culture, ELISAs, FACS, etc.) to investigate clinically relevant questions pertaining to immunopathology or immunodeficiencies. *Molecular Immunobiology Lab* teaches students to answer questions about the underlying molecular mechanisms for immunological signal transduction events using western-blots. This comprehensive immunology curriculum is further strengthened by complimentary microbiology coursework (Table 1) where students learn how disease-causing pathogens evade host immune response, potentially leading to chronic pathologies. Every IMMB student is required to present their colloquia projects at our departmental undergraduate poster symposia. Their poster presentations are evaluated by graduate students and research faculty, providing a valuable opportunity for students to hone their scientific communication skills. In addition, many IMMB students participate in scientific outreach events including the West Virginia Undergraduate Research Day at the Capitol, career days at local elementary schools, or

TABLE 1 Immunology and Medical Microbiology Bachelor of Science curriculum summary.

Subject	Course	Relevant topics covered	Year taken
Core Immunology Courses*	Immunology Colloquium I	• Tissue Culture • ELISAs • Fluorescent Microscopy • Investigate how cortisol affects salivary IgA and IL-18	2
	Principles of Immunobiology 1.1;1.3; 2.1; 2.3	• Innate and Adaptive Immunity • Complement System • Hematopoiesis • Lymphoreticular System • Primary and Secondary Lymphoid organs and tissues • Lymphocyte maturation • Innate recognition of pathogens • Phagocytic degradation • Extravasation mechanisms • Antigen processing and presentation • T-cell activation • T-cell subset polarization and effector functions • Thymus-dependent and -independent B-cell activation • Immunoglobulin structure and isotypes • Immunization and immunologic memory	2
	Immunology Colloquium II	• Tissue Culture • ELISAs • FACS Analysis • Investigate cellular profiles of immunodeficient mouse models	3
	Cellular Immunobiology 1.2; 2.2; 2.3; 3.2; 3.3; 5.1	• Immunodeficiencies • Hypersensitivities • Tolerance and autoimmunity • Transplantation immunology • Tumor immunology • Hematopoietic cancers	3
	Molecular Immunobiology 3.1	• Signal transduction and cellular phenotype changes in immunological events • First and Second messengers • Post-translational modifications (i.e., ubiquitination and phosphorylation) • Immunologically relevant receptor families • Molecular mechanisms of signaling throughout the phagocytic process • Epigenetic and post-transcriptional regulation • Signal transduction pathways leading to nuclear responses through relevant receptors (i.e., T-cell receptor, B-cell receptor, pattern recognition receptors, IL-1 receptor, Interferon receptor, and the TNF receptor family)	4
	Molecular Immunobiology Lab	• Tissue Culture • Western Blots • Fluorescent Microscopy • Investigate the expression and localization of signaling molecules important for immune regulation and function	4
Core Microbiology Courses*	Microbiology Colloquium I	Laboratory or colloquium courses complement the immunology curriculum by employing different microbiology techniques (i.e., staining, biochemical, and molecular assays) to investigate how different microbial components can impact the host. Content courses focus on the mechanisms employed by disease-causing microbes to establish infection and evade the host immune response.	1
	Medical Microbiology		2
	Medical Microbiology Lab		2
	Microbial Genetics		3
	Bacterial Pathogenesis		3
	Bacterial Pathogenesis Lab		3
	Medical Virology		4

(Continued)

TABLE 1 (Continued)

Subject	Course	Relevant topics covered	Year taken
Elective Courses	Parasitology	Content courses focus on the mechanisms employed by disease-causing microbes to establish infection and evade the host immune response.	3–4
	Medical Mycology		3–4
	Vaccinology		3–4
	Zoonotic Diseases		3–4

*Courses show the Immunology (top) or microbiology (middle) focused curriculum that is required by every WVU-IMMB student. IMMB students are also required to complete general biology I & II, general chemistry I & II, organic chemistry I, biochemistry, calculus, statistics and other major specific courses including elective courses (bottom) and senior capstone among others. Lab-focused courses are shaded grey and lecture Immunology courses are white; numbers listed under the lecture courses indicate to which key concepts from the Immunology Learning Framework these courses are mapped. 1.1: The immune system is an interconnected and coordinated network of macromolecules, cells, tissues, and/or organs within an organism; 1.2: Cellular and molecular processes maintain homeostasis of the immune system, and loss of homeostasis may result in a variety of immune-mediated disorders; 1.3: Immunological memory plays a critical role in protective immunity; 2.1: Immune responses are influenced by the presence, location and organization of lymphoid organs/tissues within an organism; 2.2: Immune cell function is characterized by the presence of macromolecular features; 2.3: Macromolecular interactions influence the outcome of an immune response; 3.1: Antigen recognition and associated cellular signaling result in differential gene expression, which shapes the organism's targeted immune response; 3.2: During development, immune cells differentiate to acquire characteristic phenotypes; 3.3: Gene expression and regulation influence the recognition of diverse antigens by the immune system; 5.1: Immune defenses vary based on organismal complexity. Although none of our Immunology lecture courses specifically mapped to 4.1: Immune system activation is an energy-intensive process that can influence and can be influenced by other metabolic demands (e.g., stress, malnutrition, reproduction, circadian rhythm disruption, exercise etc.), this is covered by our human biochemistry course, which is required by all IMMB students.

discussing immunology and microbiology at their former high schools. Nearly all IMMB seniors performed some kind of community outreach through one of the aforementioned mechanisms.

The IMMB curriculum's emphasis on scientific communication, students' active involvement in outreach, and the fact that 82% of the 162 alumni have pursued careers related to healthcare or biomedical science make this population well-suited to investigate how undergraduate immunology education impacts communication with scientific and lay audiences. Through email and social media campaigns, we surveyed IMMB seniors and alumni to identify which immunology courses and topics most significantly impacted their ability to communicate with scientific and lay audiences (Supplementary Data Sheet 1). We received responses from 20 graduating seniors and 17 alumni in various healthcare or biomedical sciences-related careers. The survey was approved by the WVU Institutional Review Board (2408023534). Details regarding respondent demographics, participant recruitment (Supplementary Data Sheet 2), and data analysis can be found in the (Supplementary Data Sheet 3).

The results of this survey will help other undergraduate programs prioritize which immunology topics to incorporate into their curriculum. Our goal is to provide an adaptable immunology curricular framework that focuses on enhancing the ability of undergraduate students to communicate complex immunology concepts, thereby better preparing them for their future healthcare and/or biomedical professions.

2 Discussion

2.1 Immunology discussions with scientific and lay audiences — most valuable courses

Respondents agreed on the usefulness of the Immunology lecture courses, ranking them from most to least useful as follows: *Principles of Immunobiology*, *Cellular Immunobiology*, and *Molecular Immunobiology*. *Principles of Immunobiology* is taken by IMMB students during the spring semester of their sophomore year and provides comprehensive foundational knowledge across the scope of the immune system by building off content mastered in general biology, general chemistry, and microbiology; this course lays the groundwork to expand into more complex topics in *Cellular Immunobiology* and *Molecular Immunobiology*. Seniors and alumni both ranked *Principles of Immunobiology* as the course that best prepared them to discuss immunology topics with lay audiences (Figure 1, top, bold block), while *Cellular Immunobiology* was identified as more effective in preparing them for discussions within scientific audiences. (Figure 1, bottom, bold block). Several alumni indicated that the more introductory concepts presented in *Principles of Immunobiology* best prepared them for their respective healthcare careers that involve frequent patient interaction. One Physician Assistant alumnus noted, "*Topics in (Principles of Immunobiology) are easy for patients and laypersons to understand, as opposed to cell signaling.*" Another alumnus highlighted the importance of understanding subjects such as allergies and autoimmune diseases for effectively engaging with lay audiences in their careers. Additionally, one senior noted, "*Principles of Immunobiology is very basic and provides a strong background for understanding more in-depth immunology, which helps when explaining the basics to lay audiences.*"

Individuals identified content in *Cellular Immunobiology* to be important for both progressing through their professional studies and informing lay audiences. One 3rd-year PhD student stated that "*Principles of Immunobiology taught us the basics of immune cells and their interactions, which others may get at the undergraduate level, however then applying that in a bigger picture in the Cellular Immunobiology course to understand how the immune response works in allergy, autoimmune diseases, etc. was beneficial to learning the impact of the immune response on our daily lives. These two courses helped me be able to understand immunology on a deeper level and also be able to communicate better with lay audiences.*"

Molecular Immunobiology ranked last in preparing current seniors and alumni for immunology discussions with lay audiences (Figure 1, top). This suggests that although topics presented in *Molecular Immunobiology* are important, they may be seen as less significant in preparing undergraduate students for careers that involve frequent patient interaction. The depth of immunology content provided in *Molecular Immunobiology* is likely more akin to what students would study during graduate careers in immunology. Along these lines, alumni in biomedical research-focused careers found *Molecular Immunobiology* to be the most beneficial in providing a strong foundation for graduate-level studies. One PhD alumnus stated, "*Learning about molecular immunobiology has really helped me in my graduate-level immunology courses since signaling pathways are crucial in immunology and cellular function.*" Seniors found that *Molecular Immunobiology* provided a strong foundation for understanding

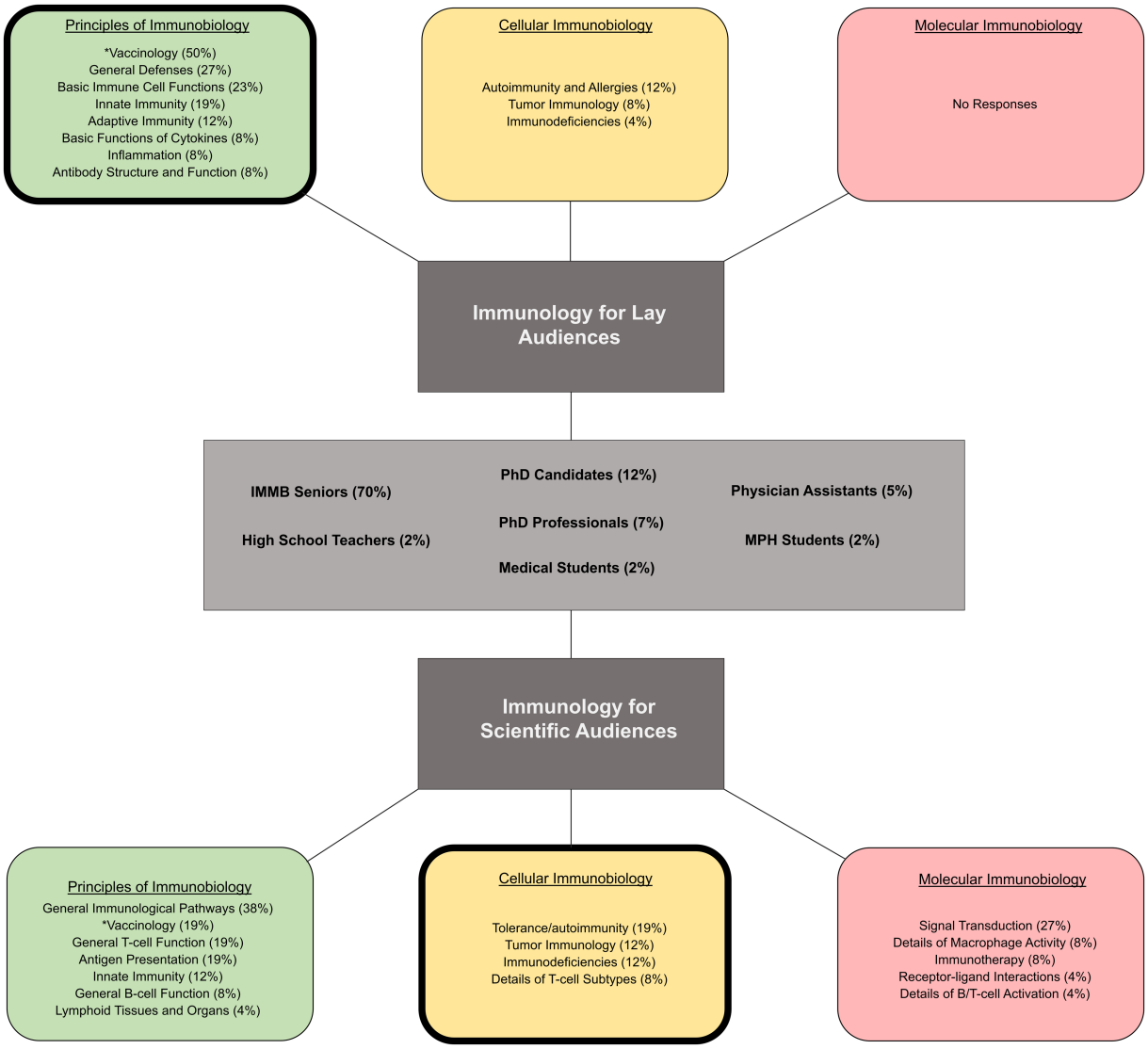

FIGURE 1
Immunology curriculum for communication with scientific and lay audiences: A survey administered to graduating seniors and alumni of the West Virginia University Immunology and Medical Microbiology Bachelor of Science Program. The light grey box in the middle displays career demographics; percentages were calculated based on the total number of respondents. Relevant immunology topics were identified from participant responses and are categorized (1) based on the courses in which they were most thoroughly discussed and (2) whether they were deemed important for communication with either lay audiences or scientific audiences. Percentages listed next to each topic represent the proportion of respondents who indicated its importance for discussions with respective audiences. Blocks that are bolded indicate the courses that current seniors most frequently mentioned when asked about which course best prepared them for respective scientific or lay discussions. Topics presented in Principles of Immunobiology are shown in green, topics presented in cellular immunobiology are shown in yellow, and topics important for molecular immunobiology are shown in red. A total of 26 respondents completed these questionnaire items. *Vaccinology is covered in our 'Principles of Immunobiology' course; however, an undetermined number of survey respondents also completed the elective course 'Vaccinology,' which was not included in our analysis of the three required courses shown in the figure.

immunomodulatory drug targets and the underlying mechanisms of immunotherapies. As one senior described, *"Molecular Immunobiology allowed me to understand the specifics of the complex mechanisms being explored in most labs today."*

Interestingly, current IMMB seniors found *Cellular Immunobiology* to be the most useful for preparing them for communication with scientific audiences, followed by *Molecular Immunobiology* and lastly, *Principles of Immunobiology*. This result is unsurprising, as *Cellular Immunobiology* delves deeper than a typical introductory course and is more closely aligned with clinical immunology, particularly in its focus on disorders that are central to current research and drug development. As one senior noted, *"I feel most comfortable discussing the concepts that we learned in the Cellular Immunobiology course, specifically the more medical aspects of immunology."*

2.2 Immunology discussions with scientific and lay audiences — most valuable topics

For both scientific and lay audiences, respondents found vaccinology to be the most important topic (Figure 1, top and bottom). One senior reflected, *"I now understand what vaccines are actually*

composed of and how those components are not only safe but effective," demonstrating this student's confidence in communicating vaccine efficacy and safety. This highlights students' recognition of the need to deepen their immune literacy to better inform non-scientific audiences, especially amid rapid advances in vaccinology and persistent public misconceptions. While we discuss vaccinology in *Principles of Immunobiology*, we also offer *Vaccinology* as an elective course (Table 1). This is one of our most popular electives and a majority of IMMB students choose to take this course in addition to the required curriculum. In *Vaccinology*, students analyze vaccine science from a multi-faceted approach including history, discovery and design, pediatric immunology, adjuvants, delivery technology, efficacy, manufacturing, public health implications, misconceptions, and scientific validation. Three seniors and one alumnus independently highlighted the course's value in enhancing their ability to communicate effectively with both scientific and lay audiences. One senior shared, "*I think that* Cellular Immunology *and* Vaccinology *were the most useful for discussing immunology with lay audiences because they focus on topics people care about, such as diseases and vaccines.*" Another alumnus reflected, "*The Vaccinology course has helped me better understand the research projects of some of my graduate school classmates and enhanced my ability to communicate with lay audiences. This course was critical in connecting concepts from other immunology and microbiology courses, allowing me to see the bigger picture while also recognizing the importance of well-designed (vaccinology) research studies.*"

General defenses and basic immune cell functions followed vaccinology in significance in immunology discussions with lay audiences. One first year postdoctoral researcher stated that "*the introduction to interactions between cell types was the most memorable that I have since referred back to and I still reference notes on MHC pathways from this class.*" Additional topics important for communicating immunology with lay audiences included innate immunity, adaptive immunity, autoimmunity and allergies, basic functions of cytokines, inflammation, antibody structure and function, tumor immunology and immunodeficiencies (Figure 1, top).

Many respondents identified autoimmunity and immunodeficiencies from *Cellular Immunobiology* as being important in preparation for both scientific and lay audience discussion. Comprehension of these two topics was viewed as important for clinical management of disease and for success in biomedical research for IMMB alumni pursuing PhDs in relevant fields. Respondents also found T-cell function and differentiation, antigen presentation, cellular function, and signal transduction to be important in communicating with scientific audiences. While introduced in *Principles of Immunobiology*, T-cell function and differentiation is further explored in *Cellular Immunobiology* and *Molecular Immunobiology*, where it is expanded and applied to clinical and research contexts. This topic plays a critical role in understanding tolerance, immune dysfunction, tumor immunology, autoimmunity, and allergy—areas central to ongoing research and therapeutic development, with broad implications for both basic science and clinical practice.

Interestingly, none of the topics from *Molecular Immunobiology* were identified by respondents as important for discussing immunology with lay audiences. This course introduces key immune signal transduction pathways and investigates how they can be targeted by emerging therapeutics. Alumni praised the course's in-depth coverage of these pathways and their therapeutic intervention, noting that it provides a strong foundation for understanding and discussing novel treatments. One alumnus, now a healthcare provider, specifically highlighted how the course content offered valuable context for understanding therapies such as CAR T-cell therapy and TNF pathway inhibitors. While the material in *Molecular Immunobiology* appears to be more relevant for professional discussions about novel immunotherapies, content from *Principles of Immunobiology* and *Cellular Immunobiology* are more effective in helping professionals communicate these complex treatments to their patient populations.

3 Conclusion

Overall, our curriculum provides a comprehensive educational framework in Immunology. Beginning their sophomore year, students are introduced to fundamental concepts and terminology through *Principles of Immunobiology*. Students then learn how to apply these foundational concepts to clinical manifestations in *Cellular Immunobiology.* Lastly, the curriculum culminates in *Molecular Immunobiology,* which focuses on detailed molecular mechanisms and signal transduction pathways essential to immune responses, which helps students understand how novel immune therapies can be employed. This structured progression equips students with a strong foundation, preparing them for entry-level laboratory positions and further academic pursuits, whether in research-focused graduate education or professional programs in healthcare and public health. When asked how well the sequence of courses prepared them for graduate school or professional careers, all alumni respondents provided favorable feedback, including the following: "*Very effective. The classes built on one another well and allowed for the mastery of lower-level information before adding more complicated topics.*"

Foundational topics—such as immune cell functions, cellular interactions, antibody structure, and antigen presentation—introduced in *Principles of Immunobiology* were consistently valued for building immune literacy and supporting effective communication with non-scientific audiences, particularly in healthcare settings. In contrast, more advanced topics—such as T-cell function and differentiation, immunodeficiencies, autoimmunity, and signal transduction—covered in *Cellular Immunobiology* and *Molecular Immunobiology* were considered essential for engaging with scientific audiences and preparing for careers in research and clinical immunology. Vaccinology emerged as a cross-cutting topic, underscoring its relevance across courses and its role in connecting scientific understanding with public engagement. Undergraduate programs that wish to enhance immunology communication among scientific and lay audiences should prioritize these topics as they were regularly identified as the most beneficial by our targeted population. We further recommend including these topics even when only a single, stand-alone immunology course can be offered.

It is important to note the limitations of our survey, which focused solely on identifying which lecture-based immunology topics were considered most important for communicating with scientific and lay audiences. While the IMMB curriculum also emphasizes lab skills, poster presentations, and community outreach—which likely enhance communication abilities—we view these as complementary to the foundational course content (Table 1). Although evaluating the impact of these co-curricular experiences would be valuable, it falls outside the scope of this perspective. In addition, our survey relied on open-ended responses, which may have introduced recall bias. However, we believe that the concepts most frequently recalled and used in discussions by seniors and alumni still provide valuable insight into

which topics that had the greatest instructional impact, long-term relevance, and influence on communication.

While this study is qualitative and did not capture all aspects and nuances of our curriculum, our preliminary findings identified several core immunology concepts as critical components of undergraduate education that foster immune literacy to support communication with both scientific and lay audiences. Collectively, these findings suggest that undergraduate immunology curricula should prioritize both foundational immune mechanisms and their clinical applications, while integrating specialized topics like vaccinology to foster students' ability to communicate effectively across diverse audiences.

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 West Virginia University Institutional Review Board. 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

CS: Writing – review & editing, Writing – original draft. KC: Writing – original draft, Writing – review & editing.

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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 author(s) declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

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