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Pedagogical and evaluative competencies for the 21st century in molecular biology education and their relationship with honors programs: a systematic literature review

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Introduction: Pedagogical and evaluative competencies for the 21st century are essential in molecular biology. Literature suggests that teaching methods should assess both knowledge and disciplinary skills, as this approach is a prerequisite for student employability in biomolecular sciences.

Methods: In this systematic review, we conducted a search in Web of Science and Scopus, selecting 55 studies that met the inclusion criteria for the development of this research. The keywords used in WoS and Scopus were "molecular biology" and "students," limited to articles published between 2020 and 2024.

Results: This study identified a set of key competencies for the practice of molecular biology. However, it was observed that other equally relevant competencies received less attention in the analyzed reports. Honors programs implemented by universities promote innovative methodologies and technologies to enhance academic performance in molecular biology. These programs also encourage active teaching, which fosters students' overall development.

Conclusion: The most frequently noted molecular biology competencies were critical thinking, collaboration, problem-solving, communication, and creativity. In contrast, other important skills such as research, reading, self-directed learning, motivation, and digital literacy were less emphasized, despite their relevance and connection to honors programs. In terms of teaching modalities, the face-to-face laboratory teaching was the most highly valued for its practical approach, followed by the hybrid approach. The traditional mode ranked third, while the virtual mode, despite its advantages, came in fourth. Desktop-based exams predominate as an evaluative tool, but there is a gap in this approach, since all the evaluation tools detected in this study mainly measure theoretical knowledge, omitting competency evaluation. This contradiction is relevant, as today's employers demand precisely such competencies. Implementing honors programs is one way to address this gap by focusing on developing skills that align with current labor demands.

KEYWORDS

critical thinking, problem solving, research skills, honors programs, IT skills, problem-based learning, project-based learning, inquiry-based learning

Introduction

The Development of Pedagogical and Evaluative Competencies for the 21st Century in Higher Education and Honors Programs in the Field of Molecular Biology

Honors programs have emerged with tangible results in student education. These programs are closely related to the pedagogical and evaluative competencies of the 21st century and offer concrete advantages. One of these is their ability to motivate students, especially in areas such as molecular biology, fostering a greater commitment from them that translates into better academic performance. Additionally, these initiatives reduce dropout rates and promote equity by providing students from diverse backgrounds with access to and the ability to utilize benefits (Basnet et al., 2024). Honors programs can be used to attract talented students and encourage them to engage with cutting-edge science. These programs can also help students develop skills such as data interpretation, research, critical thinking, leadership, communication, scientific writing, and teamwork. Another advantage is that honors programs strengthen professional research in this discipline by producing research published in high-impact, indexed publications (Shipton et al., 2024).

The aforementioned skills align with the 21st-century pedagogical and evaluative competencies and are defined as the set of skills, knowledge, and attitudes that citizens require in today's context. These competencies are considered essential to succeed in the modern socioeconomic environment. They include a combination of technical, interpersonal, and methodological skills and are designed to prepare people not only for their current jobs but also to adapt to future changes in the workplace (Alhloul and Kiss, 2022).

These competencies are grouped and categorized in various ways due to the diversity found in the educational literature. Among the most commonly used terms are "soft skills," "transversal competencies," "generic competencies," "life skills," "21st century skills," and "21st century competencies." However, this terminological variability and the lack of consensus in the grouping of competencies have generated confusion, hindering progress toward their effective implementation. This situation has been metaphorically described as "getting lost in translation" (Thornhill-Miller et al., 2023).

For instance, the World Economic Forum (WEF) organizes them into broad categories covering thinking (creativity and innovation, critical thinking, problem solving, decision making, and independent learning), interaction with others (effective communication and collaboration or teamwork), tool management (information and digital literacy), and general life skills (citizenship, personal and professional life management, individual and social responsibility, and cultural awareness) (World Economic Forum, 2016).

It is important to note that other authors refer to these skills as the 4Cs: creativity, critical thinking, communication, and collaboration (Celume and Maoulida, 2022a; Griffin and Care, 2015). Other research extends this set to include ICT skills and problem-solving (Celik et al., 2024), self-management, flexibility, and adaptability (OECD, 2018). Their development is considered a determining factor for professional growth and fulfillment, and it contributes to more active participation in society (Thornhill-Miller et al., 2023).

However, honors programs at universities are designed to develop competencies such as communication, teamwork, innovation, creativity, technical writing, ethics, responsibility, leadership, critical thinking, research, and problem-solving (Basnet et al., 2024). Similarly, technological competencies and teaching methodologies are closely linked to honors programs. For instance, incorporating research-based approaches and applications in biomolecular sciences enhances the educational experience, encouraging students to develop scientific, technological, cognitive, and social skills. This prepares future graduates for professional growth (Carreras et al., 2024).

Since honors programs are designed to foster personal and professional growth, most students who enroll in an honors program are highly motivated. Students in these programs may take multiple honors courses, but they must maintain high academic standards and participate in extracurricular activities, such as research. In addition, discipline-specific evaluation methods are used in honors courses (Basnet et al., 2024). One of the most prominent molecular biology-related competencies highlighted in this research is skills. As mentioned above, research is one of the extracurricular activities that is considered a priority within the honors programs.

The competency approach holds particular relevance for employability, where graduates must master not only theoretical knowledge but also practical skills aligned with labor market demands (Mertens and Gräsel, 2018). In this context, molecular biology graduates with specialized training can pursue careers in both public and private sectors, including research positions in academia and industry (Yurtseven et al., 2021).

However, for graduates in molecular biology or related disciplines, to achieve excellence in their fields, their training must include a core set of learning objectives. While each profession requires specific competencies, establishing a core set of shared skills for disciplines incorporating molecular biology is essential, as it encompasses not only theoretical knowledge but also practical skills and laboratory techniques (Goller et al., 2021). These competencies not only stimulate scientific interest but also foster a research-oriented learning environment (Herrera Sandoval et al., 2024).

These skills are particularly noteworthy as they were developed during undergraduate studies, extend through graduate training, and encompass both continuing education and formal research development (Cardoso and Lockwood, 2025). This is especially important given the rapid evolution of molecular biology, which demands continual adaptation of teaching methodologies in the classroom (Walther et al., 2024).

Another point to consider is that core research techniques that were formerly essential for students' training can now be performed by specialized companies, for example, DNA sequencing and primer synthesis. This change has shifted the focus from molecular biology to the acquisition of other laboratory skills. Educators must prioritize developing additional relevant skills in line with contemporary demands and adapt the curriculum to meet the current needs of the professional field (Walther et al., 2024).

It is also important to update teaching methods to ensure that students in this discipline acquire the necessary skills and are prepared to face a work environment that includes both theoretical and practical training (Walther et al., 2024). Therefore, it is essential that educators in this educational program provide students with the necessary competencies to foster innovation and self-sufficiency. To achieve this objective, the learning environment must be designed to promote motivation and facilitate the development of these skills (Yurtseven et al., 2021).

However, transversal competencies are not always effectively integrated into established frameworks of formal curricula and disciplines, nor are they fully aligned with the norms and regulations that govern educational practices in school and classroom contexts (Berg et al., 2021). Therefore, curriculum design must prepare students for an uncertain work environment, emphasizing that scientific knowledge alone is not enough and that mastery of transferable key skills is necessary to ensure their success in future courses and careers (Liu et al., 2021; Macaulay et al., 2019).

It is important to mention that molecular biology is a scientific discipline that is not limited exclusively to life science students because it involves collaboration between various related disciplines, such as biochemistry, cell biology, and genetics. Its interdisciplinary nature and the different perspectives it offers facilitate the integration of multiple higher education programs, including computer science, education, social sciences, mathematics, and social work, among others. This suggests that its techniques are pertinent in various interdisciplinary areas, as they require knowledge and experience in this field to provide comprehensive, technical, or specialized training.

The importance of integrating technology into molecular biology teaching methods

The COVID-19 pandemic forced educators, without exception, to make a disruptive transition from face-to-face teaching to urgent remote learning, creating significant challenges for teachers. Many teachers did not feel prepared or have the necessary digital skills to face this change in teaching methodologies; however, after an initial period of adaptation, it was observed that teachers preferred to return to face-to-face teaching due to the direct interaction and immediate feedback with students, while incorporating best practices and newly acquired methodological skills during the online teaching stage, such as the use of new digital tools (Tick et al., 2023).

Another relevant aspect to consider is that the pandemic became a turning point in the transformation of teaching methods, offering an alternative to face-to-face classes. Hybrid and virtual education, as new learning modalities, have proven to be viable alternatives due to their flexibility and accessibility, consolidating themselves as an integral part of the contemporary educational landscape.

The change has prompted a reassessment of the impact of these modalities on student learning, marking a key milestone for adapting competencies needed in higher education (Totlis et al., 2021), as 21st-century education demands an approach that integrates innovative technologies and methodologies (Bilan et al., 2024). Therefore, molecular biology instructors should emphasize both theoretical learning and laboratory research projects equally, as the latter is the most effective way to apply theoretical knowledge (Suárez-Carballo, 2020); however, the complexity of these projects should be adjusted according to the students' level of education to ensure an appropriate learning progression.

In molecular biology, teaching methods should focus on laboratory practice and the application of theoretical concepts (Hock Siew, 2021), aspects that have been significantly affected by the closure of classrooms and laboratories during the COVID-19 pandemic. It is important to emphasize that, from a practical point of view, laboratory work is essential for gaining experience and developing the necessary skills for future employment in the industry, as well as for academic and professional development.

For this reason, integrating interactive learning technologies into traditional teaching methods enhances higher education students' learning experience, encouraging active participation, as the use of multimedia content and interactive simulations facilitates a deeper understanding of complex concepts. For example, digital tools help visualize dynamic processes such as DNA replication or protein folding in molecular biology. Previously, conventional methods focused on the unidirectional transfer of information to students, who had a passive role. Nevertheless, with the advent of digital tools, the adoption of more interactive and collaborative approaches has been encouraged (Qolamani and Mohammed, 2023); particularly in honors programs, where fostering technology skills, critical thinking, and scientific research are key competencies in molecular biology.

Thus, it is a priority that teaching methods undergo significant changes to align with 21st-century skills, which consist of integrated competencies that must be incorporated into all disciplines and academic activities. It is also imperative that teachers adopt an innovative and adaptive approach to their educational practice (Niu et al., 2021). Selecting and adapting appropriate methods to students' needs is essential to improve learning. On the other hand, it should not be overlooked that educators must have a deep knowledge of the educational methodologies they are employing, as this will allow them to personalize their teaching approach effectively (Mohiuddin et al., 2020).

With this technological boom, students must develop digital competencies that allow them to use technologies effectively in their learning process. This involves skills such as self-directed learning, communication platform management, and the ability to search for, critically analyze, and evaluate information (Hashim and Köprülü, 2024). Therefore, the need to integrate new competencies into technology-related curricula and interpersonal skills is emphasized (Alhloul and Kiss, 2022).

Teaching methods and their evaluation

To date, traditional assessment practices are still in place and focus mainly on summative techniques, such as examinations and standardized tests. These methodologies prioritize quantitative metrics and, in many cases, fail to adapt to student needs. This creates a rigid environment that encourages "teaching to the test," while contemporary approaches prioritize personalized and dynamic learning through innovative practices that adapt to the diversity of the student body and promote deeper understanding (Meylani, 2024). Honors courses employ diverse assessment methods to evaluate students' understanding of molecular biology concepts and their applications, as well as the challenges of research. These methods also promote advanced skill development and professional growth (van Eijl et al., 2024).

On the other hand, it is important to mention that assessment is interrelated with teaching methods because these approaches, whether traditional or innovative, contribute in a systematic and planned way to guide student learning. It should also be noted that the diversity of assessment methods, as well as their adaptation and application, depends to a great extent on the teacher and the needs of each institution (Perfumo and Ares, 2020). Additionally, assessment strategies should be tailored to the type of activity and its learning objectives. In molecular biology honors programs, for example, assessment focuses on evaluating research skills and their practical application (Shipton et al., 2024). Therefore, the various alternatives, both in teaching and assessment, must continue their evolutionary process, and their purposes and perspectives must be primarily oriented toward enhancing the learning process.

Modern teaching should focus not only on assessing knowledge but also on evaluating at least the competencies that facilitate students' autonomous learning and development (Kulik et al., 2020). Teachers must master their teaching method and adjust it to assess its effectiveness and students' understanding, thereby facilitating student learning (Hashim and Köprülü, 2024). In the context of molecular biology and research, knowledge assessment should not be the sole priority. This indicates that, in addition to mastering their teaching methods, teachers must also assess competencies, technical skills, and research skills, especially in honors programs.

The way in which an assessment of cognitive abilities will be applied with a metric tool must also involve a continuous process of competence evaluation (Holmes et al., 2021). This process must adapt to new technologies, such as artificial intelligence, which is currently the most modern technology and is expected to replace several professions in the next decade, highlighting the need for students to acquire the necessary knowledge and skills for a job landscape full of uncertainty (Mahmud and Wong, 2022). Therefore, it is critical to update training programs—such as those in molecular biology, including honors programs—to align them with current technological innovations and rapid advancements, particularly through the integration of cutting-edge technologies like artificial intelligence.

Molecular biology is a discipline that presents significant challenges, and the lack of hand-on experience, as well as the complexity of learning its concepts, represents the initial problem; therefore, it is important to develop innovative and effective teaching strategies. New content that involves practical activities should be developed, in addition to creating conceptual content and deepening competency formation that is directly related to professional performance, such as creativity and innovation, critical thinking, problem solving, decision making, autonomous learning, effective communication, and collaboration or teamwork. In order to analyze the relevance of these competencies in the impact on teaching in molecular biology, this systematic literature review was carried out.

In this context, the present systematic literature review is focused on an exploratory analysis of the selected documents using the PRISMA diagram (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), conducted manually. For this purpose, the following main objective is established: to identify the essential competencies for the 21st century, including those not previously considered in this classification; to analyze learning environments, educational programs, and teaching methods; and to assess the context of molecular biology in higher education and its relationship with honors programs.

In order to achieve a more complete investigation and meet the stated research objective, the research questions (RQs) are organized into four operational dimensions: (a) journal indicators, (b) educational context, (c) strategies and technologies for research and teaching, and (d) honors programs.

a Journal indicators:

> RQ-1: Which countries are leading in scientific production for educational research on molecular biology teaching in higher education?
>
> RQ-2: What are the most prominent scientific journals for publishing research on molecular biology and its applications in higher education?
>
> RQ-3: What types of studies are published in this research field?

b Educational context:

> RQ-4: In which educational modalities or learning environments is molecular biology taught and applied in higher education?
>
> RQ-5: What are the academic levels of students participating in molecular biology teaching studies?
>
> RQ-6: In what areas of higher education programs is molecular biology incorporated?

c Strategies and technologies for research and teaching:

> RQ-7: What are the types of applications for improving educational quality in molecular biology?
>
> RQ-8: Which assessment tools are most commonly used in molecular biology studies applied to education?
>
> RQ-9: What skill or competency is most frequently emphasized in teaching and learning molecular biology?
>
> RQ-10: What teaching methods are used for molecular biology students?
>
> RQ-11: What technological tools are used to develop skills related to molecular biology?

d Honors programs:

> RQ-12: How would competencies for the 21st century, pedagogical and evaluative methods in teaching molecular biology in higher education benefit students from the honors program?

Methods

To address the research questions in this study, a scientific literature review was carried out using a PRISMA diagram (UNC, 2020), which facilitated the precise definition of criteria for the selection of research articles. These criteria included variables such as the authors, the article title, the source, the language, the type of document, the abstract, the publication year, and the DOI (Delgado Hernández et al., 2021).

Search strategy

In this systematic review, we used Clarivate Web of Science (WoS) and Scopus, as they are the two most comprehensive and reliable bibliographic databases; thus, they are indispensable for a wide range of research and academic tasks (Pranckutė, 2021). They cover distinct scientific domains: WoS focuses primarily on the natural sciences and engineering, while Scopus provides broader coverage of the social sciences and related fields, making both essential tools for research and academic work (Kumpulainen and Seppänen, 2022). In the case of PubMed and MEDLINE, these are highly specialized databases, which makes them less suitable for inclusive analyses or the evaluation of multidisciplinary research units (Pranckutė, 2021). For this reason, they have limitations for bibliometric analyses comparable to those conducted in WoS and Scopus (Kokol, 2023). After determining the keywords, an exhaustive search was conducted in WoS and Scopus databases on 23 November 2024, considering articles published between 2020 and 2024 (the last 5 years). The search strategy used the keywords ("Molecular biology") and ("Students"), with identical search strings applied in both databases. The metadata supporting this study is available in Supplementary material, which provides a step-by-step breakdown of the entire research process.

WoS search string

("Molecular biology") AND ("students") (Topic) and Open Access and 2024 or 2023 or 2022 or 2021 or 2020 (Publication Years) Research or Education Scientific Disciplines (Web of Science Categories) and Review Article or Book Chapters (Document Types).

Scopus search string

(TITLE (("Molecular biology")) AND TITLE-ABS-KEY (("students"))) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (EXACTKEYWORD, "Education") OR LIMIT-TO (EXACTKEYWORD, "Students") OR LIMIT-TO (EXACTKEYWORD, "Molecular Biology")).

Study inclusion and exclusion criteria

The inclusion criteria were as follows: (1) that the title included the expression "Molecular Biology"; (2) that the abstract contained the term "students"; (3) that the articles were published between 2020 and 2024; (4) that the selected studies were research articles or reviews, which were evaluated based of their characteristics, content, and length (Manterola et al., 2023; UNESCO, 2022); (5) that they were open access, (6) that they were focused on the context of higher education, and (7) that they were written in English.

The exclusion criteria were as follows: (1) studies not focused on the context of higher education, (2) publications written in a language other than English, (3) materials outside the established search range, (4) duplicated articles, and (5) studies not addressing the objective of the present research.

Selection of articles

The PRISMA diagram (see Figure 1) illustrates the article selection and screening process for this study. Initially, the search string retrieved a total of 210 records in two databases: WoS (47 records) and Scopus (163 records). Before the selection stage, 29 duplicated records and 114 records that did not meet the established publication year range (2020–2024) were eliminated, leaving a total of 67 unique records to be evaluated. Afterward, the remaining 67 records were reviewed, and none were excluded during this stage. There were no reports of documents that could not be retrieved.

During the eligibility stage, the 67 articles were evaluated in detail to verify their compliance with the inclusion criteria. Twelve articles were excluded for the following reasons: 5 were not related to higher education, 4 were written in languages other than English, and 3 did not address the objective of the study. Finally, 55 articles met all the inclusion criteria and were considered suitable for the study analysis.

Research questions

In order to achieve a comprehensive analysis of the study, it was structured in four dimensions: (1) scientific journal indicators, (2) educational context, (3) strategies and technologies for research and teaching and (4) honors programs. The 12 research questions (see Table 1) were analyzed and validated through common acceptance among the authors, based primarily on their disciplinary and scientific expertise.

The answers to the questions were obtained by standardizing the metadata terms, which consist of different words that share the same meaning, grouped under a single reference term. The abbreviation of scientific journal names for RQ-2 was performed by consulting the Web of Science (2025) and PubMed National Library of Medicine (2025) help portals, which comply with ISO 4:1997 (ISO, 1997), the standard regulating this procedure. For RQ-3, the UNESCO (2022) framework "Typology of documents/works for bibliographic management in COBISS," which classifies academic genres according to the characteristics of scientific articles (structure, content, length, and purpose), was adopted. In RQ-9, it was decided to include only those competencies that are explicitly found in the analyzed documents; however, an inferential analysis was also performed to determine which competencies were not directly expressed and to include them in the study, in accordance with the competency analysis performed

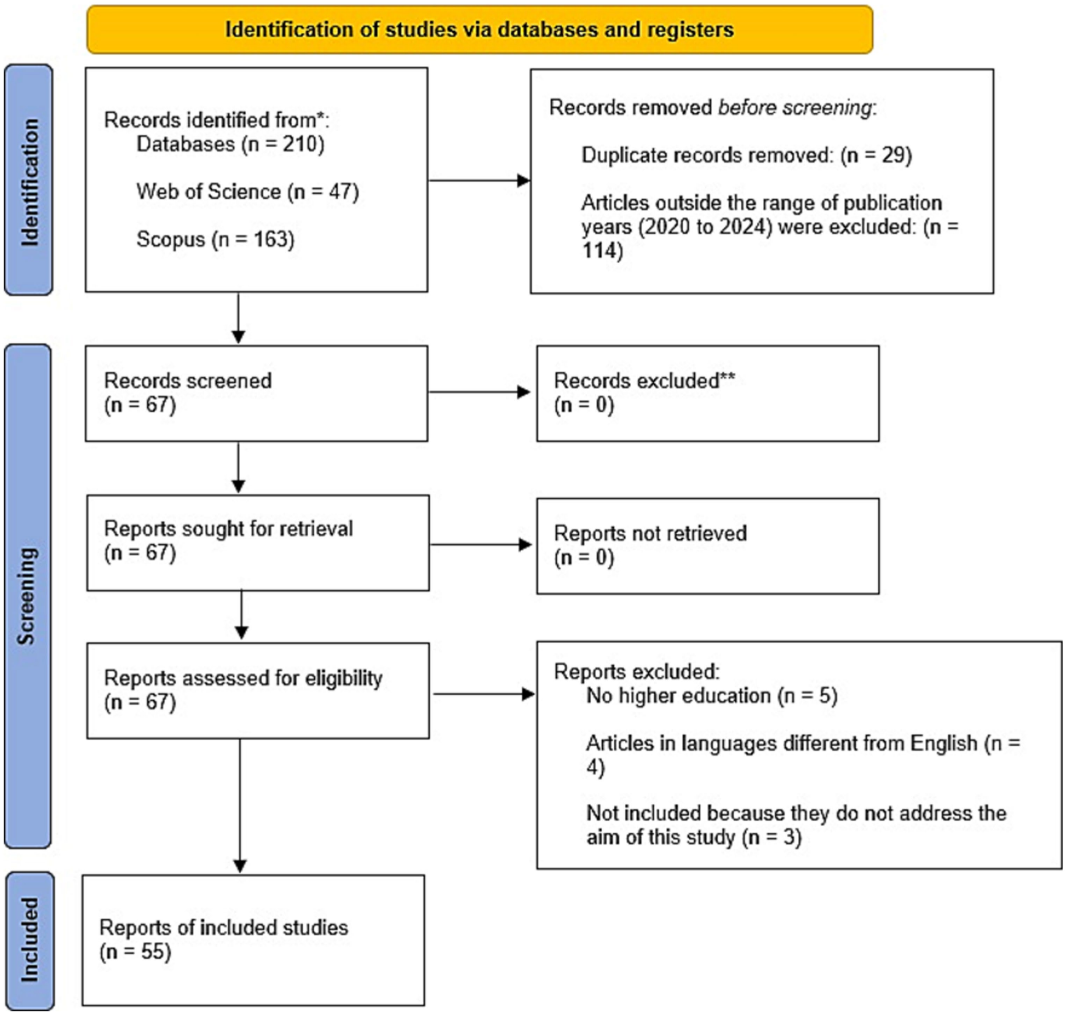

FIGURE 1
PRISMA diagram.

by Jose et al. (2023). The responses to research question RQ-12 were generated by consulting the key findings from previous results and relating them to the honors programs.

Results

RQ-1: which countries are leading in scientific production for educational research on molecular biology teaching in higher education?

The world map (see Figure 2) provides an overview of the scientific output in the field of molecular biology applied to higher education worldwide from 2020 to 2024. The data reveal that the United States leads in this field, accounting for a significant proportion of the world's scientific output, with a total of 27 publications. China is in second place, with 11 items. Together, the two countries account for 69.1% percent of the scientific production in this field. The remaining 30.9% corresponds to other countries, including Australia, Mexico, New Zealand, Palestine, the Philippines, Poland, Spain, Sweden, Turkey, Brazil, Canada, Ecuador, Ireland, and Malaysia.

RQ-2: what are the most prominent scientific journals for publishing research on molecular biology and its application in higher education?

The distribution of articles types published in various scientific journals (see Table 2) reveals that Biochemistry and Molecular Biology Education (Biochem Mol Biol Educ) dominates this field, accounting for 63.7% of the reviewed studies. These are distributed in a variety of formats, including research reports, original articles, short communications, conference presentations, and essays.

On the other hand, other journals also contribute, though to a lesser extent, as is the case with American Biology Teacher (Am Biol Teach), which represents 7.3% of the total number of publications, with contributions including reports and research articles. Similarly, the Journal of Microbiology & Biology Education (JMBE) and Applied Sciences (Appl. Sci.) have a smaller presence, with 3.6 and

TABLE 1 The relationship between the research questions and their corresponding answers.

Research questions	Answers
Scientific journal indicators	
RQ-1: Which countries are leading in scientific production for educational research on molecular biology teaching in higher education?	Country names
RQ-2: What are the most prominent scientific journals for publishing research on molecular biology and its application in higher education?	Names of abbreviated scientific journals
RQ-3: What types of studies are published in this research field?	Research article, research report, review article, conference presentations, essay, short communication, case study
Educational context	
RQ-4: In which educational modalities or learning environments is molecular biology taught and applied in higher education?	Face-to-face laboratory, hybrid, face-to-face class, online class, virtual laboratory work, not mentioned, face-to-face conference
RQ-5: What are the academic levels of students participating in molecular biology teaching studies?	Undergraduate, (undergraduate and postgraduate), not mentioned, postgraduate, (undergraduate, graduate, and post-doctoral), (undergraduate, graduate, and postgraduate)
RQ-6: In what areas of higher education programs is molecular biology incorporated?	Bioengineering, biology, chemistry, medicine, not mentioned, pharmacy, STEM education, social sciences, computer science, mathematics, public health, biomedical science, education, social work, nursing, stomatology, metabolic engineering, veterinary science
Strategies and technologies for research and teaching	
RQ-7: What are the types of applications for improving educational quality in molecular biology?	Method of teaching students, curriculum design, certification exam to assess students, not applicable, student evaluation, teacher training
RQ-8: Which assessment tools are most commonly used in molecular biology studies applied to education?	Exhibition, laboratory practice, Likert scale, not mentioned, questionnaire, rubric, survey, test, final project, interview, report, homework, teamwork, self-assessment
RQ-9: What skill or competency is most emphasized in teaching and learning molecular biology?	Critical thinking, teamwork, problem solving, research skills, oral/written communication, innovation and creativity, reading skill, self-learning, motivation, not mentioned, cognitive skills, core competences, employability skills, IT skills, adaptability, leadership
RQ-10: What teaching methods are used for molecular biology students?	Problem-based learning, project-based learning, inquiry-based learning, not mentioned, flipped learning, lecture-based learning, learning based on teaching, discussion-based learning, virtual reality-based learning, gamification
RQ-11: What technological tools are used to develop skills related to molecular biology?	BLAST, CLC Genomics Software, SnapGene Software, Nephele, Benchling, MEGA 7, OligoAnalyzer, uMELT, Integrative Genomics Browser, Saccharomyces Genome Database, TCGA Database, GEO Database, Allen Brain Atlas (ABA) Database, My NASA Database, AlphaFold Protein Structure Database, Arabidopsis Database, InterPro Database, Versatile Genetic Assembly System (VEGAS), Social networking platform (WebChat), Biological data analysis (Kbase), SPSS 13.0, Statistix statistical software, Dalian Medical University (DMU), 3DVLE.
Honors programs	
RQ-12: How would competencies for the 21st century, pedagogical and evaluative methods in teaching molecular biology in higher education benefit students from honors program?	Relevant findings from the analysis of the results and their benefits of the honors programs

1.8%, respectively, focusing mainly on original articles and short communications. Additionally, journals such as Frontiers in Education (Front Educ), Folia Medica Cracoviensia (Folia Med Cracov), and Cogent Education (Cogent Educ) contribute to the subject, although their frequency is lower, at 1.8%.

RQ-3: what types of studies are published in this research field?

Figure 3 shows the distribution of the different types of studies included in the publications analyzed in this systematic review. The results indicate that research articles are the most frequent type of study, representing 40.0% of the total, equivalent to 22 publications. In second place are research reports, which comprise 29.0% of the studies, with a total of 16 publications. These two categories highlight the relevance of the primary forms of scientific dissemination in the analyzed area.

In the third place, short communication releases represent 11.0% of the total, with six publications, reflecting a moderate interest in this more concise format. Similarly, papers presented at conferences account for 9.1%, with a total of five publications, highlighting the importance of this type of academic event as a means of dissemination. In smaller proportions, review articles account for 5.4% of the total,

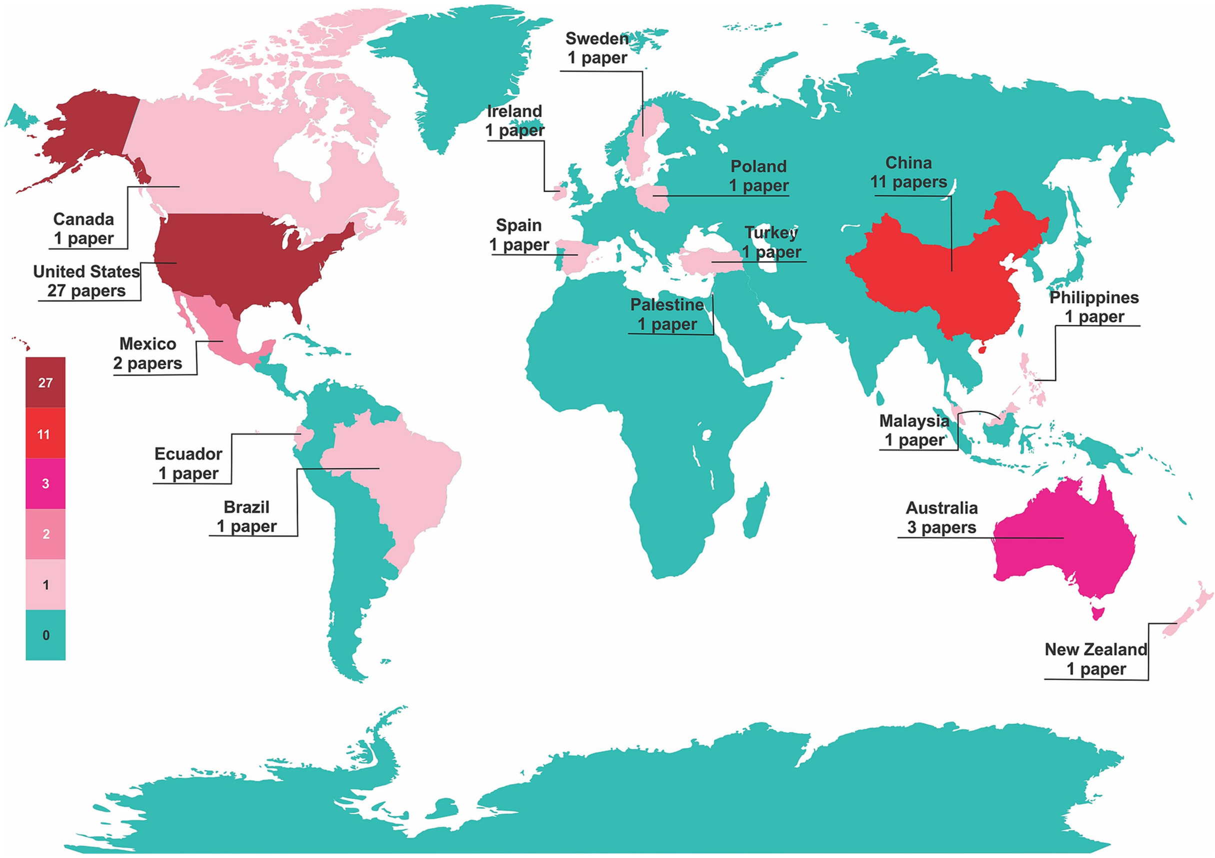

FIGURE 2
Geographic distribution of molecular biology research with educational applications at a higher education level.

with only three publications. Next, case studies represent 3.6%, with two publications, while essays are the least common format, with only one publication, equivalent to 1.8% of the total.

It is concluded that these results reflect a clear preference for original and complete studies, such as research articles and research reports, which together account for 69% of the analyzed publications.

RQ-4: in which educational modalities or learning environments is molecular biology taught and applied in higher education?

As illustrated in the ring graph (see Figure 4), the analysis of the educational modalities in which molecular biology is taught and applied reveals a wide variety of learning environments, with a marked prevalence of face-to-face modalities. The largest proportion corresponds to face-to-face laboratory work, which comprises 25.5% of the analyzed articles. This preference emphasizes the importance of hands-on experiments in molecular biology, where direct contact with laboratory equipment and samples is essential for developing and research skills.

In second place, the hybrid modality, which combines face-to-face and virtual elements, accounts for 23.6%. Traditional face-to-face classes rank third at 18.2%, underscoring their role in the educational landscape.

As for the virtual modality, online classes represent 14.5%, suggesting that the incorporation of this modality is indispensable and positively perceived in molecular biology teaching. However, virtual laboratory work has a significantly lower representation, reaching only 1.8%, which suggests that this approach has relevant disadvantages compared to face-to-face practices. Finally, other educational environments, such as face-to-face conferences and articles that did not specify the modality or setting, account for 9.1 and 7.3%, respectively.

RQ-5: what are the academic levels of students participating in molecular biology teaching studies?

Figure 5 displays the analysis of the academic level of participants in studies on molecular biology teaching, showing a notable prevalence of undergraduate students, who accounted for 72.7% of the sample obtained from the PRISMA diagram analysis. Similarly, the participation of both undergraduate and graduate students stands out with 14.5%. In contrast, graduate students alone represent only 1.8%, indicating a lower involvement of this population in this study.

The participation of students combining undergraduate, graduate, and postdoctoral studies was similarly low, each representing only 1.8% of the sample. Finally, a small percentage of the publications consulted, 7.3%, did not specify the academic level.

TABLE 2 Frequency analysis of article typology distribution in molecular biology scientific journals.

Type of article	Frequency	Journal	Percentage
Research article	17	Biochem Mol Biol Educ	63.7%
Research report	7	Biochem Mol Biol Educ	
Conference presentation	5	Biochem Mol Biol Educ	
Short communication	5	Biochem Mol Biol Educ	
Essay	1	Biochem Mol Biol Educ	
Research report	2	Am Biol Teach	7.3%
Research article	1	Am Biol Teach	
Review article	1	Am Biol Teach	
Research report	2	J Microbiol Biol Educ	3.6%
Review article	1	J Biol Chem	1.8%
Research report	1	J Biol Educ	1.8%
Research article	1	JMBE	1.8%
Short communication	1	JMBE	1.8%
Case study	1	Folia Med Cracov	1.8%
Case study	1	Front Educ	1.8%
Research article	1	Front Med-Lausanne	1.8%
Research report	1	Front Microbiol	1.8%
Research article	1	Front Virtual Real	1.8%
Research report	1	Indep J Teach Learn	1.8%
Research article	1	Appl Sci	1.8%
Research report	1	J Coll Sci Teach	1.8%
Review article	1	TUSED	1.8%
Research report	1	Cogent Educ	1.8%

RQ-6: in what areas of higher education programs is molecular biology incorporated?

The data analysis reflected in Figure 6 shows a clear trend toward integrated molecular biology in a wide variety of higher education-related programs, highlighting a high degree of interdisciplinarity.

The three most mentioned areas are medicine, with 19.2%, biology and STEM education, with 16.4%. On the other hand, chemistry, with 9.6%, as well as bioengineering and pharmacy, with 4.1%, show significant percentages, but in a lower range. In contrast, biomedical sciences and nursing show a more moderate incorporation of molecular biology, with 2.7%, and at a much lower level, other degrees unrelated to health sciences, such as mathematics, computer science, education, and social work, with 1.4%.

A relevant aspect is that 12.3% of the articles consulted do not mention any training area integrated with molecular biology, which could be attributed to the diversity of the studies included in the publications consulted or the absence of specific data. In summary, the data show a general trend to incorporate molecular biology in higher education, especially in areas related to the life sciences and health.

RQ-7: what are the types of applications for improving educational quality in molecular biology?

Figure 7 shows the analysis of applications to improve the quality of education in molecular biology, with a predominant focus on teaching methods at 54.6%. Curriculum design also plays a significant role, accounting for 38.2%. In contrast, areas such as student evaluation, certification exams, and teacher training show significantly lower implementation rates, at 1.8%, indicating opportunities for improvement in these aspects.

RQ-8: which assessment tools are most commonly used in molecular biology studies applied to education?

The pie chart (see Figure 8) provides an overview of the distribution of assessment tools used in molecular biology studies. The analysis shows a trend toward diversification of the instruments used to measure student learning.

The results show a clear preference for the traditional method, where written tests, at 20.0%, are positioned as the main evaluation tool. Additionally, tools such as surveys, with 13.6%, laboratory

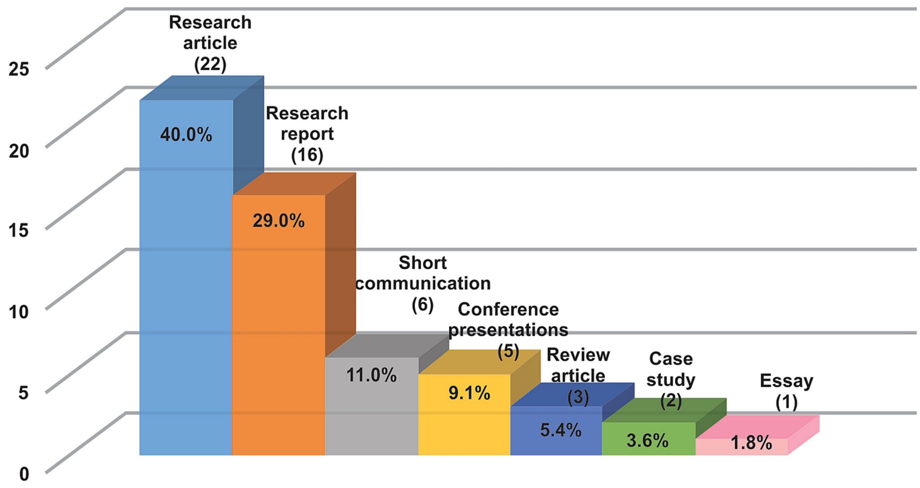

FIGURE 3
Distribution of the different types of research articles according to UNESCO (2022).

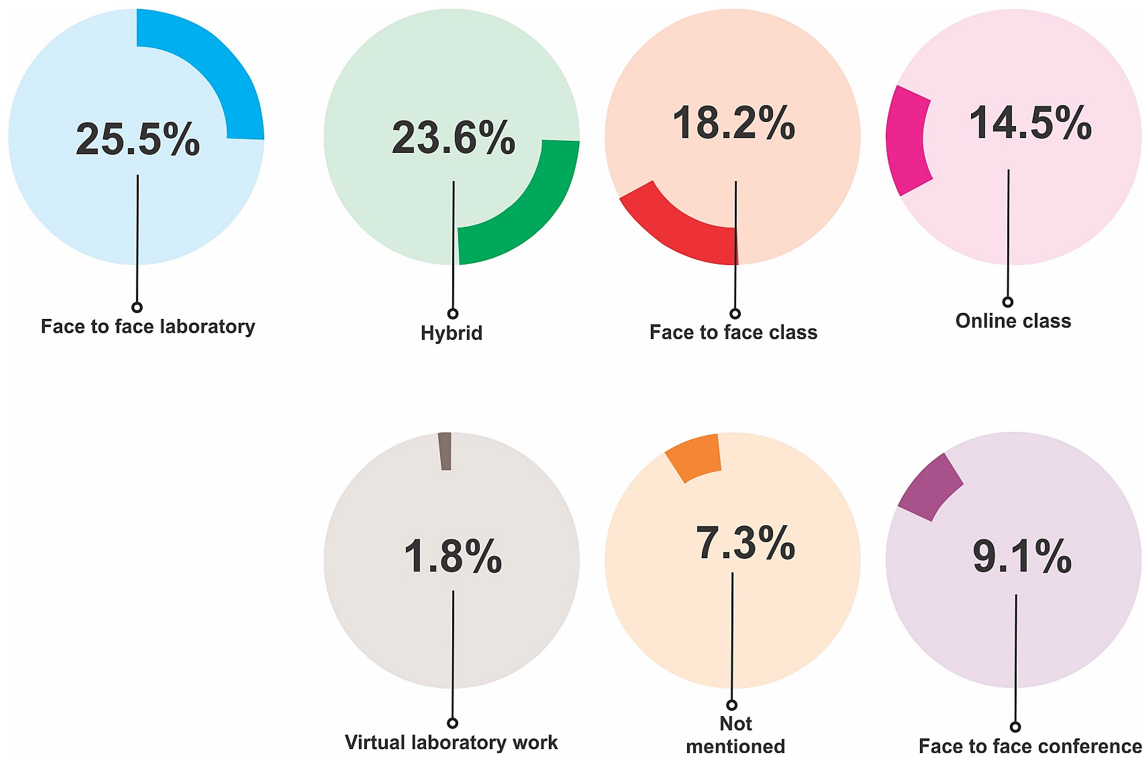

FIGURE 4
Educational modalities and learning environments for the teaching and application of molecular biology.

practices, with 12.7%, and Likert scales, with 12.7%, are widely used.

Furthermore, questionnaires, with 11.0%, are also considered an evaluation instrument, while final projects, assignments, and self-evaluation show a lower frequency of use, 1.0%. The data suggests a preference for more traditional evaluation approaches.

RQ-9: what skill or competency is most emphasized in teaching and learning molecular biology?

Figure 9 presents the analysis of the most frequently mentioned skills and competencies, showing that critical thinking is the main

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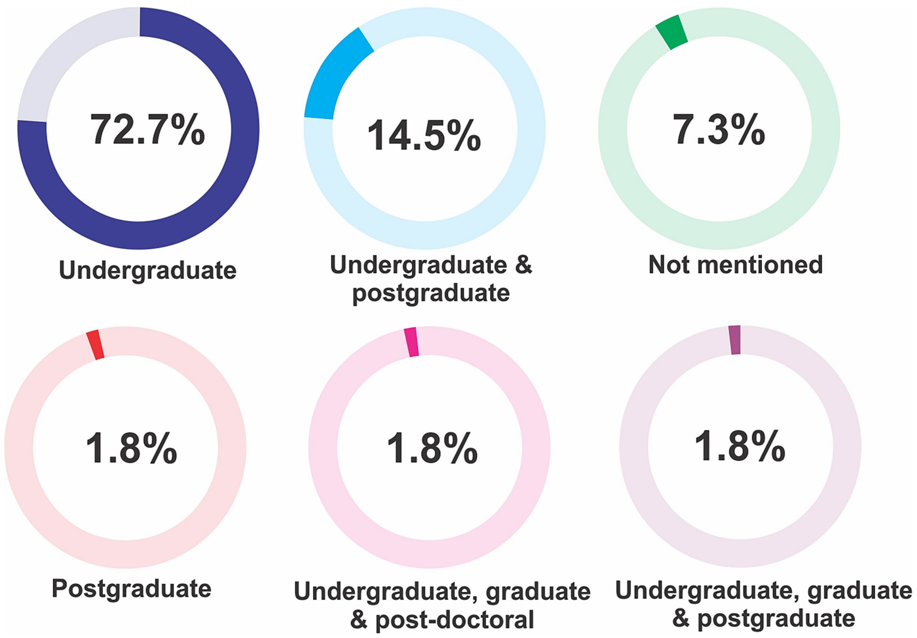

FIGURE 5
Molecular biology students by academic level.

competency, with 21.3% of the responses. The second most mentioned competency was teamwork or collaboration, with 16.0% of the sources consulted. Close behind, at 15.2%, were problem solving, research skills, and oral and written communication.

On the other hand, skills related to innovation and creativity represented 5.0% of the responses, while reading skills obtained 3.0%. Competencies such as autonomous learning and motivation registered a lower impact, at 2.4%. Finally, skills such as leadership, adaptability, digital competencies, employability skills, IT skills, and cognitive skills, among others, had the lowest incidence, with 0.6%.

RQ-10: what teaching methods are used for molecular biology students?

When analyzing the didactic strategies (see Figure 10), the present study reveals that a considerable percentage of the research consulted, 21.8%, reports the implementation of project-based learning and problem-based learning as the most frequently used strategies. In second place is inquiry-based learning, with 20% of the mentions.

Although active methods predominate, a significant percentage of studies (12.7%) fail to specify the methodology used. As for the least frequent methodologies, they include flipped learning, with 9.1%; lecture-based learning, with 5.4%, and finally, gamification, virtual reality-based learning, and discussion-based learning, each at 1.8% (or similar variations).

RQ-11: what technological tools are used to develop skills related to molecular biology?

The study identified several bioinformatics technology tools and statistical applications that facilitate obtaining accurate results through the analysis of information. These tools allow students to integrate knowledge and solve problems in the field of molecular biology.

For example, for the analysis of nucleic acid (DNA/RNA) or protein sequences, the use of tools such as BLAST, CLC Genomics Software, and MEGA 7 has been reported. SnapGene Software is used for DNA cloning and primer design, while Benchling (a bioinformatics software platform) is used for gene editing using CRISPR technology. Similarly, for the analysis of protein tertiary structures, the AlphaFold Protein Structure Database is available; and to consult genomic information related to cancer, the database The Cancer Genome Atlas (TCGA) is used.

In addition, virtual reality has proven to be an effective tool for the simulation of laboratory practices, thus complementing the experiential training of students. Other technologies include statistical analysis software, such as SPSS, and social platforms like WebChat, which facilitate communication and collaboration between students and teachers.

The use of these online platforms contributes to the development of key competencies in students, such as critical thinking, problem solving, teamwork, effective communication, and technological skill acquisition (the main bioinformatics tools identified in this study are available in the Supplementary material).

RQ-12: how would competencies for the 21st century, pedagogical and evaluative methods in teaching molecular biology in higher education benefit students from the honors program?

According to the presented analysis and results, there are significant benefits to be achieved from honors programs, assessments, and teaching methods based on the 21st-century competencies. Pedagogical competencies applied to molecular biology in higher

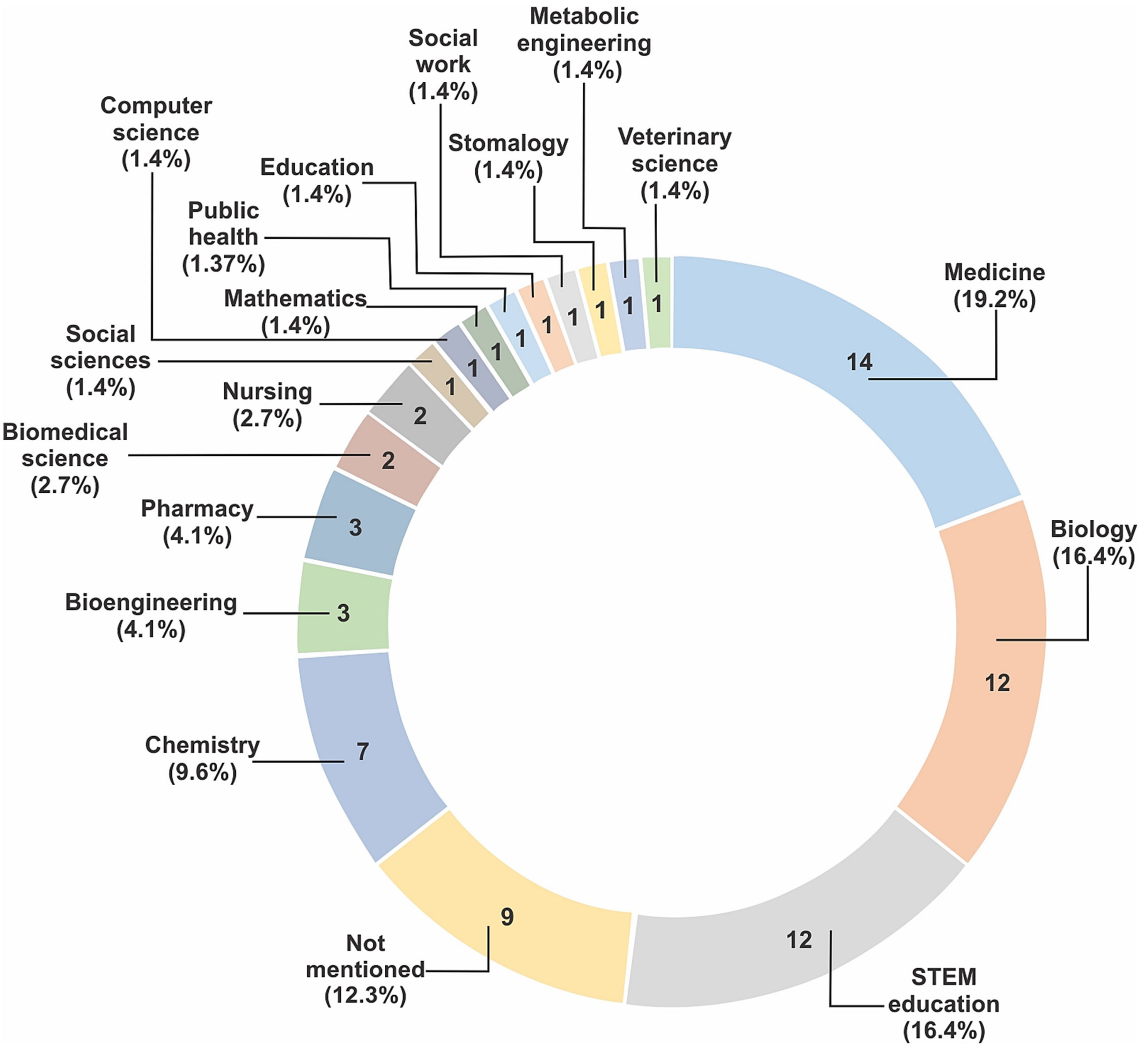

FIGURE 6
Interdisciplinary trends in molecular biology within higher education.

education align with the academic rigor in honors education. This is due not only to the students' motivation but also to the meaningful purpose and sense of fulfillment they derive from their professional training.

It is important to note that students in honors programs can apply competencies such as critical thinking, problem solving, collaboration, research skills, oral and written communication, innovation, and creativity in the field of molecular biology. This would enable them to tackle complex academic tasks, including analyzing data, designing experiments, critically evaluating results, writing scientific publications, and applying knowledge in real-world contexts. Additionally, this approach would encourage more active and innovative teaching methods, promoting comprehensive student development.

Similarly, students with the potential to succeed in honors programs would benefit from this approach in academic programs in molecular biology. Focusing assessments on collaboration, scientific project presentations, laboratory practices, and presentation of reports would ease continuous feedback. This would strengthen the interpretation of results, an irreplaceable process in teaching this discipline, while also encouraging the technical knowledge and the acquisition deeper understanding of complex concepts.

On the other hand, honors programs can benefit from integrating molecular biology and research-focused methodologies, which can transform traditional approaches to align with contemporary requirements, making them more relevant.

Similarly, fostering quality learning, supported by expert teachers who are constantly updated and motivated by innovative pedagogical practices, enhances students' academic commitment. In this way, honors programs may become an instrument to improve quality by utilizing ongoing assessments to reinforce evaluative models and prioritize transversal-skill development—elements essential to 21st-century teaching, especially within the context of molecular biology.

Specialized molecular biology technologies and software, such as databases, online analysis tools, statistical analysis, virtual reality, and constantly evolving multimedia content, should be more effectively integrated into the teaching of this discipline, particularly in honors programs. Their implementation paves the way for access to innovative academic resources and enriches learning with advanced digital materials that analyze large datasets.

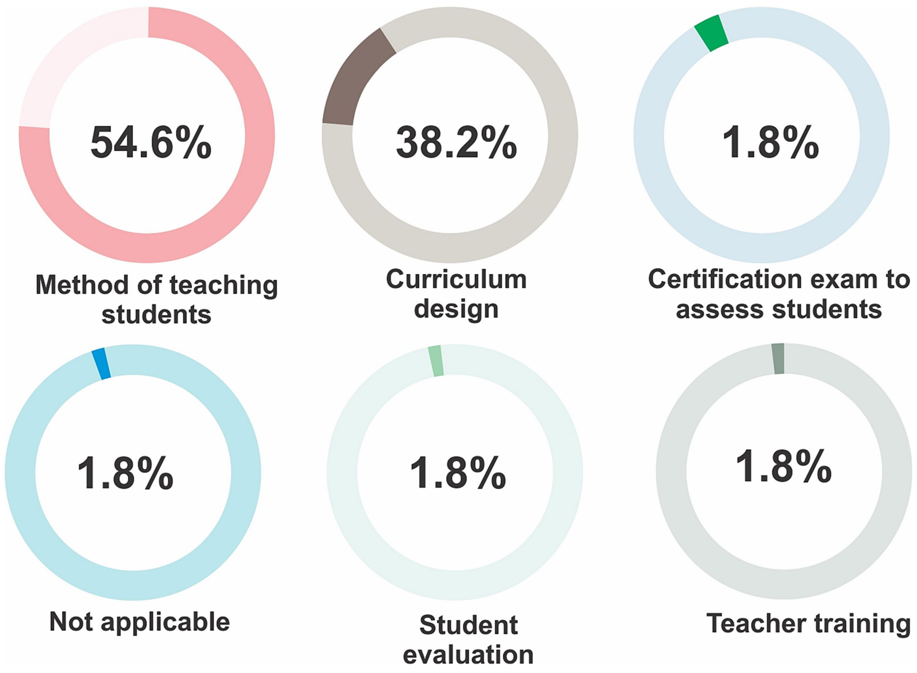

FIGURE 7
Types of applications used to improve the quality of education in molecular biology studies.

On the other hand, introducing simulations and virtual laboratories ensures that students enrolled in honors programs can develop digital skills, furthering conceptual understanding. Although these tools are often used, they can be very effective. They allow students to avoid using dangerous reagents and visualize virtual processes, promoting active learning and complementing practical training in digital environments with innovative methodologies.

Although virtual laboratories have their advantages, they cannot fully replace real laboratories. The latter inspires more confidence when executing practical tasks. These hands-on experiences make it easier for honors students to interpret data, design experiments, and gain a deeper understanding of biological processes.

Discussion

Digital transformation is revolutionizing the educational sector, especially in higher education; digital devices facilitate access to global resources and the creation of innovative materials such as videos, multimedia presentations, and bioinformatics tools. This advancement drives a change in teaching models to adapt to new learning needs (UNESCO, 2021). This context prompted the present review, the objective of which was to analyze the application of pedagogical and evaluative competencies for the 21st century in molecular biology.

In the context of higher education, there is an increasing emphasis on not only the transmission of traditional knowledge but also on the development of skills that allow students to apply this knowledge and adapt to a constantly changing world (Celume and Maoulida, 2022b). To enhance students' skills, developing competencies is considered a key factor in applying their knowledge to real-life contexts within a highly competitive and digitized labor market.

This research shows that the competencies for molecular biology most frequently mentioned are critical thinking, teamwork or collaboration, problem solving, research skills, and oral and written communication; competencies that are relevant in the preparation of future molecular biology professionals to face the work demands of the 21st century. Competencies such as creativity, IT skills, employability skills, and leadership, among others, are highlighted in fewer studies, despite their relevance in the training of competitive molecular biologists.

Molecular biology is a discipline that, in addition to its theoretical basis, requires laboratory practice. In this context, the most frequent learning modalities and environments included laboratory practices, the hybrid modality, and face-to-face classes, followed by online classes and traditional lectures. On the other hand, methodologies such as cooperative and project-based learning, already widespread before the pandemic, have become even more relevant as teachers seek to promote social skills, collaboration, and active participation in the classroom (Ray and Sikdar, 2023).

The systematic review revealed that the countries with the highest academic production on the subject are the United States and China. It is worth noting that the United States ranks among the top three most innovative countries, while China holds the eleventh position according to the Global Innovation Index 2024 (WIPO, 2024). The United States university system stands out for its educational innovation, with universities that constantly develop specialized programs. In global rankings, the United States dominates, with 46 universities among the 100 most innovative, compared to only two in China (uPlanner, 2016). This result could reflect the greater participation of the United States in this field of study, demonstrating

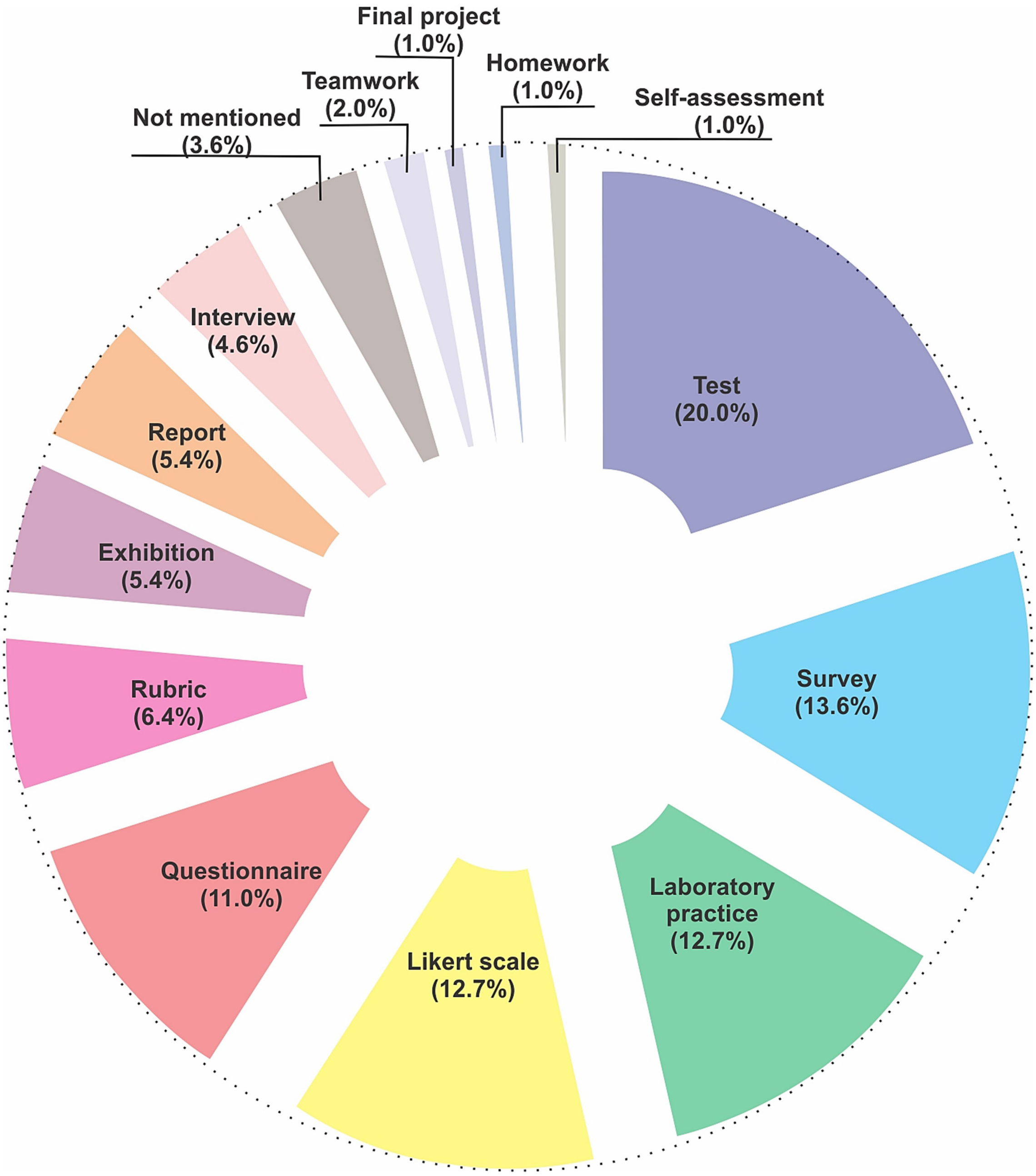

FIGURE 8
Learning-assessment tool diversification in molecular biology.

its interest in leading applied educational innovation in molecular biology.

For this review, it is important to note that only articles indexed in the WoS and Scopus were included, in order to ensure the selection of high-quality content. The diversity of publications contributes to the advancement of teaching in molecular biology, since they present experiences and curricular designs that can serve as a reference or models for implementation in different universities. For example, a theoretical-practical course in which students identify or develop genetically modified foods allows for the integration of several basic concepts of molecular biology. This methodology not only strengthens laboratory skills and the use of information technologies but also establishes the foundation for linking scientific knowledge with social problems. Additionally, it motivates students to create educational outreach materials, such as podcasts or websites (Gordy and Goller, 2020).

Modern education must integrate artificial intelligence and innovative didactics in virtual and face-to-face formats, all of which fall under "digital literacy," a key disruptor among the 21st-century skills. Thus, it is essential to highlight the importance of integrating digital competence into curricular reforms in the educational context (Anderson-Levitt and Gardinier, 2021).

Another priority is that courses and curricula must be constantly updated to avoid outdated teaching in a volatile future labor scenario.

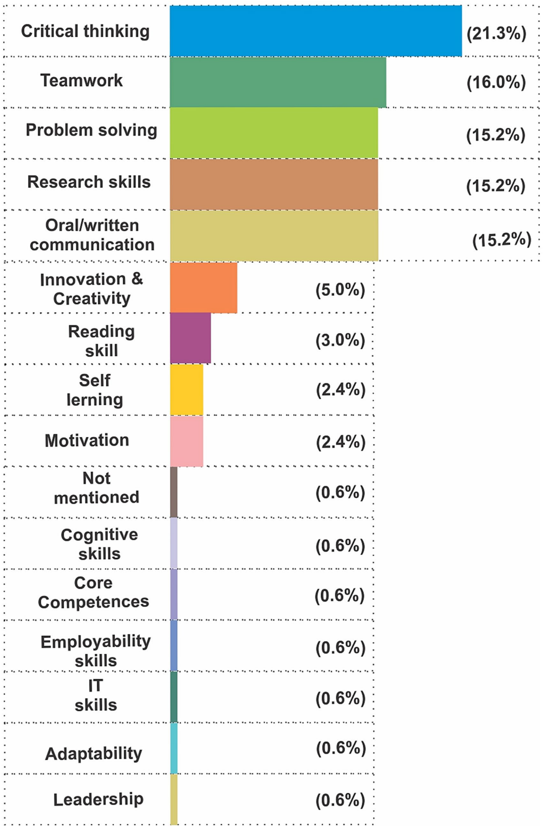

FIGURE 9
Skills and competencies analysis in molecular biology based on Jose et al. (2023).

Similarly, evaluations should always be aligned with their objectives and teaching styles, ensuring a comprehensive assessment of learning. However, evaluation methods must measure cognitive progress in academic work in a valid and reliable way while also assessing acquired competences.

The predefined courses within honors programs strengthen the development of pedagogical and evaluative competencies for the 21st century, including critical thinking, teamwork, problem-solving, research skills, oral and written communication, information technology management, innovation, creativity, and motivation (Macaulay et al., 2019). Some organizations foster innovation by adapting to new learning models in molecular biology and biochemistry, as well as the competencies these disciplines require in teaching. A notable example is the International Union of Biochemistry and Molecular Biology (IUBMB), which advances innovative pedagogical strategies through global initiatives. Additionally, the organization provides free access to educational resources—including textbooks and specialized journals—particularly in developing countries.

Molecular biology educators should continually seek to transform higher education and design curricula that integrate the development of skills and competencies, fostering relevant practices with an impact on the working world. This means that institutions and their educators must identify strengths and weaknesses in their teaching methods; they must also be evolutionary, innovative, and adaptive, reconfiguring pedagogical approaches to ensure transition standards toward an increasingly digitalized future.

Honors programs prepare students for advanced research studies, such as pursuing MD or PhD degrees. In addition to promoting research development, these programs offer competitive training for careers in academia and the workplace (Shipton et al., 2024). Moreover, these programs are not limited to graduate studies; they also extend to undergraduate education, providing students with early opportunities to engage in rigorous projects and strengthen their professional profiles (Carreras et al., 2024).

The COVID-19 pandemic has prompted the consolidation of the online format, a model that is here to stay and which, together with the advancement of information technology, has boosted the rise of the hybrid format. Furthermore, thanks to these technological developments, it is now possible to work in virtual laboratories for the design of experiments and the analysis of hypothetical results using specialized platforms and software, such as CLC Genomics Workbench, Nephele, and KBase (Goller et al., 2021), BLAST, Ensembl, PubMed (Covey, 2021), and the CRISPR Guide RNA design tool (Sankaran et al., 2021), among others. All these advances require teachers to constantly update their skills in order to train highly competitive professionals capable of meeting the demands of the labor market and the challenges of contemporary research.

After the pandemic, there has been a remarkable increase in the development and implementation of digital assessment and teaching methods, characterized by their flexibility and adaptability to online and hybrid environments. In the pedagogical field, approaches such as hybrid learning and the flipped classroom model have gained special relevance by enhancing educational interaction and offering greater flexibility due to the strategic use of digital tools. This phenomenon was significantly accelerated by the health crisis, which catalyzed the widespread adoption of these methodologies and consolidated digital education, establishing virtual platforms as a standard in various educational contexts (Rawal, 2024).

Honors programs are typically funded through institutional resources available to their respective universities and departments, rather than a separate budget line from the institution's own funds (Kolster, 2021). Funding for the honors programs in molecular biology research and education is obtained through diverse budgets, depending on the country and the educational program. For example, the European Molecular Biology Organization (EMBO) which supports scientists at all career stages through various programs, including the EMBO Young Investigator Program and EMBO Postdoctoral Fellowships. The National Institutes of Health (NIH) offers various research training and career development programs, including those specifically designed for undergraduate and graduate students, which can be integrated with honors programs at universities. The American Society for Biochemistry and Molecular Biology (ASBMB) offers various awards, grants, and scholarships for undergraduate research (to support summer research projects) and honors programs. Additionally, private organizations, including companies in the biotechnology and pharmaceutical sectors, offer funding opportunities for molecular biology research in which honors program students participate. Furthermore, there are university-specific honors programs that offer scholarships to students.

There must also be diversity in assessment methods, including formative processes, as well as the assignment of grades, to adjust the

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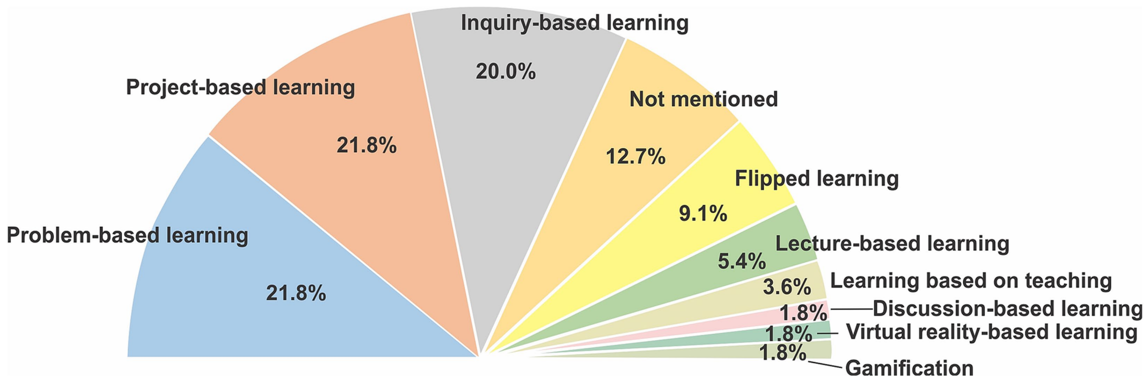

FIGURE 10
Types of teaching methods implemented in molecular biology.

teaching method and understand if there is progress in student learning. Evaluations should be conducted in a rigorous manner, using both quantitative and qualitative methods. In this study, the analyzed articles show that the evaluation methods focus on the cognitive and practical domains; however, there is no mention of the methodology for assessing the competencies acquired by molecular biology students.

Competencies must be measured not only psychometrically, because their evaluation in the 21st century, must be more dynamic and formative, revealing the true capabilities of the students, and both reliability and validity must define these instruments. In addition, further research is needed on standardized and adaptable methods for measuring competencies that reflect authentic progress in the educational context.

Molecular biology has a significant impact on various educational programs, especially in the areas of life and health sciences, such as medicine, biology, chemistry, pharmacy, bioengineering, biomedical sciences, nursing, and veterinary medicine. This is due to its direct application in the molecular processes that govern biological phenomena, as well as its impact on disease diagnosis, prognosis, prevention, and treatment.

Molecular biology has also proven to be relevant in forensic sciences, where it has contributed significantly to the advancement of criminal investigation, the resolution of paternity disputes, the identification of missing persons, and the exoneration of wrongfully convicted persons (Sessa and Salerno, 2024). Its integration with the social sciences is favored in fields where a ratio of 1.4% of scientific publications has been identified.

On the other hand, molecular biology requires the support of the exact sciences to link DNA fundamentals with biochemical principles using computational tools. This requires computer specialists capable of collaborating in molecular biology and related disciplines, such as organic chemistry and bioengineering. Similarly, there is a need for bioinformatics researchers with the skills to develop algorithms and computational tools to predict the structure and function of biomolecules (Liang et al., 2019). These results indicate that, based on this study's analysis, 16.4% of the examined articles are directly related to STEM education.

For employers, the requirement of skills in students is a priority to ensure their employability and contribution to society, as it represents the formation of skilled citizens. In the same way, educators must be trained to meet current challenges, integrating these competencies into both teaching methods and evaluation methods (Perfumo and Ares, 2020).

As for assessments, new methodologies have emerged since the pandemic, especially those based on real-world tasks, collaborative projects, digital portfolios, and online simulations that allow the assessment of practical skills and competencies in contexts that replicate real scenarios. These methods are particularly valued for their ability to foster 21st-century skills, especially in today's job market. In contrast, traditional approaches such as standardized written tests have lost relevance compared to these more innovative alternatives (Vlachopoulos and Makri, 2024). However, the same is not true for evaluations related to laboratory practices, which are essential in molecular biology.

Limitations of this research

This systematic review has some methodological limitations. Although a comprehensive search was conducted in WoS and Scopus, the exclusion of PubMed may have limited the identification of additional relevant articles, which could have enriched the evidence available for analysis.

Future lines of research

Although competencies are recognized by both the academic community and training programs as well as by the present research did not find evaluation methodologies specifically related to these competencies. This gap in the literature suggests the need to develop specialized assessment instruments to measure their reliability.

Conclusion

Molecular biology is a discipline included in honors programs due to its scientific relevance and the academic challenges it presents to students. This field employs active pedagogical approaches, such as inquiry-based, problem-based, and project-based learning, which encourage students to take initiative and manage their work autonomously.

Through hands-on experiences, students develop 21st-century pedagogical and evaluative competencies, including critical thinking, teamwork, problem-solving, research skills, as well as oral and written communication, innovation, creativity, and information technology management. These skills are demonstrated in projects that require methodological rigor, analytical depth, and data analysis.

In the laboratory, students use bioinformatics tools to compare predictions with experimental results, both in real and simulated projects. This process integrates theoretical knowledge with analytical skills, practical abilities, and collaboration, while fostering creativity and effective communication.

In addition, molecular biology courses incorporate formative and summative assessments aligned with the pedagogical process, including written exams, laboratory work, presentations, and the preparation of scientific articles or technical reports. These assessment tools allow students to demonstrate their practical application of research skills, supported by clear assessment criteria.

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

RPZ: Methodology, Validation, Project administration, Formal analysis, Supervision, Data curation, Conceptualization, Writing – original draft, Visualization, Investigation, Resources, Writing – review & editing, Funding acquisition. MM: Conceptualization, Methodology, Validation, Supervision, Writing – review & editing. MC-V: Investigation, Supervision, Writing – review & editing, Conceptualization. LS-O: Visualization, Conceptualization, Investigation, Validation, Writing – review & editing, Writing – original draft, 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.

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

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2025.1616858/full#supplementary-material

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