Strategies and Effective Learning in Genetics and Genomics Courses for Undergraduate Students: A Systematic Literature Review

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ABSTRACT

Genetics and genomics courses often contain complex and abstract content that can be challenging for students to comprehend. To address this, educators must employ engaging and effective learning strategies. This paper systematically reviews the literature on trends and strategies for enhancing learning in undergraduate genetics and genomics courses. The review follows a systematic literature review (SLR) methodology using the PRISMA flow for identification, evaluation, and interpretation of studies. The search was limited to articles published between 2008 and 2025, using the keywords " learning in genetics and genomics." From 3562 articles initially identified, 28 were selected for in-depth review. The study found that Problem-Based Learning (PBL) was the most prominent approach, appearing in various forms such as PBL-RQA, PBL-Online Discussion, PBL with Scientific Argumentation, and PBL-STEM. Other strategies included STEM learning, the learning cycle, inquiry learning, case-based learning, and several hybrid models. PBL is particularly prevalent due to its ability to enhance student knowledge, creativity, and problem-solving skills by encouraging exploration of real-world issues, critical reading, and questioning. Furthermore, PBL promotes collaboration, self-directed learning, and the development of communication skills competencies highly relevant in the 21st-century academic and professional landscape. These findings suggest that integrating PBL and other active learning models into genetics education can significantly improve student outcomes and engagement.

Keyword- Genetics Education, Active Learning Strategies, Undergraduate, Systematic Literature Review, Innovative Instructional Models

I.INTRODUCTION

The invention of recombinant DNA technology, commonly known as genetic engineering, has significantly advanced the field of genetics and genomics. As a core course in many undergraduate biology programs, Genetics and Genomics is distinguished by its complexity and intricate nature. Genetics, the study of heredity, encompasses the structure and function of genetic material, mechanisms of inheritance, gene expression regulation, genetic variation, population genetics, and genetic engineering [1]. Although the concept of heredity has been applied since the 18th century, it lacked a comprehensive scientific foundation at the time [2]. The field began to take shape following the pioneering work of Gregor Mendel in the 1860s. Mendel, through his experiments with pea plants, established the fundamental principles of inheritance, earning him the title "Father of Modern Genetics." Further breakthroughs, such as the discovery of the DNA double helix by James Watson and Francis Crick in 1953, provided deeper insights into genetic material and its transmission across generations [3].

In addition to classical Mendelian genetics, which explores the inheritance of genotypes and phenotypes from parent organisms, the Genetics and Genomics course also delves into the molecular basis of inheritance [4], [5]. It examines mutations, their consequences, and provides a comprehensive overview of genetic disorders and diseases [5]. A significant challenge in teaching this subject is students' difficulty in grasping molecular-level concepts, which are often abstract and not directly observable. Consequently, effective and targeted learning strategies are essential to enhance student understanding and memory.

However, integrating current scientific knowledge in genetics and genomics into undergraduate curricula faces several challenges. First, there is a need to balance the complexity of advanced concepts with accessibility for students from diverse academic backgrounds and varying levels of preparedness [6]. Second, instructors must possess sufficient pedagogical and domain expertise to teach these rapidly evolving fields effectively [7]. Third, the development of learning materials must ensure both scientific accuracy and relevance to real-world applications, such as biotechnology, personalized medicine, and global health issues [8], [9]. Based on this description, it is evident that the expansion of genomics knowledge and its societal applications represent a turning point in genetics education. These developments have stimulated pedagogical innovation, underscored the importance of scientific literacy, and reshaped how genetics and genomics are taught at the undergraduate level. Nonetheless, significant challenges remain to ensure the adequacy, accessibility, and relevance of instruction. Therefore, through this research, we aim to deepen understanding of current trends, identify effective practices, and propose recommendations for strengthening genetics and genomics education in higher education.

In this context, bibliometric analysis provides a systematic approach to examining current research trends and practices in genetics and genomics education for undergraduate students [10]. This method enables the identification of publication patterns, the evaluation of contributions from leading researchers and institutions, and the mapping of thematic evolution and methodological approaches within this field [11]. By applying bibliometric techniques, it becomes possible to capture how the academic and educational communities address the challenges of teaching complex genetics and genomics concepts, while also highlighting strategies that foster deeper understanding, critical thinking, and the development of essential scientific competencies [12].

This research describes and analyzes recent developments in strategies and effective learning practices in genetics and genomics courses for undergraduate students. Specifically, it identifies innovative and evidence-based teaching approaches, evaluates the integration of technology and active learning models, and examines substantial pedagogical shifts in response to the growing complexity of genetics and genomics education. Furthermore, this study investigates how diverse instructional strategies such as problem-based learning, inquiry-based approaches, case studies, and stochastic models enhance student comprehension, critical thinking, and scientific reasoning in genetics. Leveraging leading scientific publication databases such as Scopus, this research systematically reviews articles focusing on undergraduate genetics and genomics education, with analyses encompassing publication trends, geographical distribution, and patterns of institutional collaboration. At the content level, the review explores the core topics emphasized in genetics and genomics courses, including molecular mechanisms, genetic variability, data analysis, and their applications in human health and biotechnology. This systematic analysis provides insights into priority areas for curriculum development and highlights effective instructional strategies that align with both scientific advancements and the competencies required in the 21st-century biological sciences.

This research will identify current trends in genetics and genomics learning strategies and project the direction of their development in the coming years. Accordingly, the study is expected to make a significant contribution to improving the quality and relevance of undergraduate biology education, particularly in genetics and genomics, while also preparing future graduates with the knowledge, skills, and competencies needed to address emerging challenges in biotechnology, medicine, and global health.

RESEARCH METHODOLOGY

Data and Sources of Data

The method used in this study is a Systematic Literature Review (SLR), conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. This method involves the identification, evaluation, and interpretation of all relevant findings concerning the application of teaching strategies and learning models in Genetics and Genomics courses, based on predefined research questions. The literature search was restricted to research articles published between 2008 and 2024 from scopus database. Articles were retrieved using the search query “learning in genetics and genomics," filtered for research articles with relevant terms in the title or keywords within the Scopus database.

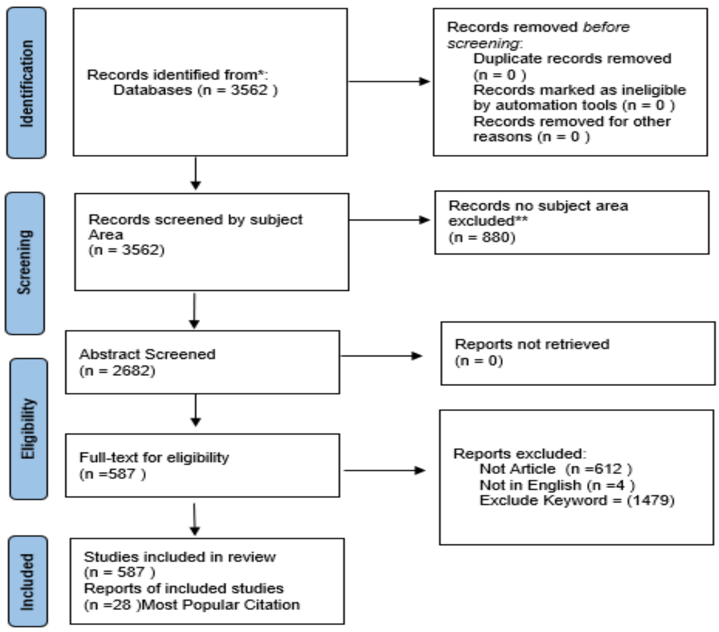

Fig. 1 PRISMA Diagram

The figure depicts the PRISMA flow diagram during the screening stage, 880 records were excluded due to irrelevance to the subject area, leaving 2,682 abstracts for further assessment. Following abstract screening, 587 articles were retained for full-text eligibility evaluation. Of these, several reports were excluded for not being categorized as articles (n = 612), not published in English (n = 4), or due to exclusion based on keywords (n = 1,479). Ultimately, 587 reports were included in the systematic review process, with 28 articles meeting all eligibility criteria and forming the final dataset for in-depth analysis.

In total, 28 articles met all criteria and were included in the final analysis of this literature review. In terms of national context, most studies originated from the United States, followed by China, UK, Australia, Germany, Canada, Brazil, India, South Korea and Japan. Furthermore, most of the articles (n = 20) were published between 2020 and 2025, while the remaining 8 articles were published between 2008 and 2017, indicating a growing trend in research on this topic in recent years.

Data Analysis

The data analysis process was conducted using VOSviewer software and Biblioshiny. Once the data was collected, the extracted files in CSV format were imported into VOSviewer software and Biblioshiny for further analysis and visualization. VOSviewer software and Biblioshiny was used to generate various network maps and overlays based on the data from all the articles found [11].

This research uses the co-occurrence analysis type with the unit of analysis in the form of author keywords. The choice of author keywords is the unit of analysis because the keywords provided reflect the core of their research focus, making it relevant to identify trends, significant themes, and relationships between topics in the reviewed literature. With co-occurrence analysis, the relationship between keywords can be visualized as a network map, which helps uncover research patterns and identify dominant emerging topics. This methodological approach makes it possible to gain an in-depth understanding of current research in virus learning at the post-pandemic senior secondary school level. By focusing on bibliometric analysis using VOSviewer based on Scopus data, this study is expected to determine the development of trends in virus learning in the next few years.

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RESULTS AND DISCUSSION

The Co-Occurrence of Learning Models Implemented In Genetics And Genomics

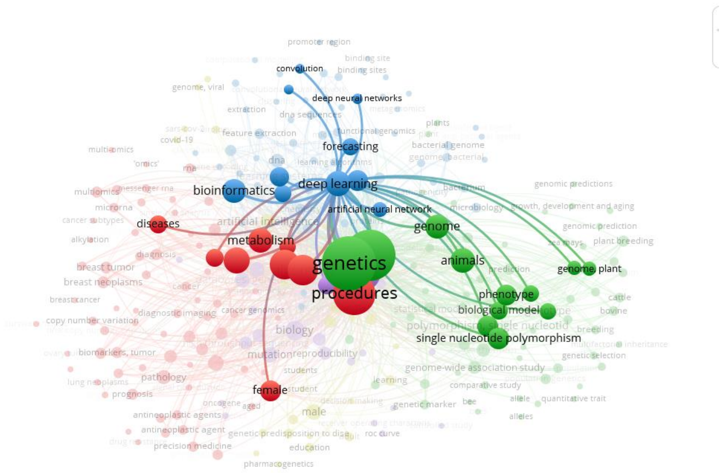

Fig. 2 Co-Occurence of Learning Models Implemented In Genetics And Genomics

The visualization highlights the interconnections among frequently used terms, with node size representing frequency and color clusters indicating thematic groupings. The largest cluster centers around “genetics” and “procedures”, reflecting the core focus of the reviewed studies. Surrounding clusters reveal related themes: the green cluster emphasizes genome, animals, phenotype, biological models, and single nucleotide polymorphism, highlighting applications in biological and genomic research; the red cluster associates diseases, metabolism, pathology, and cancer-related terms, reflecting biomedical and clinical contexts; while the blue cluster connects deep learning, bioinformatics, forecasting, and artificial neural networks, underscoring the integration of computational methods in genetics education and research. Overall, this network visualization demonstrates the multidimensional nature of genetics and genomics education, where biological, biomedical, and computational domains converge to inform effective learning strategies.

Distribution of Country

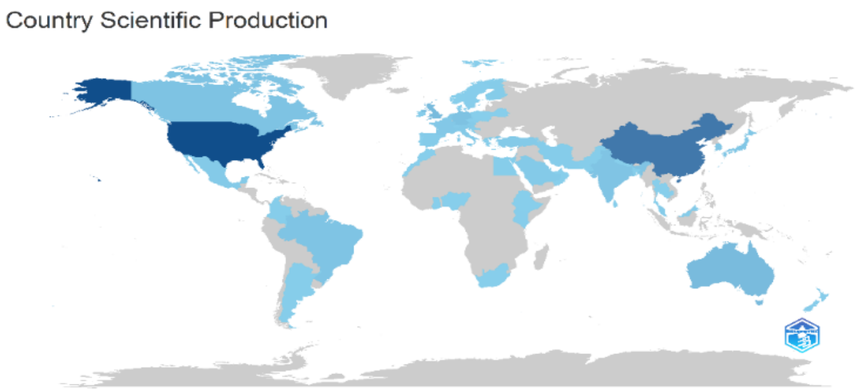

Fig. 3 Country Scientific Production

Figure 3 illustrates the global distribution of Country Scientific Production. The map employs a gradient of blue shades to indicate the intensity of scientific output, with darker colors representing higher levels of publication activity. As depicted, the United States, China, and several European countries emerge as the leading contributors to the body of literature in this field. Other nations, including Japan, Australia, Brazil, and South Africa, also contribute, though to a comparatively lesser extent. This visualization highlights the geographical concentration of research productivity, suggesting that scholarly discussions on effective strategies for teaching genetics and genomics at the undergraduate level remain predominantly driven by research communities in highly developed countries with substantial research capacity.

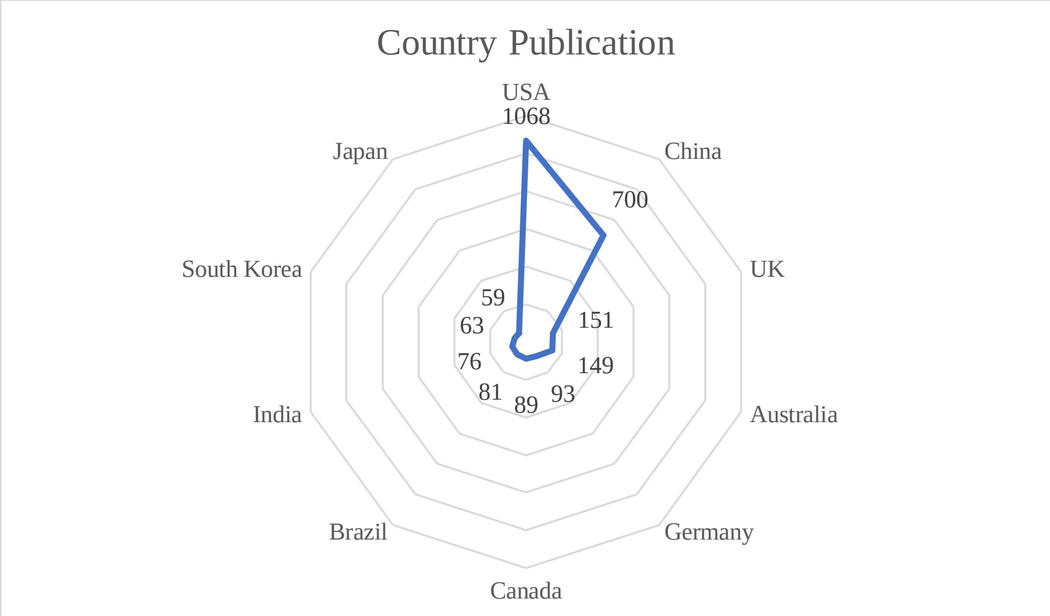

Fig. 4 Top 10 Country Publication

Figure 5 illustrates the comparative number of publications across different countries. The United States demonstrates the highest contribution with 1,068 publications, followed by China with 700 publications. The United Kingdom and Australia occupy the next ranks with 151 and 149 publications, respectively, while Germany and Canada contribute 93 and 89 publications. Brazil (81), India (76), South Korea (63), and Japan (59) show relatively lower yet notable contributions. This pattern emphasizes that the discourse on genetics and genomics education at the undergraduate level is largely dominated by research outputs from developed nations, particularly the United States and China, highlighting their central role in shaping global perspectives and pedagogical strategies within this field.

This visualization effectively highlights the global landscape of academic contributions, indicating that the United States is a key contributor to research on genetics and genomics education. The data also reflect varying levels of engagement from other countries, suggesting opportunities for increased research efforts and collaboration in underrepresented regions.

Despite the global relevance of genetics and genomics education, the geographic distribution of research remains uneven. Most of the reviewed studies originate from high-income countries such as the United States, China, the United Kingdom, Australia, and Germany. In contrast, regions with emerging scholarship such as Southeast Asia, Sub-Saharan Africa, Latin America, and the Middle East are minimally represented. This imbalance limits the diversity of pedagogical perspectives captured in the current literature. Educational challenges, resource availability, and sociocultural contexts in these regions differ significantly from those in high-income countries; therefore, more inclusive geographic representation is essential for developing globally applicable learning models in genetics education.

Distribution of Years and Number of Articles

A review of the literature on learning models used in genetics and genomics courses, published between 2008 and 2025, reveals varying levels of research focus. Several models, notably Problem-Based Learning (PBL) and STEM-based learning, appear more frequently, as indicated by a higher number of publications. In contrast, other models receive minimal attention, reflected in the lower number of related articles (Figure 1). PBL, in particular, is widely adopted due to its ability to foster student creativity and critical thinking in solving real-world problems. Creativity, in this context, can be assessed through indicators such as curiosity, fluency, originality, elaboration, flexibility [13], and metaphorical thinking [14]. Figure 1 presents the trends in publication and citation of studies on learning models in genetics and genomics courses over the 2008–2025 period. The data show a general increase in the number of publications per year, with slight fluctuations. The highest number of publications occurred in 2022, with five articles published.

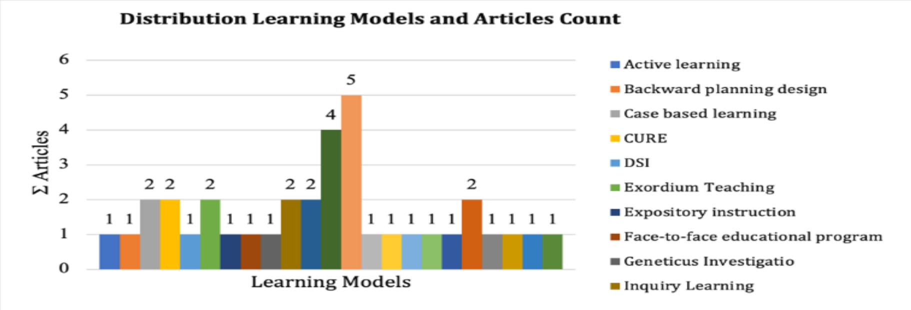

Fig. 3 Distribution Learning Models and Article Count

The Learning Models Implemented in Genetics and Genomics

Based on the literature exploration from 28 articles, there are nineteen types of learning models are widely applied in genetics and genomic courses (Table 1). These learning models includes Problem-based learning (PBL) is implemented in four learning approaches, namely PBL-RQA, PBL-Online Discussion, PBL with scientific argumentation, and PBL-STEM. While the rest is applied in learning STEM, learning cycle, Inquiry learning, Case-based learning, Course-based research experience learning (CURE), Differentiated science inquiry (DSI) learning, exordium teaching, RQA, active learning, Backward planning design, Expository instruction, Geneticus Investigation, Face-to-face educational program, Remote learning, RQA, Scaffolding complex learning, Service-Learning, Stochastic Model, and Student-centered learning. Each learning models has its own advantages and disadvantages also has it focused on specific aspects of the learning activities.

TABLE 1 Learning Model or Strategies in Genetics and Genomics Course

Learning Model or Strategies	**Syntax**	**Difficulties in Learning Model**	**Advantages in Learning Model**	**References**
Service-Learning	1. Identifying the required service 2. Locating a suitable community collaborator 3. Connecting the service activity with learning objectives 4. Overseeing the execution of the project or initiative 5. Encouraging continuous student reflection during the process	Teachers require more time in online learning compared to face-to-face instruction, while students experience unfamiliarity due to limited interaction and decreased motivation, posing significant challenges to the learning process.	Experiential learning in real classroom settings enabled undergraduate students to apply knowledge in practical contexts, enhancing comprehension, motivation, and cognitive development.	[15]
Student-centered learning	Topic selection Collaboration planning Implementation Analysis Presentation of final results Evaluation	Key concerns in student-centered learning involve variations in individual skills and competencies, including independence, cooperation, and	Student-centered learning fosters active knowledge acquisition, deeper conceptual understanding, and enhanced communication through student–lecturer discussions that promote	[16]

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		personal understanding..	diverse perspectives and critical data analysis.	
Stochastic Model	1. Introduces the fundamental structure and demonstrates concepts using several widely recognized learning algorithms. 2. Provided students with essential mathematical foundations to analyze the convergence behavior of stochastic learning algorithms. 3. Explores the performance of stochastic learning algorithms on large datasets, addressing both statistical accuracy and computational demands.	In genetics learning, stochastic models face difficulties due to the complexity, noise, and inherent variability of biological data, which can lead to inaccurate or unstable outcomes and limit their ability to capture full biological diversity.	Stochastic models effectively introduce beginner students to mechanistic and probabilistic concepts, such as genetic drift, while challenging deterministic views and fostering quantitative reasoning in understanding biological phenomena.	[17], [18]
Learning cycle model	1. The teacher engages students in practical activities that relate directly to the learning content (Exploration). 2. The teacher guides a discussion where students exchange their observations with classmates. 3. The teacher links students' experiences to the appropriate scientific concepts. 4. Students take part in additional tasks that apply their new understanding in varied contexts.	This study cannot indicate a significant contribution of self-efficacy to genetics achievements.	Students showed significantly higher improvement in understanding concrete concepts and more frequently progressed between developmental stages compared to those in the expository teaching group.	[19]
Case-study model	1. Define the case 2. Analyze the case	The application of case studies and case study articles used is quite complicated and there is too much reading. It	The assessment results indicate improvements in both content knowledge and students' perceptions of their learning after	[20]

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	3. Independently find information, data and literature 4. Students determine the solution steps of the case that has been provided 5. Making 6. Conclusions from the answers that have been discussed together 7. Presentation improvement	takes a lot of time about more than 1 hour to analyze the article or case study to solve the problem to find a way out of the case.	implementing the case study approach.	
Problem based learning – Online Discussion	1. Clarify and reach consensus on the definitions of ambiguous terms and concepts 2. Identify the core problem and agree on the phenomena that need to be explained 3. Break down and examine the problem in detail 4. Organize possible explanations into a preliminary solution 5. Formulate and rank learning objectives by importance 6. Investigate the objectives through independent study 7. Share findings, integrate explanations, and relate new knowledge back to the original problem	The competencies of the teacher for this type of strategy can also be challenging Competencies for the teacher regarding concepts and genetic literacy skills are essential to avoid any misconceptions.	Problem-Based Learning (PBL) enhances 21st-century skills by fostering problem-solving, critical thinking, genetic literacy, and interactive teacher–student collaboration, while challenging students to present solutions, engage in discussion, and strengthen argumentation through feedback and rebuttals.	[21]
Course-based research experience learning (CURE)	1. Learn Essential Experimental Techniques a. Guided question	Student struggle with time management and learning new tools and research on genetics course.	The laboratory fosters discovery through unfamiliar data, iterative processes, and extensive collaboration, enabling students to develop core scientific practices while	[22]

	b. Literature review 2. Design an Experiment a. Develop group question b. Write protocol 3. Carry out Experiment a. Autonomy b. Time (open lab) c. Collect & analyze data 4. Interpret Data & Communicate Results a. Poster, presentation, or formal paper		engaging with topics of broader relevance and potential scholarly impact.	
Case-study Model	1. Define the case 2. Case-study analysis 3. Independently find Information, data and literature 4. Students determine the solution steps of the case that has been provided 5. Making conclusions from the answers that have been discussed together 6. Presentation 7. Improvement	Detail assessment is required to assess the score of the student from their response or results of the discussion.	Case-based learning enhances problem-solving, critical thinking, and higher-order cognitive skills through active, collaborative, and integrative engagement with relevant information.	[23]
Problem-based learning – STEM	1. Problem orientation 2. Opinion expression 3. Evaluation. 4. Implementation. 5. Presentation. 6. Reflection.	Effective PBL activities require motivating and conceptually deep problems that foster rational decision-making, integration of prior knowledge, and collaborative problem-solving, with initial phases	PBL encourage students to directly involve in the execution of project and assignments. This method gives opportunities for first-year students to collaborate trying to looking for solution to the given problem that related	[24], [25]

		designed to be open-ended and engaging.	with real-world phenomena	
Remote Learning	1. Setting the lesson 2. Define lesson objectives 3. Assess current understanding 4. Introduce content dan assign application activity 5. Assess mastery	Limited teacher–student and peer interaction, a training-oriented approach, the demand for teachers to master remote learning, and low student motivation collectively hinder both academic and social dimensions, increasing the risk of academic failure.	A remote learning time management tool based on the Pomodoro Technique enhances task completion by structuring 25-minute focus cycles with short breaks, effectively reducing procrastination, multitasking, and distractions.	[26]
Inquiry learning	1. Inquiry: beginning with a question to explore 2. Gathering: brainstorming potential answers 3. Hypothesis: choosing a statement to test 4. Planning: creating a strategy for investigation 5. Evaluation: collecting evidence and forming conclusions 6. Presentation: sharing and communicating the results or discoveries	Scheduling may be more difficult for these classes because the module is structured for multiple consecutive days, whereas most college courses do not have back-to-back sessions.	Although the results varied, they generally indicate that the module effectively enhanced students' knowledge of plant genetics and boosted their interest and confidence in the subject.	[27]
Learning cycle	1. The teacher offers students practical activities connected to the learning material. 2. The teacher leads a discussion where students exchange their observations with classmates. 3. The teacher links students' experiences to the appropriate scientific concepts.	Learning effectiveness depends on teachers' mastery, sincerity, and creativity, supported by well-planned management and the substantial time and effort required for lesson preparation and implementation.	The learning cycle approach enhances genetics achievement by engaging students in hands-on experiments, problem-solving, and concept integration, with success linked to strong reasoning and meaningful conceptual connections.	[28]

	4. Students engage in additional tasks that apply their newly acquired knowledge in various contexts.			
Expository instruction	1.Delivery of Learning Objectives and 2.Learning Material 3.Apperception 4.Carrying Out Expository a. Explaining facts, concepts, principles, laws directly, through questions and answers, illustrations, demonstrations and the use of media to clarify concepts. b. Practice questions c. Summarising 5.Evaluation a. Giving test for evaluation b. Giving homework assignment	Lack of opportunities for the development of students' exploration ability, creativity, independence and critical thinking. Tends to cause passivity in students because they are used to receiving. Activities tend to be mechanistic	The expository learning model is effective for delivering extensive material within limited time by allowing teachers to control content scope and sequence through explanations and demonstrations, making it practical for large classes.	[28]
Backward planning design	1.Determine the intended outcomes. Define what students are expected to comprehend and be able to perform by the conclusion of the unit or course. 2.Establish acceptable evidence. Decide how students will demonstrate their understanding and what types of evidence will be considered valid to show they have achieved the learning objectives. 3.Design learning activities and	One of the difficult parts of the backward design process is determining the desired result.	The flexibility to use the textbook as a supportive reference rather than letting it dictate the direction of the course	[29]

	instruction. Plan the knowledge and skills students will require to succeed in the unit or course, and develop corresponding instructional experiences.			
STEM	1. Observe 2. New Idea 3. Reconstruction 4. Innovation 5. Creativity 6. Society	Beliefs linking genetics to determinism and racial essentialism may discourage marginalized students from pursuing biology and create cognitive dissonance when contrasting social science perspectives with genetics or medical education.	STEM education fosters problem recognition, knowledge acquisition, and inquiry-based understanding of disciplinary processes while engaging students in problem-solving that reflects global intellectual and cultural contexts.	[30]
Face-to-face educational program	1. Review the existing nursing curriculum to determine how well it incorporates genetics and genomics-related content. 2. Use a survey to evaluate the faculty's current understanding of genetics/genomics and their level of confidence in teaching the subject. 3. Improve faculty knowledge and teaching confidence regarding genetics/genomics through professional development sessions and by expanding access to relevant genomic resources. 4. Measure changes in faculty knowledge and confidence following participation in the development sessions. 5. Create a new course and update the current	Systemic obstacles to implementing genetics/genomics initiatives included competing institutional priorities, limited faculty engagement, undervaluing of content, concerns over evaluations, and weak leadership support without active promotion or mandatory participation.	Workshop participation increased faculty confidence, particularly in discussing the influence of family history on screening recommendations.	[31]

	curriculum to better integrate genetics/genomics content.			
Problem-based Learning (PBL)	The PBL teaching approach is implemented in two phases. **Asynchronous phase (4 days):** 1. Begin with orienting students to the problem at hand. 2. Facilitate student organization into study groups. 3. Support and guide group investigations into the problem. **Synchronous phase (2 days):** 4. Students collaborate to develop their solutions and present their findings through group presentations. 5. Finally, the class engages in analyzing and evaluating the overall problem-solving process.	While PBL effectively develops professional skills when carefully structured, its main drawback is the considerable time required for students to identify solutions.	Findings showed that PBL fostered student creativity across classes, as reflected in curiosity, fluency, originality, elaboration, flexibility, and metaphorical thinking, despite no significant differences in improvement levels.	[32]
RQA	The RQA (Read, Question, Answer) teaching strategy is divided into two phases: **Asynchronous phase (4 days):** 1.Students begin by reading the assigned material and creating summaries. 2.Next, they formulate questions based on their understanding of the content.	The RQA class faces a limitation in that many students tend to produce similar questions and answers. This similarity likely results from all students using the same reading material provided by the lecturer as their reference.	The results showed improved student creativity across classes, reflected in curiosity, fluency, originality, elaboration, flexibility, and metaphorical thinking, with the RQA method further fostering curiosity and idea generation.	[32]

	3.Then, they attempt to answer the questions they have developed. **Synchronous phase (2 days):** 4.Students engage in group discussions to share and refine their understanding. 5.Finally, they participate in a review session to reinforce and reflect on what they have learned.			
PBL-RQA	The PBL-RQA (Problem-Based Learning – Read, Question, Answer) strategy is carried out in two phases: **Asynchronous phase (4 days):** 1. Students are introduced to the problems and directed to explore related literature, followed by writing summaries of their readings. 2. They then formulate questions based on the material and attempt to answer them as preliminary solutions. 3. Students are organized into study groups to facilitate collaborative learning. 4. Instructors guide students through the investigation process and support group discussions to deepen understanding. **Synchronous phase (2 days):**	The PBL-RQA class presents certain limitations due to its relatively extended sequence of stages, which requires more time compared to using PBL or RQA alone. Additional challenges arise from technological constraints, such as students lacking adequate digital devices like laptops or smartphones, as well as experiencing unstable internet connections.	The PBL-RQA approach, combining Problem-Based Learning with Read-Question-Answer strategies, enhanced student creativity—reflected in curiosity, fluency, originality, elaboration, flexibility, and metaphorical thinking—by enriching knowledge, stimulating idea generation, and fostering creative problem-solving.	[32]

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	5. Students develop and present their group findings and solutions. 6. The class concludes by analyzing and evaluating the overall problem-solving process.			
Blend of problem-based learning (PBL) with scientific argumentation	1. Begin by presenting an open-ended or ill-structured problem to spark students' curiosity and engagement. 2. Facilitate small group discussions organized around three guiding questions: "What do we know?", "What do we need to know?", and "What are our hypotheses?" 3. Introduce the second part of the scenario to provide additional details, prompting students—working in diverse small groups—to explore possible solutions and select what they believe to be the most appropriate one. 4. Clearly define the topics to support students in researching relevant information and evidence that strengthens their chosen solution through sound reasoning. 5. Conduct a whole-class discussion focused on scientific argumentation, where each group's representative presents their solution and supporting evidence, while others offer	The study, limited to a six-week genetics unit with Grade 9 students taught by a non-expert teacher, highlights the need for replication with larger, cross-national samples and expert-led instruction to strengthen and generalize the findings.	The method proved effective in teaching basic genetics by addressing common misconceptions and fostering student enjoyment, deeper engagement, and characteristics of self-directed, independent learning.	[24]

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	rebuttals to challenge competing claims. 6. The process should lead the class toward a shared agreement on the most valid and well-supported solution to the problem.			
Geneticus Investigatio (GI) Scaffolding complex learning	1. Define the problem 2. Identify hypothesis 3. Design and predict result 4. Perform experiment 5. Observe result 6. Evaluate 7. Summarize	No significant improvement was found in students' skills in designing breeding experiments or formulating hypotheses, reinforcing evidence that such abilities require sustained practice and long-term engagement.	Guided Inquiry (GI) produced high learning gains by supporting conceptual understanding and inquiry practices, with students effectively applying domain-specific concepts through interactive video-based learning rather than direct teacher instruction.	[33]d
Exordium Teaching	1. Build on the courses students have already studied and teach new material by connecting it to their existing knowledge base. 2. Carefully plan instruction to stimulate students' interest and enthusiasm for learning. 3. Clearly identify the research topics and specific tasks related to genetics. 4. Present the historical development of genetics to ignite students' passion and provide meaningful insights. 5. Relate genetics content to real-life situations and highlight its practical applications.	A predominantly narrative approach, such as Exordium, may be ineffective for teaching genetics, as its complex concepts, technical terminology, methodologies, and quantitative analyses require clear, structured, and systematic instruction.	This vivid language enhances cognitive engagement with genetic concepts and generates a strong interest in the subject of genetics.	[34]
Exordium Teaching	1.Understand the having-studied courses and teach the students	Implementing the Exordium model is challenging as it	The Exordium approach offers a powerful framework for introducing	[35]

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	with students' having learned knowledge 2.Elaborately design and inspire the students' learning interest 3.Define the research subject and task of genetics 4.Teach the developing history and inspire students' learning passions and make students gain revelation 5.Integrating with reality and emphasizing the application of genetics	demands extensive teacher preparation, continuous professional growth, and deep expertise in genetics to effectively engage students with complex life science content.	students to complex life sciences, but its success depends on teachers' thoughtful preparation, continual skill refinement, and up-to-date expertise in genetics.	
Active learning	A. Experience 1. Making observations 2. Doing an experiment 3. Reading 4. Conducting an interview 5. Making things B. Interaction 1. Asking questions 2. Asking for others' opinions 3. Making comments 4. Working in a group C. Communication 1. Demonstrating/showing/explaining 2. Speaking/telling/telling 3. Reporting 4. Expressing opinions/thoughts (oral/written)	Designing a study that convincingly demonstrates the effectiveness of flipped classrooms compared to other forms of collaborative learning presents a significant challenge, due to the complexity of isolating variables and accounting for the diverse contexts in which active learning occurs.	A key advantage of active learning lies in positioning undergraduate students as active participants in the learning process, where the collaborative construction of knowledge through social interaction significantly enhances understanding beyond individual cognitive efforts.	[36]

	5. Exhibition of work D.Reflection			
PBL- STEM	1.Problem Identification in PBL Process 2.Idea Generation Identification in PBL Process 3.Learning Issues Identification in PBL Process 4.Self-Directed Learning in PBL Process 5.Synthesis and Application in PBL Process 6.Reflection and Feedback in PBL Process	In higher education, active learning presumes that students are self-directed and intrinsically motivated; however, many undergraduates struggle to meet this expectation, finding it difficult to take full ownership of their learning without structured guidance.	The research findings suggest that incorporating STEM problem-based learning into genetics instruction can be an effective strategy for enhancing first-year undergraduates' interest and engagement with genetic concepts.	[37]
Inquiry Learning - Differentiated Science Inquiry (DSI) learning	1.Inquiry – initiating the process by posing a question that needs exploration. 2.Idea Generation – thinking broadly to come up with various potential answers. 3.Hypothesis Formation – choosing a specific idea or statement to evaluate or test. 4.Planning – creating a structured approach or strategy to investigate the chosen idea. 5.Conclusion Drawing – collecting data or information and forming conclusions based on the findings. 6.Presentation – conveying and discussing the outcomes	The initial implementation of inquiry-based learning can be challenging due to diverse student characteristics, including their interests, learning preferences, readiness, and capacity to absorb and interpret information. Moreover, transitioning to this new instructional approach demands time for adaptation, which may postpone the attainment of desired outcomes. The teacher's proficiency in facilitating this strategy also poses difficulties. Additionally, inquiry-based	1. DSI learning method provides opportunities for students with higher perception and abilities to improve their skills, encouraging students to actively explore processes and empowering cognitive processes while considering students with lower skills. 2. Inquiry learning also gives opportunities to indulge curiosity, develop creativity, generate and discuss ideas, give arguments, make plans, and troubleshoot, 3. Inquiry learning has its level which is differentiated based on the intervention or guidance from the teacher toward learning activities: 4. Demonstration Inquiry (Level 1) -> The teachers play roles in providing the	[18], [38], [39]

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	or discoveries with others.	learning involves intricate assessment methods that often require strong alignment with and support from the existing curriculum.	problem, planning the procedures, and analyzing the results 5. Structured inquiry (Level 2) -> The teachers play roles in providing the problem and planning the procedures while students are tasked to analyze the results 6. Guided inquiry (Level 3) -> The teachers only play roles in providing the problem while students were tasked to plan the procedures and analyze the results 7. Self-directed inquiry (Level 4) -> student actively executes all activities, from providing the problem to analyzing the results.	
Course-based research experience learning (CURE)	A. Learn Essential Experimental Techniques 1. Guided question 2. Literature review B. Design an Experiment 1. Developed group question 2. Write protocol C. Carry out Experiment 1. Autonomy 2. Time (open lab) 3. Collect & analyze data D. Interpret Data & Communicate Results 1. Poster, presentation, or formal paper	Student might Experience high frustration level during learning Rigid structure and focused on or few topics per course Students might have diverse time to adapt to the system	CURE allow students to develop basic research skills and involved in comprehensive research within curriculum. Research skills that can be acquired include research ethics, research plan formulation, information gathering, data collection and analysis. This learning method allows students to improve their self-confidence, knowledge, and work efficiency.	[40], [41]

The table provides a comprehensive comparison of various learning models and strategies, outlining their syntax, potential difficulties, advantages, and supporting references. Each approach ranging from service-learning, student-centered learning, stochastic models, learning cycles, case-based learning, and problem-based learning (PBL), to more specialized strategies such as CURE, RQA, PBL-RQA, Exordium teaching, and active learning presents unique strengths and challenges. While difficulties often relate to time demands, teacher competencies, student motivation, or content complexity, the advantages consistently highlight enhanced problem-solving, critical thinking, creativity, scientific reasoning, and student engagement. Collectively, the table emphasizes that selecting an appropriate learning model requires balancing pedagogical objectives, subject matter complexity, and learner needs, while also considering institutional support and teacher expertise to maximize effectiveness in genetics and related disciplines.

Genetics is a fundamental subject for biology majors at universities and colleges. However, some introductory concepts in genetics are highly abstract and pose challenges for students' comprehension. In such cases, instructors are encouraged to use vivid and accessible method to facilitate student understanding and engagement. Our study identified four dominant variations of problem-based learning (PBL) applied in genetics education: PBL-RQA (Reading, Questioning, and Answering), PBL with online discussion, PBL integrated with scientific argumentation, and PBL-STEM. The prevalence of PBL in the literature suggests that it is widely regarded as an effective and relevant instructional model for teaching complex genetic concepts. The effectiveness of PBL is attributed to its ability to foster critical thinking, independent inquiry, and practical problem-solving skills key competencies in modern genetics education.

PBL also supports the development of essential 21st-century skills by encouraging students to approach problems using diverse strategies and by fostering their abilities to respond to feedback, construct rebuttals, and articulate scientific arguments. Furthermore, PBL promotes greater student engagement in classroom activities by encouraging active participation in the process of knowledge construction. Through the identification and resolution of real-world, ill-structured problems, students are empowered to build meaningful understanding of genetics [24]. While PBL offers several advantages for application in genetics education, certain considerations must be addressed to ensure its suitability. The problems posed to students should be designed to encourage rational decision-making and the ability to defend arguments appropriately. These problems must also include objectives that promote connections with prior knowledge and coursework. In group-based PBL models, problem complexity is essential to foster effective collaboration among students in solving the presented challenges [24], [25].

PBL is particularly well-suited for genetics education due to the inherently complex and applicable nature of genetic content. Many genetics concepts are closely linked to real-world case studies, such as genetic disorders, inheritance patterns, and advances in biotechnology. PBL enables students to engage with these authentic problems, thereby enhancing conceptual understanding along with analytical and critical thinking skills. This instructional model emphasizes collaborative problem-solving, aligning with the necessity to develop both critical thinking and teamwork competencies in genetics. Students in this field often work in groups to analyze genetic data, design experimental studies, and assess the ethical implications of genetic research. PBL helps prepare students for such tasks by promoting independent inquiry, which may involve reviewing scientific literature, interpreting genetic data, or exploring cutting-edge technologies such as CRISPR. Furthermore, PBL frequently incorporates a practical component that requires students to design and execute experiments to resolve specific problems. Given the highly experimental nature of genetics, where theoretical concepts are often validated through laboratory work, PBL provides an effective platform for integrating theory with practice. Research on the use of PBL in genetics may thus focus on how this model can be leveraged to enhance the integration of practical activities.

The findings of this study which show that PBL effectively improves students' understanding and skill development in genetics courses highlight the growing academic interest in this instructional model. Trends in higher education pedagogy increasingly favor active learning approaches, making PBL a prominent and relevant topic in science education research, particularly in the context of genetics.

CONCLUSION

Based on a review of literature from 2008 to 2025 on learning models and strategies in genetics and genomics courses, Problem-Based Learning (PBL) emerged as the most frequently implemented approach. PBL was applied through four distinct methods: PBL-RQA, PBL-Online Discussion, PBL with Scientific Argumentation, and PBL-STEM. Other models identified in the literature include STEM Learning, Learning Cycle, Inquiry Learning, Case-Based Learning, Course-Based Undergraduate Research Experiences (CURE), Differentiated Science Inquiry (DSI), Exordium Teaching, RQA, Active Learning, Backward Design, Expository Instruction, Geneticus Investigatio, Face-to-Face Educational Programs, Remote Learning, Scaffolding Complex Learning, Service-Learning, Stochastic Models, and Student-Centered Learning. Among these, PBL stands out as the most effective model for teaching genetics and genomics. It enhances essential 21st-century skills such as problem-solving and critical thinking. PBL also provides opportunities for first-year students to collaborate in finding solutions to real-world problems, thereby deepening their conceptual understanding and engagement.

Future studies should intentionally incorporate findings from regions with growing research capacity in genetics education, particularly Southeast Asia, South Asia, Sub-Saharan Africa, and Latin America. Greater geographic diversity would provide a more comprehensive understanding of how different institutional infrastructures, cultural contexts, and technological conditions shape effective learning strategies. Such inclusion is crucial for producing recommendations that are globally relevant and sensitive to diverse educational realities.

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REFERENCES

1. W. S. Klug, M. R. Cummings, C. A. Spencer, and M. A. Palladino, Concepts of Genetics (10th Ed.). California: Pearson, 2012.
2. S. Safrida et al., PENGANTAR BIOLOGI: Teori Komprehensif. PT. Sonpedia Publishing Indonesia, 2023.
3. H. Adrianto, Buku Ajar Biologi Sel dan Molekuler. Deepublish, 2018.
4. J. Gayon, “De Mendel à l’épigénétique : histoire de la génétique,” Comptes Rendus - Biol., vol. 339, no. 7–8, pp. 225–230, 2016, doi: 10.1016/j.crvi.2016.05.009.
5. J. Zschocke, P. H. Byers, and A. O. M. Wilkie, “Mendelian inheritance revisited: dominance and recessiveness in medical genetics,” Nat. Rev. Genet., vol. 24, no. 7, pp. 442–463, 2023, doi: 10.1038/s41576-023-00574-0.
6. S. N. Sato et al., “Navigating the new normal: Adapting online and distance learning in the post-pandemic era,” Educ. Sci., vol. 14, no. 1, p. Article 19, 2024, doi: 10.3390/educsci14010019.
7. Y. R. Langoday, Nurrahma, and S. Rijal, “Policy reflection: Kurikulum merdeka as educational innovation in the era of society 5.0,” Edunesia J. Ilm. Pendidik., vol. 5, no. 2, pp. 957–978, 2024, doi: 10.51276/edu.v5i2.915.
8. M. E. Auld et al., “Health literacy and health education in schools: Collaboration for action,” NAM Perspect., 2020, doi: 10.31478/202007b.
9. L. Darling-Hammond, L. Flook, C. Cook-Harvey, B. Barron, and D. Osher, “Implications for educational practice of the science of learning and development,” Appl. Dev. Sci., vol. 24, no. 2, pp. 97–140, 2020, doi: 10.1080/10888691.2018.1537791.
10. M. Aria and C. Cuccurullo, “Bibliometrix: An R-tool for comprehensive science mapping analysis,” J. Informetr., vol. 11, no. 4, pp. 959–975, 2017, doi: 10.1016/j.joi.2017.08.007.
11. N. J. van Eck and L. Waltman, “Software survey: VOSviewer, a computer program for bibliometric mapping,” Scientometrics, vol. 84, no. 2, pp. 523–538, 2010, doi: 10.1007/s11192-009-0146-3.
12. N. Suprapto, B. K. Prahani, and U. A. Deta, “Research trend on ethnoscience through bibliometric analysis (2011-2020) and the contribution of Indonesia,” 2021. doi:

https://digitalcommons.unl.edu/libphilprac/5599.
13. L. M. Greenstein, Assessing 21st century skills: A guide to evaluating mastery and authentic learning. Corwin Press, 2012.
14. D. J. Treffinger, G. C. Young, E. C. Selby, and C. Shepardson, "Assessing Creativity: A Guide for Educators," National Research Center on the Gifted and Talented, 2002.
15. H. E. Chrispeels et al., "Undergraduates achieve learning gains in plant genetics through peer teaching of secondary students," CBE—Life Sci. Educ., vol. 13, no. 4, pp. 641–652, 2014.
16. E. D. Pratiwi, M. Masykuri, and M. Ramli, "Active Learning Strategy on Higher Education Biology Learning: A Systematic Review," Tadris J. Kegur. Dan Ilmu Tarb., vol. 6, no. 1, pp. 75–86, 2021.
17. A. R. Mohammed, R. R. Habeeb, and N. A. H. Al-Muhja, "Genetic Literacy for Students in Faculties of Education in Universities," J. Varidika, vol. 34, no. 2, pp. 10–22, 2022.
18. "Rais, M. A., Amin, M., & Lukiati, B. (2021). Teaching Genetics Through Differentiated Science Inquiry Based On Research Results Of Gene Variation Analysis To Increase Cognitive Learning Outcomes Undergraduate Biology Student. BIOEDUKASI, 19(1), 9–14.".
19. D. Murni, M. Amin, U. Lestari, S. R. Lestari, and S. E. Indriwati, "Students' Responses and Expectations about the Opportunity of Virtual Laboratory Using in Genetics Courses."
20. C. C. Alexander et al., "A case study to engage students in the research design and ethics of high-throughput metagenomics," J. Microbiol. Biol. Educ., vol. 25, no. 1, pp. e00074-23, 2024.
21. Y. Maryuningsih, T. Hidayat, R. Riandi, and N. Y. Rustaman, "Application of genetic problem base online discussion to improve genetic literacy of prospective teachers," JPBI (Jurnal Pendidik. Biol. Indones., vol. 8, no. 1, pp. 65–76, 2022.
22. N. R. Forte et al., "Engaging students in a genetics course-based undergraduate research experience utilizing Caenorhabditis elegans in hybrid learning to explore human disease gene variants," J. Microbiol. Biol. Educ., vol. 24, no. 3, pp. e00078-23, 2023.
23. M. Murray-Nseula, "Incorporating case studies into an undergraduate genetics course," J. Scholarsh. Teach. Learn., pp. 75–85, 2011.
24. T. Choden and S. Kijkuakul, "Blending Problem Based Learning with Scientific Argumentation to Enhance Students' Understanding of Basic Genetics," Int. J. Instr., vol. 13, no. 1, pp. 445–462, 2020.
25. S. P. A. Rahim, N. Nordin, and M. A. Samsudin, "Integrated STEM problem-based learning approach: A study on Malaysian undergraduates' achievement in learning genetics concepts," Int. J. Educ. Psychol. Couns., vol. 7, no. 48, pp. 27–39, 2022.
26. "Gurat, M., & Santiago, C. (2023). The Effect of Pomodoro Technique on Student Mendelian Genetics Concept Mastery during Synchronous Remote Learning.".
27. J. L. Hsu, H. S. Atamian, and K. Avendano-Woodruff, "Promoting student interest in plant biology through an inquiry-based module exploring plant circadian rhythm, gene expression, and defense against insects," J. Microbiol. Biol. Educ., vol. 25, no. 1, pp. e00166-23, 2024.
28. P. Dogru-Atay and C. Tekkaya, "Promoting students' learning in genetics with the learning cycle," J. Exp. Educ., vol. 76, no. 3, pp. 259–280, 2008.
29. D. L. Carlson and P. A. Marshall, "Learning the science of research, learning the art of teaching: Planning backwards in a college genetics course," Biosci. Educ., vol. 13, no. 1, pp. 1–9, 2009.
30. E. Guevara et al., "Getting it right: Teaching undergraduate biology to undermine racial essentialism," Biol. Methods Protoc., vol. 8, no. 1, p. bpad032, 2023.
31. M. A. Smania, A. Annis, D. Pathak, E. Wasilevich, and K. Poindexter, "Faculty education to improve integration of genomics education in nursing curriculum," J. Prof. Nurs., vol. 43, p. 74, 2022.
32. E. Angraini, S. Zubaidah, H. Susanto, and N. Omar, "Enhancing creativity in genetics using three teaching strategies-based TPACK model," Eurasia J. Math. Sci. Technol. Educ., vol. 18, no. 12, p. em2196, 2022.
33. A. Deep, S. Murthy, and J. Bhat, "Geneticus Investigatio: a technology-enhanced learning environment for scaffolding complex learning in genetics," Res. Pract. Technol. Enhanc. Learn., vol. 15, pp. 1–23, 2020.
34. Y. Li, "Stimulate Students' Interest by Genetics Exordium Teaching," Int. Educ. Stud., vol. 2, no. 2, pp. 99–102, 2009.
35. A. Nisselle et al., "Investigating genomic medicine practice and perceptions amongst Australian non-genetics physicians to inform education and implementation," NPJ Genomic Med., vol. 8, no. 1, p. 13,

2023.

36. D. Lombardi and T. F. Shipley, "The curious construct of active learning," Psychol. Sci. Public Interes., vol. 22, no. 1, p. 8, 2021.
37. S. Rahim, M. Samsudin, M. E. Ismail, M. Amiruddin, and C. Abdul Talib, "Undergraduates' Interest Towards Learning Genetics Concepts Through Integrated Stemproblem Based Learning Approach," J. Univ. Shanghai Sci. Technol., vol. 22, 2020.
38. D. Llewellyn, Differentiated science inquiry. Corwin Press, 2010.
39. S. Zubaidah, N. M. Fuad, S. Mahanal, and E. Suarsini, "Improving creative thinking skills of students through differentiated science inquiry integrated with mind map," J. Turkish Sci. Educ., vol. 14, no. 4, pp. 77–91, 2017.
40. G. Bangera and S. E. Brownell, "Course-based undergraduate research experiences can make scientific research more inclusive," CBE—Life Sci. Educ., vol. 13, no. 4, pp. 602–606, 2014.
41. Y. Zhu, C. Wang, D. I. Hanauer, and M. J. Graham, "Course-based undergraduate research experiences (CUREs) and student interest development: a longitudinal study investigating the roles of challenge, frustration, and meaning making," Stud. High. Educ., pp. 1–16, 2024.