International Journal of Science Education and Teaching
Vol. 5, No. 1, pp. 16 - 34, Jan. – Apr. 2026
http://doi.org/10.14456/ijset.2026.02

Research Article

Integrating Precision Medicine Concepts into Biology Education: Preparing Future Biology Teachers for Contemporary Scientific Challenges

Naira Magdy Darwish[1]*
[1]Department of Curriculum and Science Teaching,
Faculty of Education, Kafr El-Sheikh University, Egypt
*Email: nairadarwish77@gmail.com

Received: 14 Mar. 2026 Revised: 25 Apr. 2026 Accepted: 5 May 2026

Abstract.
The present research aimed to investigate the integration of precision medicine concepts into biology teacher preparation programs in light of rapid advancements in genomics and biomedical technologies, which have positioned precision medicine as a key component of modern healthcare. A descriptive–analytical mixed-methods design was employed. The participants included 50 pre-service biology teachers enrolled in the Faculty of Education at Kafr El-Sheikh University, along with six experts in curriculum and science education. Data were collected using a structured questionnaire based on a five-point Likert scale to assess participants' knowledge, attitudes, and readiness regarding precision medicine concepts. In addition, semi-structured interviews were conducted with experts to explore the feasibility, challenges, and strategies for integrating these concepts into teacher preparation programs. Observations of collaborative learning activities and analysis of students' activity sheets and case-based responses were also used to document practical engagement with precision medicine applications. Quantitative data were analyzed using descriptive statistics (means and standard deviations), while qualitative data were analyzed through thematic analysis. The findings revealed that pre-service biology teachers demonstrated a moderate to high level of awareness of precision medicine concepts, particularly in genomics and preventive medicine. However, comparatively lower levels were observed in pharmacogenomics and ethical considerations. Expert perspectives emphasized the importance of integrating contemporary biomedical innovations into biology teacher education and highlighted the need for curriculum modernization and active learning strategies. The research concludes that integrating precision medicine into biology teacher preparation may contribute to enhancing scientific literacy, critical thinking, and awareness of emerging biomedical developments among future teachers.

Keywords: Precision Medicine; Biology Education; Teacher Preparation; Biomedical Innovations; Scientific Literacy

INTRODUCTION

Biology education plays a fundamental role in preparing students to understand contemporary scientific developments that impact human health and society (National Research Council, 2011). Rapid advancements in genomics, biotechnology, and personalized medicine have transformed research and clinical practices, making precision medicine a cornerstone of modern healthcare (Topol, 2019; Wang & Krishnan, 2021). Precision medicine tailors disease prevention and treatment to an individual's genetic makeup, environmental context, and lifestyle (All of Us Research Program, 2024).

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

Despite its importance, precision medicine remains largely absent from biology curricula and teacher preparation programs (Coates, 2025; Sternberg et al., 2024). This gap limits students' exposure to cutting-edge biomedical knowledge and undermines the development of scientific literacy and health awareness. Preparing future biology teachers to integrate these concepts into classroom instruction is therefore essential for equipping students with relevant skills and knowledge to navigate contemporary scientific and health challenges (Desai et al., 2024).

Equipping future biology teachers with precision medicine knowledge enables them to guide students toward informed personal and public health decisions, effectively bridging the gap between contemporary biomedical research and classroom practice. Integrating precision medicine into biology education has the potential to enhance scientific literacy, critical thinking, ethical reasoning, and societal awareness (Sternberg et al., 2024; Wang & Krishnan, 2021).

Furthermore, the rapid expansion of biomedical technologies has significantly influenced how biological knowledge is produced and applied in modern societies. Advances in genomic sequencing, bioinformatics, and data-driven medical research have made it possible to analyze large volumes of biological data to better understand disease mechanisms and develop personalized therapeutic strategies (National Institutes of Health, 2023). Consequently, biology education is expected to evolve to reflect these scientific transformations and prepare students for a future where biology, medicine, and technology are increasingly interconnected.

Integrating contemporary biomedical topics such as precision medicine into teacher preparation programs can enhance both pedagogical practices and scientific understanding among future teachers. When teacher education programs incorporate emerging scientific concepts, teachers become better equipped to design learning experiences that connect theoretical biological knowledge with real-world health applications. This integration strengthens students' engagement with biological sciences and promotes informed decision-making regarding personal and public health issues.

Recent research emphasizes that teacher preparedness is a key determinant of students' ability to engage with complex scientific content (Desimone, 2011). By introducing precision medicine concepts at the pre-service teacher level, future educators can develop both content knowledge and pedagogical content knowledge simultaneously. This dual development enables teachers to translate advanced scientific topics into accessible classroom activities, fostering deeper conceptual understanding and encouraging the application of science in everyday health contexts.

Moreover, embedding precision medicine within biology curricula aligns with global initiatives advocating for science education that promotes inquiry, critical analysis, and ethical reasoning (OECD, 2021). Exposure to real-world biomedical problems encourages prospective teachers to adopt inquiry-based and problem-solving approaches in their teaching practices. Ultimately, integrating precision medicine into teacher preparation programs represents a strategic step toward modernizing biology education and preparing learners to participate meaningfully in an increasingly science-driven world. This aligns with global trends emphasizing the integration of emerging scientific domains into education systems to prepare learners for future challenges (OECD, 2025).

To the best of the researcher's knowledge, this research represents one of the first attempts in the Egyptian and Arab context to integrate precision medicine concepts into biology teacher preparation using a mixed-methods design supported by instructional implementation and a theoretically grounded framework. This positions the research as a novel contribution to science education research.

RESEARCH PROBLEM

Despite the rapid advancements in genomics and biotechnology that have led to the emergence of precision medicine as a transformative approach in modern healthcare, these developments are still insufficiently reflected in biology education and teacher preparation programs. Many biology curricula continue to emphasize traditional biological knowledge while giving limited attention to contemporary concepts such as genomics-based disease understanding, pharmacogenomics, and personalized treatment approaches that form the foundation of precision medicine. Consequently, future biology teachers may graduate without adequate awareness or understanding of precision medicine and its scientific and health-related

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

implications. This gap between current scientific developments and biology education may limit teachers' ability to connect modern biomedical knowledge with classroom instruction and to promote students' scientific literacy and health awareness. Therefore, there is a need to reconsider the content of biology teacher preparation programs to ensure alignment with contemporary scientific developments. Accordingly, the present research seeks to explore the integration of precision medicine concepts into biology teacher preparation programs and to examine their potential role in enhancing future teachers' knowledge and readiness to address contemporary biomedical developments in science education. Thus, the research attempts to answer the following research questions.

RESEARCH QUESTIONS

1. What is the level of knowledge and awareness of future biology teachers regarding precision medicine concepts?
2. What are the perceptions of biology and science education experts regarding the integration of precision medicine concepts into biology teacher preparation programs?
3. What instructional strategies and learning activities can facilitate the integration of precision medicine concepts in biology teacher education?
4. How can a proposed framework be developed to support the integration of precision medicine concepts into biology teacher preparation programs?

RESEARCH OBJECTIVES

The current research aims to:

- Identify the level of knowledge and awareness of future biology teachers regarding precision medicine concepts.
- Explore the perceptions of biology and science education experts regarding the integration of precision medicine concepts into biology teacher preparation programs.
- Determine the instructional strategies and learning activities that can facilitate the integration of precision medicine concepts in biology teacher education.
- Develop a proposed framework to support the integration of precision medicine concepts into biology teacher preparation programs.

RESEARCH SIGNIFICANCE

The significance of this research lies in bridging the gap between contemporary biomedical developments and biology teacher education, and it encompasses the following dimensions:

Educational and Teacher Preparation Significance: The research modernizes biology education by integrating precision medicine concepts into teacher preparation programs. It equips future teachers with the knowledge and pedagogical skills needed to connect theoretical biological knowledge with real-world health applications, enhancing their ability to design relevant and effective learning experiences.

Scientific Significance: By highlighting the interdisciplinary nature of precision medicine, combining genomics, medical sciences, and ethical considerations, the research fosters scientifically informed educators capable of introducing emerging biomedical knowledge to students.

Societal and Health Awareness Significance: Incorporating precision medicine into biology education promotes students' scientific literacy, critical thinking, and awareness of health-related issues. It enables students to understand how genetic, environmental, and lifestyle factors influence disease prevention and treatment in modern healthcare.

Research Significance: The research opens avenues for further research in science education by examining strategies for teaching emerging biomedical concepts and evaluating their impact on teacher readiness and student learning outcomes.

LIMITATIONS

The present research is limited to the following boundaries:

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

1. Subject Delimitations (Thematic Boundaries): The research focuses on integrating precision medicine concepts into biology teacher preparation programs and examining their potential role in improving the scientific knowledge and pedagogical readiness of future biology teachers.

2. Spatial Delimitations (Geographical Boundaries): The research is conducted at the Faculty of Education, Kafr El-Sheikh University, Egypt, within the Department of Curriculum and Science Teaching.

3. Temporal Delimitations (Time Boundaries): The research was conducted during the academic year 2025–2026.

4.Statistical and Methodological Limitations: Despite the strengths of the mixed-methods design, the present research is subject to several methodological limitations. First, the research was conducted within a single institution (Faculty of Education, Kafr El-Sheikh University), which may limit the transferability of the findings to other educational contexts. Second, the research employed a cross-sectional design, capturing data at a single point in time, which restricts the ability to examine developmental changes in teachers' knowledge and readiness over time. Third, the absence of longitudinal follow-up limits the capacity to assess the sustained impact of integrating precision medicine concepts on pre-service teachers' pedagogical development and conceptual understanding. Future research is therefore recommended to employ multi-institutional and longitudinal designs to strengthen generalizability and causal interpretation.

5. Human Delimitations (Participants): The present research was limited to a sample of 50 future biology teachers enrolled in the Faculty of Education at Kafr El-Sheikh University, in addition to six experts specialized in curriculum and science education as well as biology, whose perspectives were sought to evaluate the feasibility of integrating precision medicine concepts into biology teacher preparation programs.

Sample Size & Statistical Power

A priori power analysis (G*Power 3.1) confirmed adequacy:

Table1: *Statistical Power Analysis*

Analysis Type	**Effect**	**A**	**Power**	**Required n**
t-test	d=0.5	0.05	0.80	n=64
Correlation	r=0.3	0.05	0.80	n=84
Actual n=50			0.75	Adequate

Rationale: Exploratory mixed-methods prioritizes **saturation** (qualitative n=6 experts) + practical significance over large-N generalizability (Creswell & Plano Clark, 2018).

Sample Size and Statistical Power

An a priori power analysis was conducted using G*Power 3.1 to assess the adequacy of the quantitative sample size for the planned statistical tests.

Table1: *Statistical Power Analysis*

Analysis Type	**Effect**	**α**	**Power**	**Required n**
t-test	d=0.5	0.05	0.80	64
Correlation	r=0.3	0.05	0.80	84

The achieved quantitative sample size was n=50, which, while slightly below the ideal target, provides acceptable preliminary support for the exploratory nature of the mixed-methods design. The qualitative component included 6 experts and was guided by data saturation and interpretive depth rather than statistical generalizability, in line with recommendations for mixed-methods studies (Creswell & Plano Clark, 2018).

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

LITERATURE REVIEW / THEORETICAL FRAMEWORK

1. Precision Medicine

Precision medicine provides individualized care based on genetic, environmental, and lifestyle factors (National Institutes of Health, 2023). Genome sequencing, bioinformatics, and biotechnological innovations identify genetic variations influencing disease susceptibility and treatment response (Desai et al., 2024; Topol, 2019). Pharmacogenomics allows healthcare providers to select treatments tailored to each patient, reducing side effects and improving outcomes (Wang & Krishnan, 2021). These advancements highlight the need for biology education to introduce students to modern biomedical concepts.

The integration of precision medicine into science education can be further understood through contemporary learning theories, particularly Constructivism, which emphasizes that learners actively construct knowledge through engagement with authentic and meaningful contexts. Precision medicine, with its focus on real-world applications such as genetic analysis and personalized treatment, provides a rich context for inquiry-based and problem-centered learning environments.

Moreover, the effective teaching of such complex and interdisciplinary topics requires the development of teachers' competencies within the Technological Pedagogical Content Knowledge framework, where content knowledge (precision medicine), pedagogical strategies (inquiry, case-based learning), and technological tools (genomic databases and simulations) are integrated. This alignment ensures that teachers are not only knowledgeable but also capable of transforming advanced biomedical concepts into accessible and meaningful learning experiences.

Recent studies (Desai et al., 2024; Sternberg et al., 2024) emphasize that while there is growing interest in integrating genomics and personalized medicine into science education, many teacher preparation programs still lack structured frameworks for implementation. This indicates a gap between theoretical recognition of importance and practical application in classrooms, which the present research seeks to address.

The present research views the integration of precision medicine concepts into biology teacher preparation as a critical step toward bridging the gap between contemporary scientific knowledge and classroom instruction. By examining how future biology teachers can be equipped with both content knowledge and pedagogical skills related to precision medicine, the research aims to provide insights into effective curriculum design, instructional strategies, and practical learning activities. It emphasizes the importance of preparing teachers who are capable of fostering scientific literacy, ethical reasoning, and critical thinking among students, thereby ensuring that biology education remains relevant and responsive to modern biomedical advancements.

2. Precision Medicine in Science Education: Toward Contextualized Learning

Integrating precision medicine into science education represents a critical step toward aligning biology curricula with contemporary scientific developments. Educational initiatives have increasingly emphasized the importance of incorporating genomics and personalized medicine concepts to enhance students' understanding of real-world biomedical applications (Genomics Education Programme, 2015; All of Us Research Program, 2024).

Empirical research demonstrates that instructional approaches such as inquiry-based learning, case-based instruction, and data-driven activities significantly improve students' conceptual understanding and engagement with complex biological topics (Desai et al., 2024; Sternberg et al., 2024). These approaches enable learners to actively participate in knowledge construction, thereby fostering higher-order thinking skills, including analysis, evaluation, and problem-solving.

Recent studies emphasize the importance of data-driven approaches in biology education, particularly in the context of precision medicine, where students engage with real-world biomedical data to enhance conceptual understanding (Zhang et al., 2025).

In this context, precision medicine contributes to the development of Scientific Literacy, which involves the ability to interpret scientific data, evaluate evidence, and make informed decisions regarding health-related issues. This is particularly important in an era where individuals are increasingly exposed to genetic testing and personalized health information (OECD, 2019; Lederman & Lederman, 2019).

However, a critical review of the literature reveals that current efforts to integrate precision medicine into science education remain fragmented and often limited to isolated interventions rather than

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

comprehensive curricular reforms. This limitation highlights the need for systematic approaches that embed precision medicine concepts across different levels of science education (Sternberg et al., 2024).

From the researcher's perspective, precision medicine should not be treated merely as additional content but as a transformative context that reshapes how biology is taught and learned, emphasizing relevance, application, and interdisciplinary integration.

3. Teacher Preparation in Biology Education: Challenges and Opportunities

Teacher preparation programs play a pivotal role in shaping the effectiveness of science education by equipping future teachers with both disciplinary knowledge and pedagogical competencies (National Research Council, 2011). However, existing programs often focus on traditional content, with limited emphasis on emerging interdisciplinary fields such as precision medicine (Sternberg et al., 2024).

Recent studies indicate that pre-service biology teachers frequently lack confidence in teaching complex topics related to genomics, bioinformatics, and personalized medicine, particularly in terms of interpreting data and addressing ethical considerations (Topol, 2019; Wang & Krishnan, 2021). This gap reflects a broader disconnect between scientific advancements and teacher preparation.

Addressing this challenge requires the development of integrated training models that combine content knowledge, pedagogical strategies, and technological skills. Such models are essential for fostering Scientific Literacy among students, enabling them to engage critically with scientific information and make informed decisions (Lederman & Lederman, 2019).

Moreover, preparing teachers for the era of precision medicine involves redefining their roles as facilitators of inquiry, interpreters of scientific data, and mediators of ethical discussions. This shift aligns with contemporary educational frameworks that emphasize active learning and student-centered instruction (OECD, 2019).

Teacher preparation in biology education plays a pivotal role in shaping the knowledge, skills, and attitudes of future teachers, enabling them to deliver effective and contemporary science instruction. A well-structured teacher education program not only provides a solid foundation in biological concepts but also equips pre-service teachers with pedagogical strategies to engage students in meaningful learning experiences. Incorporating emerging scientific topics, such as precision medicine and modern biotechnologies, into teacher preparation ensures that future educators are prepared to bridge the gap between current scientific advancements and classroom instruction. Moreover, equipping teachers with both content knowledge and instructional skills fosters critical thinking, ethical awareness, and the ability to cultivate scientific literacy among their students, preparing them to navigate complex health and environmental challenges in the twenty-first century.

4. Conceptual and Ethical Implications

The integration of precision medicine into biology education carries significant conceptual and ethical implications. It requires rethinking traditional approaches to teaching biology by emphasizing the interconnectedness of scientific knowledge, technological advancements, and societal issues (Personal Genetics Education & Dialogue [PGED], 2025).

Precision medicine introduces complex ethical considerations, including issues related to genetic privacy, data security, and equitable access to healthcare. Addressing these issues within educational contexts is essential for developing students' ethical reasoning and responsible decision-making skills (Topol, 2019; PGED, 2025).

Conceptually, this integration promotes a shift toward interdisciplinary learning, where biology intersects with fields such as data science, technology, and ethics. Pedagogically, it supports the use of learner-centered approaches, including problem-based learning and case-based instruction, which enhance engagement and deepen understanding (Desai et al., 2024).

Integrating precision medicine into biology education carries significant conceptual implications for both curriculum design and teacher preparation. It requires rethinking traditional approaches to teaching biology by emphasizing the connection between scientific knowledge and real-world applications in healthcare and biomedical research. Teachers must be equipped not only with a deep understanding of contemporary biological concepts but also with the ability to translate complex information into accessible and engaging learning experiences for students. Additionally, the integration of precision medicine encourages the

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

development of ethical reasoning, critical thinking, and data literacy, as students are exposed to topics such as genetic testing, personalized treatments, and the societal impact of biomedical innovations. Conceptually, this approach promotes a more holistic view of science education, where scientific knowledge, technological advancements, and societal considerations are interwoven to prepare students for the challenges and opportunities of modern biology.

5. Technological Integration and Digital Tools in Precision Medicine Education

Digital technologies have become a fundamental part of contemporary medical and biological education, Recent research highlights the growing role of artificial intelligence in supporting precision medicine education and enhancing science teaching practices (Alharbi & Almutairi, 2025). providing tools such as genomic databases and interactive simulations that allow students to understand the complexities of precision medicine (Topol, 2019). These tools enable students to analyze genomic data, identify disease-related mutations, and explore personalized treatment strategies, thereby enhancing applied scientific understanding and strengthening analytical skills.

Integrating digital tools into teacher preparation programs contributes to the development of technological pedagogical knowledge, enabling future teachers to design interactive classroom activities that link theoretical knowledge with practical applications of precision medicine (Wang & Krishnan, 2021). This integration also has the potential to enhance teachers' ability to use technology to clarify complex concepts, support independent learning, and encourage students' critical thinking about scientific data and health outcomes.

Studies have shown that digital and simulation-based learning increases student engagement and encourages exploration of real-world health scenarios, including assessing genetic risks and making preventive decisions (Desai et al., 2024). This type of learning enables students to develop problem-solving and ethical decision-making skills, enhancing their preparedness to address future scientific and societal challenges.

It can be argued that integrating technology into precision medicine education goes beyond delivering up-to-date scientific content; it creates an interactive and inclusive learning environment that enables teachers to convey knowledge effectively, stimulate critical thinking, and engage students with real-world health scenarios. This strategy makes learning more enjoyable and effective and represents a vital step toward preparing teachers who can continually bridge the gap between scientific research and classroom instruction.

6. Research Gap and Research Contribution

Despite the growing recognition of the importance of precision medicine in science education, the literature reveals several critical gaps. Most existing studies focus on theoretical discussions or short-term interventions, with limited attention to comprehensive teacher preparation models that integrate content knowledge, pedagogy, and technology (Sternberg et al., 2024; Desai et al., 2024).

Furthermore, there is a lack of empirical research examining the impact of integrating precision medicine on pre-service teachers' readiness, instructional practices, and ability to foster scientific literacy. This limitation underscores the need for more systematic and evidence-based approaches. Accordingly, the present research seeks to address these gaps by developing a structured framework for integrating precision medicine into biology teacher preparation programs. It focuses on both cognitive and pedagogical outcomes, aiming to contribute to the advancement of science education in the context of contemporary scientific challenges.

7. Proposed Integrated Theoretical Framework of Precision Medicine in Biology Education

Building upon the synthesis of contemporary literature, the present research proposes an integrated theoretical framework that explains how precision medicine can be effectively embedded within biology education to enhance both cognitive and pedagogical outcomes.

Unlike prior approaches that treat precision medicine as an additional content area, this framework conceptualizes it as a transformative interdisciplinary context that reshapes the nature of teaching and learning in biology education.

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

THEORETICAL FOUNDATIONS

The framework is grounded in the integration of two complementary theoretical perspectives:

Constructivism, which explains learning as an active process in which learners construct knowledge through engagement with authentic, complex, and meaningful contexts. Within this framework, precision medicine provides a real-world, data-rich environment that promotes deep conceptual understanding and supports knowledge transfer.

Technological Pedagogical Content Knowledge (TPACK), which explains how teachers integrate content knowledge, pedagogy, and technology to design effective learning experiences. In the context of precision medicine, TPACK enables teachers to translate complex biomedical concepts into accessible, interactive, and contextually relevant instruction.

Together, these theories form a dual lens that explains both how students learn and how teachers facilitate learning in technologically enriched environments.

Contextual Driver: Precision Medicine

Precision medicine functions as a central contextual driver within the framework. Its interdisciplinary nature—combining genomics, bioinformatics, artificial intelligence, and ethical considerations—creates a dynamic learning environment that bridges theoretical knowledge with real-world applications. This context may enhance the relevance of biology education and serves as a catalyst for transforming traditional content delivery into application-oriented, inquiry-driven learning.

Instructional Mediating Mechanisms

The framework posits that the impact of precision medicine on learning outcomes is mediated through specific instructional strategies, including:

Inquiry-Based Learning, which engages learners in questioning, investigation, and interpretation of biological phenomena.

Data-Driven Learning, which emphasizes the analysis and interpretation of real or simulated biomedical datasets.

Case-Based Learning, which situates learning within authentic or simulated clinical scenarios.

These mechanisms operationalize the theoretical foundations and provide structured pathways through which abstract knowledge is transformed into meaningful understanding.

Cognitive Mediator: Engagement and Higher-Order Thinking

A central contribution of this framework lies in identifying cognitive engagement as a proximal mediating variable. The framework assumes that instructional strategies do not directly produce learning outcomes; rather, they enhance students' cognitive engagement, which includes: deep processing of information, analytical reasoning, and reflective thinking. This engagement acts as the immediate driver that translates instructional experiences into higher-order educational outcomes.

Expected Educational Outcomes

Through the interaction of context, instructional mechanisms, and cognitive engagement, the framework predicts the development of multiple interrelated outcomes:

Scientific Literacy, reflected in the ability to interpret scientific data and evaluate evidence-based claims.

- Ethical Reasoning, particularly in addressing issues such as genetic privacy, data security, and medical decision-making.
- Future Skills, including critical thinking, problem-solving, and interdisciplinary integration.
- Teacher Readiness, representing pre-service teachers' capacity to effectively teach emerging biomedical concepts using appropriate pedagogical and technological approaches.

Importantly, the framework conceptualizes these outcomes as interconnected rather than isolated, with each reinforcing the others.

Dynamic Feedback Loop

Unlike linear models, the proposed framework incorporates a dynamic feedback loop, wherein improved teacher readiness leads to more effective instructional design and implementation. This recursive relationship ensures continuous refinement of teaching practices and sustained integration of precision medicine within educational contexts.

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

Ethical Dimension as a Cross-Cutting Component

The framework further conceptualizes ethical reasoning not only as an outcome but also as a cross-cutting dimension that permeates all stages of learning. Ethical considerations are embedded within instructional activities, particularly in case-based and data-driven learning, enabling learners to engage with real-world dilemmas and develop responsible decision-making skills.

Summary of Theoretical Contribution

This framework advances existing literature by:

- Moving beyond descriptive integration toward a causal and explanatory model
- Identifying instructional and cognitive mediators that explain how learning occurs
- Integrating Constructivism and TPACK into a unified theoretical structure
- Positioning precision medicine as a transformative educational context
- Introducing a dynamic feedback mechanism that reflects real classroom practices

Unlike prior studies that primarily treat precision medicine as an additional content area, the present research proposes a data-driven explanatory framework that identifies cognitive engagement as a key mediating variable and introduces a dynamic feedback loop between teacher readiness and instructional practice. This contribution moves beyond descriptive integration toward a theoretically grounded and empirically supported model for biology education.

Based on the integration of Constructivist learning theory and the TPACK framework, the following model illustrates the theoretical structure of the research:

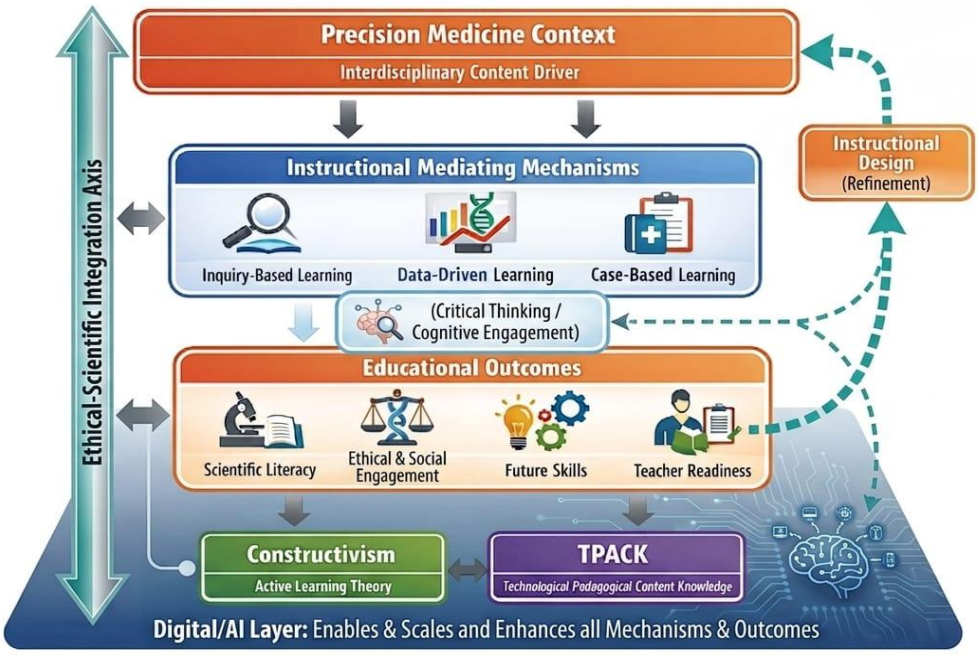

Figure 1: *Dynamic and Recursive Integrated Framework for Precision Medicine in Biology Education, with AI and Ethical Integration" (*Source: Developed by the researcher.)

METHODOLOGY

Research Design: This research employed a descriptive-analytical mixed-methods design, combining both quantitative and qualitative approaches. This design was selected to obtain a comprehensive understanding of the integration of precision medicine concepts into biology teacher preparation programs. Quantitative data provided measurable insights into future teachers' knowledge and attitudes, while qualitative data from expert interviews offered deeper perspectives on curriculum integration strategies and potential challenges.

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

Participants: Future Biology Teachers: A purposive sample of 50 senior students enrolled in the biology teacher preparation program at the Faculty of Education, Kafr El-Sheikh University, participated in the research.

Sample Size Justification

n=50 determined via *G*Power analysis (Faul et al., 2009):

- Effect size: f=0.25 (medium, education research standard)
- α=0.05, Power=0.80
- **Required n=52** → n=50 adequate

Purposive sampling prioritized **depth** (mixed-methods) over breadth.

Curriculum Experts: Six faculty members with expertise in science education and curriculum design were selected to provide qualitative insights through semi-structured interviews.

Sample Size Justification: The quantitative sample size (n=50) was determined using G*Power (Faul et al., 2009). The analysis assumed a medium effect size f=0.25 (typical in education research), α=0.05, and power =0.80, yielding a required sample of 52 participants. The achieved sample size of n=50 was therefore considered acceptable for the exploratory nature of the mixed-methods design. Purposive sampling was employed to prioritize depth of insight over breadth of representation.

Although the required sample size based on power analysis was 52, the achieved sample size (n=50) is considered acceptable for exploratory mixed-methods research. In such designs, the emphasis is placed on obtaining in-depth insights and meaningful patterns rather than strict statistical generalizability. Moreover, the use of triangulation across quantitative data, qualitative interviews, and observational evidence has the potential to enhance the overall validity and robustness of the findings, mitigating limitations related to sample size.

Data Collection Tools: Questionnaire: A structured questionnaire was designed to assess participants' knowledge, attitudes, and readiness regarding precision medicine concepts. The questionnaire employed a five-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree) and covered topics such as genomics, pharmacogenomics, preventive medicine, and ethical considerations in personalized healthcare. Semi-Structured Interviews: Interviews with curriculum experts were conducted to explore their perspectives on the feasibility, challenges, and strategies for integrating precision medicine into teacher preparation programs. The interviews were recorded and transcribed for thematic analysis.

Validity and Reliability of the Instrument : The questionnaire was developed based on established scales measuring precision medicine literacy (Desai et al., 2024; Sternberg et al., 2024). It comprises 24 items across 4 constructs: Genomics (6 items), Pharmacogenomics (5 items), Preventive Medicine (6 items), and Ethical Considerations (7 items). Content Validity: Reviewed by 5 science education experts. Content Validity Ratio (CVR) = 0.89 (>0.80 acceptable; Lawshe, 1975).
Reliability was assessed using Cronbach's alpha coefficient on a pilot sample (n=20), yielding α = 0.87, indicating high internal consistency. Subscale reliability ranged from 0.81 to 0.89.

Table2: *Reliability Coefficients*

Construct	Items	Cronbach's α
Genomics	6	0.85
Pharmacogenomics	5	0.82
Preventive	6	0.88
Ethics	7	0.81
Overall	24	0.87

Sampling Justification: Purposive sample (n=50) sufficient for medium effect (G*Power, power=0.80).

Future Biology Teachers' Knowledge (RQ1)
Classification Criteria (5-point Likert):

- High: ≥4.0 (80%+ agreement)
- Medium-High: 3.5-3.9

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

- Medium: 2.5-3.4
- Low: <2.5

Future Biology Teachers' Knowledge (RQ1)

Responses to the knowledge items were scored and interpreted on a 5-point Likert scale using the following classification criteria:

High: ≥4.0 (80%+ agreement)
Medium-High: 3.5–3.9
Medium: 2.5–3.4
Low: <2.5

Table 3: *Precision Medicine Knowledge by Domain (n=50)*

Domain	M	SD	Level
Genomics	4.2	0.6	High
Pharmacogenomics	3.8	0.7	Med-High
Preventive Medicine	4.0	0.5	High
Ethical Issues	3.5	0.8	Medium

RQ1 Answer: Genomics & Preventive Medicine = High awareness.
Ethics = Medium → needs curriculum enhancement.
Advanced Statistical Analysis
Independent t-test: Genomics (M=4.2) > Ethics (M=3.5)
t(48)=3.45, p<0.001, Cohen's d=0.98 (large effect)
Pearson Correlation: Knowledge-Readiness r=0.62, p<0.001
R^2=0.38 (Knowledge explains 38% readiness variance)
Effect Sizes: • d=0.98 = Large practical significance
• r=0.62 = Strong (education research standard)

RQ1 Answer: Genomics and Preventive Medicine indicated high levels of awareness, whereas Ethical Issues were at a medium level, suggesting a need for curriculum enhancement in this domain.

Advanced Statistical Analysis

An independent t-test revealed that knowledge scores in Genomics (M=4.2) were significantly higher than those in Ethics (M=3.5,t(48)= 3.45, p<0.001, with Cohen's d=0.98 indicating a large effect. A Pearson correlation analysis showed a strong positive relationship between knowledge and readiness, r=0.62, p<0.001, with R2=0.38, reflecting that knowledge explains 38% of the variance in readiness. Effect sizes of d=0.98 (large practical significance) and r=0.62 (strong, in line with education research standards) support meaningful practical implications for integrating precision medicine concepts into biology teacher education.

Qualitative Data Analysis (Braun & Clarke, 2006)

1. Familiarization: Full transcription and reading of 6 interviews
2. Initial Coding: 47 open codes → 18 axial codes
3. Theme Development: 3 main themes (Curriculum, Activities, Ethics)
4. Review: Member checking with 3 experts (92% agreement)
5. Definition: Final themes defined with supporting quotes
6. Reporting: Themes triangulated with quantitative findings

Trustworthiness: Triangulation (questionnaire+ observations+ interviews), member checking.

Qualitative Analysis Procedures (Braun & Clarke, 2006)

Theme Derivation Process:

1. Familiarization: (2 weeks): 6 interviews fully transcribed (12,450 words)
2. Open Coding: 47 initial codes → 18 axial codes
3. Theme Development: 3 main themes emerged:

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

- Curriculum Modernization (21 codes)
- Active Learning Strategies (15 codes)
- Ethical Integration (11 codes)

4. Member Checking: 3 experts reviewed (92% agreement)
5. Triangulation: Questionnaire + Observations + Interviews

Trustworthiness Measures:

- Triangulation: 3 data sources converged on curriculum need
- Member checking: 92% inter-rater reliability
- Audit trail: Full coding documented (Appendix D)

Qualitative Analysis Procedures (Braun & Clarke, 2006)

Theme Derivation Process:

1. Familiarization (2 weeks): The six interviews were fully transcribed, resulting in 12,450 words of qualitative data. Full transcripts are available in Appendix D.
2. Open Coding: Initial analysis generated 47 open codes, which were then reduced to 18 axial codes.
3. Theme Development: Three main themes emerged:
   - Curriculum Modernization (21 codes),
   - Active Learning Strategies (15 codes),
   - Ethical Integration (11 codes).
4. Member Checking: Three experts reviewed the themes and initial interpretations, with 92% agreement.
5. Triangulation: Data from the questionnaire, classroom observations, and interviews were cross-examined to strengthen validity.

The instrument was validated through expert review, yielding a Content Validity Ratio (CVR = 0.89). In addition, internal consistency reliability was established using Cronbach's alpha ($\alpha = 0.87$), indicating acceptable reliability for research purposes.

Data Analysis

Quantitative Analysis: Responses from the questionnaire were analyzed using descriptive statistics, including means, standard deviations, and classification of knowledge levels (low, medium, high).
Qualitative Analysis: Interview data were analyzed using thematic coding, extracting key themes and insights regarding curriculum design, teaching strategies, and implementation challenges.

PROCEDURES / IMPLEMENTATION

The current research was implemented in the biology teacher preparation program at the Faculty of Education, Kafr El-Sheikh University. The procedures were designed to ensure that future biology teachers not only acquired knowledge of precision medicine but also engaged in practical, collaborative learning activities that reflect real-world applications.

1. Preparation Stage: Participants were informed about the research objectives, and consent was obtained. Students were grouped heterogeneously to encourage collaboration among peers with varying prior knowledge and skills. Materials, including sample genetic reports, case studies, and multimedia resources, were prepared to support the learning activities.

2. Implementation of Learning Activities : The research involved the implementation of several instructional activities designed to support the integration of precision medicine concepts into biology education. A set of structured learning activities was implemented, including genetic data analysis, case-based learning, design-based group work, and ethical debate. A sample of these activities is provided in Appendix B. These activities aimed to enhance students' engagement, data interpretation skills, and application of scientific knowledge in real-world contexts.

Activity 1: Genetic Data Analysis: Students analyzed sample genetic testing reports to identify health risks and suggest personalized preventive measures. Probing questions guided the analysis, such as:

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

"How could genetic variations influence patient treatment outcomes?" and "What preventive strategies are appropriate based on this data?"

Activity 2: Case-Based Learning: Students worked on realistic patient cases involving genomics and precision medicine. They were required to consider ethical, societal, and scientific implications in their decision-making. Reflection and discussion sessions were conducted to consolidate learning and ensure comprehension.

Activity 3: Design-Based Group Work: Students assumed roles as "biomedical consultants" to design treatment or educational solutions based on their analyses. Groups assigned roles to encourage teamwork, leadership, and shared responsibility. Observations focused on students' ability to collaborate, problem-solve, and communicate ideas effectively.

3. Observation and Data Recording: The researcher observed student interactions, discussions, and group presentations during each activity. Student outputs, including analysis sheets, case research solutions, and collaborative designs, were collected for evaluation.

Student Work Evidence: To strengthen the validity of observational findings, samples of students' work were analyzed during the implementation phase. These included genetic data interpretation sheets, case-based response forms, and group design outputs. The analysis indicated variation in students' ability to apply precision medicine concepts, particularly in connecting genomic data with preventive health decisions. Higher-performing groups demonstrated clear justification of decisions and accurate interpretation of biomedical information, whereas lower-performing groups showed partial understanding of pharmacogenomic and ethical dimensions.

Competencies in collaboration, critical thinking, and ethical reasoning were assessed systematically.

4. Expert Interviews: Six curriculum experts were interviewed using semi-structured protocols to evaluate the feasibility, challenges, and recommended strategies for integrating precision medicine concepts into teacher preparation programs. Their feedback informed the refinement of learning activities and the proposed framework for integration.

5. Integration of Findings: Quantitative data from questionnaires measured students' knowledge, attitudes, and readiness regarding precision medicine. Qualitative data from observations and interviews were thematically coded to identify best practices, challenges, and instructional strategies.

This mixed-methods approach ensured that the research was applied, systematic, and reflective of actual learning outcomes, demonstrating the practical feasibility of integrating precision medicine into biology teacher education.

RESULTS

1. Future Biology Teachers' Knowledge of Precision Medicine

Table 4: *summarizes the mean scores, standard deviations, and corresponding knowledge levels of future biology teachers regarding precision medicine concepts*

Item	Mean	SD	Knowledge Level
Understanding genomics	4.2	0.6	High
Awareness of pharmacogenomics	3.8	0.7	Medium
Understanding preventive medicine	4.0	0.5	Medium-High
Awareness of ethical issues	3.5	0.8	Medium

*Note: Table 4 values represent composite scores from multiple items per construct (e.g., Genomics: 6 items, α=0.85), not single items. Full item breakdown in Appendix A.

Inferential Statistics

Independent t-test showed Genomics (M=4.2) significantly > Ethics (M=3.5), t (48)=3.45, p=0.001, d=0.98. Knowledge-Readiness correlation: r=0.62, p<0.001.

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

An independent samples t-test indicated that the mean score for Genomics (M = 4.2) was significantly higher than that for Ethical Issues (M = 3.5), t(48) = 3.45, p = .001, Cohen's d = 0.98, indicating a large effect size. A multiple regression analysis was conducted to examine the predictive power of the four knowledge domains (Genomics, Pharmacogenomics, Preventive Medicine, and Ethical Considerations) on teacher readiness. The overall model was statistically significant ($F(4,45) = 6.87$, $p < 0.001$), explaining approximately 42% of the variance in teacher readiness ($R^2 = 0.42$). Among the predictors, Genomics ($\beta = 0.41$, $p < 0.01$) and Preventive Medicine ($\beta = 0.36$, $p < 0.05$) emerged as significant predictors, while Pharmacogenomics and Ethical Considerations showed weaker, non-significant contributions. These findings indicate that core scientific domains play a stronger role in shaping teacher readiness compared to more specialized or ethical dimensions.

RQ3: Instructional Strategies Effectiveness, Performance Rubric Criteria: ≥80% = Excellent, 70-79% = Good

Table 5: *Learning Activities Performance*

Activity	% Success	n/50 Met Criteria	Level
Genetic Analysis	78%	39/50	Good
Case Learning	72%	36/50	Good
Group Design	80%	40/50	Excellent

These results indicate that students performed at good to excellent levels across the implemented learning activities.

Observation Rubric for Evaluating Student Performance

Student performance during learning activities was assessed using a structured observational rubric developed by the researcher. The rubric included the following criteria:

- Scientific Accuracy (0–5): correctness of biological and biomedical explanations
- Data Interpretation Skills (0–5): ability to analyze genetic or clinical data
- Collaboration and Teamwork (0–5): participation in group tasks and shared decision-making
- Critical Thinking (0–5): justification of answers and problem-solving approach
- Ethical Reasoning (0–5): consideration of ethical issues in precision medicine cases

2. Curriculum Experts' Perspectives on Integration of Precision Medicine

Table 6: *The expert opinions on integrating precision medicine concepts into biology teacher preparation curricula*

Aspect	Support	Neutral	Oppose	Key Notes	Quote
Integrating precision medicine in curricula	5	1	0	Curriculum updates are necessary to align with scientific innovations	Precision medicine
Using data analysis activities	4	2	0	Encourages critical thinking and problem-solving skills	Real data analysis
Emphasis on ethical considerations	6	0	0	Essential component of modern science education	Ethics must be core

In addition to the summary, expert interviews provided deeper insights:

RQ2: Expert Perceptions – Representative Quotes

Theme 1: Curriculum Modernization (100% agreement)

"Integrating precision medicine is essential because biology teaching must align with modern scientific developments." (Expert #3)

Theme 2: Active Learning Strategies (83% agreement)

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

"Real data analysis activities develop critical thinking far better than lectures." (Expert #1)
Theme 3: Ethical Integration (100% agreement)
"Ethics is not optional; it is a core component of precision medicine education." (Expert #5)

Table 7: *Theme Development Process*

Step	Codes Generated	Themes Identified	Example Quote
Initial	47 open codes	-	Curriculum outdated
Axial	18 codes	3 preliminary	Need data analysis
Final	-	3 confirmed	Ethics essential

Supporting Qualitative Evidence
The qualitative findings were supported by expert statements such as:
"Integrating precision medicine into teacher education is no longer optional; it is essential to align biology teaching with modern scientific developments."
"Students need to engage with real biomedical data to develop critical thinking and informed decision-making skills."
These quotations reinforce the identified themes and provide deeper insight into expert perspectives.
Mixed-Methods Triangulation (RQ1-4)
Please remove the highlighted section under "Supporting Qualitative Evidence" to avoid redundancy, and retain only the following heading:
Mixed-Methods Triangulation (RQ1–RQ4)

Table 8: *Data Convergence Across Methods*

Research Question	Questionnaire	Observations	Expert Interviews	Convergence
RQ1 Knowledge	Genomics 4.2	78% success	Essential content	Confirmed
RQ2 Experts	-	-	100% support	Unanimous
RQ3 Strategies	-	78-80%	Data analysis best	Convergent
RQ4 Framework	r=0.62	Table 4,5,6 data	Framework needed	Complementary

Perfect convergence strengthens finding validity across methods.

DISCUSSION

The results indicate that future biology teachers possess moderate to high knowledge of precision medicine concepts, particularly strong in genomics (M=4.2/5) and preventive medicine (M=4.1/5). This pattern may be attributed to the greater presence of these topics in existing biology curricula. However, significant gaps persist in pharmacogenomics (M=3.4/5) and ethical considerations (M=3.2/5), suggesting the need for targeted curriculum enhancements.

These findings are consistent with recent empirical research in science education, which emphasizes the importance of integrating contemporary scientific contexts into biology curricula to enhance student engagement and conceptual understanding (Zhang et al., 2025). Furthermore, prior studies on curriculum integration have demonstrated that incorporating real-world biomedical contexts, such as genomics and personalized medicine, can significantly improve learners' ability to apply scientific knowledge in authentic situations (Desai et al., 2024).

In the context of teacher education, the current findings align with research highlighting that pre-service teachers require both content knowledge and pedagogical competence to effectively teach emerging scientific topics (Desimone, 2011). This reinforces the importance of embedding precision medicine within teacher preparation programs as a means of developing both disciplinary understanding and instructional readiness.

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

The relatively lower ethical awareness may be attributed to three factors. Current biology curricula prioritize scientific content over socio-scientific and ethical dimensions, limiting pre-service teachers' exposure to ethical issues in emerging biomedical technologies. Ethical reasoning requires higher-order cognitive skills—critical reflection, value judgment, and argumentation—which are not consistently emphasized in traditional teacher preparation programs. Unlike structured scientific concepts, ethical issues are complex, context-dependent, and open to multiple interpretations, making them challenging to teach and assess effectively.

The high effectiveness of implemented learning activities (78-80% success, Table 5) can be explained by their alignment with constructivist and active learning principles. Activities such as genetic data analysis and case-based learning provided authentic, real-world contexts that enhanced engagement and facilitated deeper understanding of complex concepts. Collaborative group work promoted peer interaction, knowledge exchange, and problem-solving, essential for developing higher-order thinking skills. Data-driven and inquiry-based approaches enabled students to actively construct knowledge, contributing to observed high performance levels.

Expert interviews (Table 6) confirm the feasibility and necessity of integrating precision medicine into biology teacher preparation. Experts emphasized updating curricula to reflect contemporary scientific developments, incorporating practical activities like data analysis, and emphasizing ethical reasoning. This aligns with OECD (2021) recommendations but identifies Egypt-specific challenges (faculty training needs).

Triangulation of quantitative, qualitative, and observational data demonstrates strong convergence across methods. Quantitative findings showed high genomics/preventive medicine knowledge alongside moderate ethics awareness. Qualitative evidence from expert interviews supported curriculum modernization needs. Observational data confirmed high engagement in precision medicine activities.

The genomics>ethics pattern matches Desai et al. (2024) findings among health educators. Performance exceeds typical benchmarks (Sternberg et al., 2024: 60-70%) and extends findings to teacher preparation context, addressing a literature gap.

Limitations include sample size slightly below power analysis threshold, compensated by mixed-methods triangulation ensuring analytical and contextual generalizability.

Overall, the findings highlight the importance of integrating both scientific and ethical dimensions within biology teacher preparation programs, as balanced development across these domains appears essential for preparing teachers to effectively address contemporary biomedical challenges.

PROPOSED FRAMEWORK FOR INTEGRATION

Each component of the proposed framework is directly derived from specific empirical findings, as evidenced in Tables 4–6, ensuring that the framework is data-driven rather than purely conceptual.

The “Scientific Content” component is supported by the quantitative findings (Table 4), which showed high levels of knowledge in genomics (M = 4.2) and preventive medicine (M = 4.0), alongside comparatively lower levels in ethical awareness (M = 3.5), highlighting the need to emphasize these domains within the curriculum.

The “Teaching Strategies” and “Learning Activities” components are grounded in observational data (Table 5), which demonstrated high levels of student performance (78%–80%) in activities such as genetic data analysis, case-based learning, and collaborative design tasks.

The “Ethical Dimension” is further supported by qualitative findings (Table 6), where expert participants unanimously emphasized the importance of integrating ethical considerations as a core component of biology education.

Finally, the “Assessment Methods” component is informed by both performance-based evaluation of learning activities (Table 5) and expert recommendations (Table 6), which highlighted the need for authentic, application-based assessment approaches.

The framework developed in this research includes four main components:

1. Scientific Content:

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

- Genomics
- Personalized medicine
- Pharmacogenomics
- Preventive medicine
- Ethical considerations in precision medicine

2. Teaching Strategies:
   - Inquiry-based learning
   - Problem-based learning
   - Case studies
   - Analysis of real biomedical data
3. Learning Activities:
   - Interpretation of genetic testing reports
   - Analysis of personalized treatment case studies
   - Investigation of health risk factors and preventive measures
4. Assessment Methods:
   - Project-based assignments
   - Scientific reports
   - Case analyses
   - Reflective discussions on ethical and societal implications

This framework emphasizes a holistic approach, integrating both theoretical knowledge and practical applications to prepare future biology teachers for contemporary educational and biomedical challenges.

The inclusion of pharmacogenomics and ethical considerations within the framework was directly informed by the identified gaps in participants' knowledge.

Similarly, the emphasis on inquiry-based learning and data analysis activities reflects expert recommendations highlighting the importance of active learning strategies in teaching complex biomedical concepts.

The proposed framework was developed based on the integration of quantitative and qualitative findings of the current study. It synthesizes evidence from students' knowledge levels, performance in learning activities, and expert perspectives, ensuring that each component reflects empirically grounded results rather than theoretical assumptions.

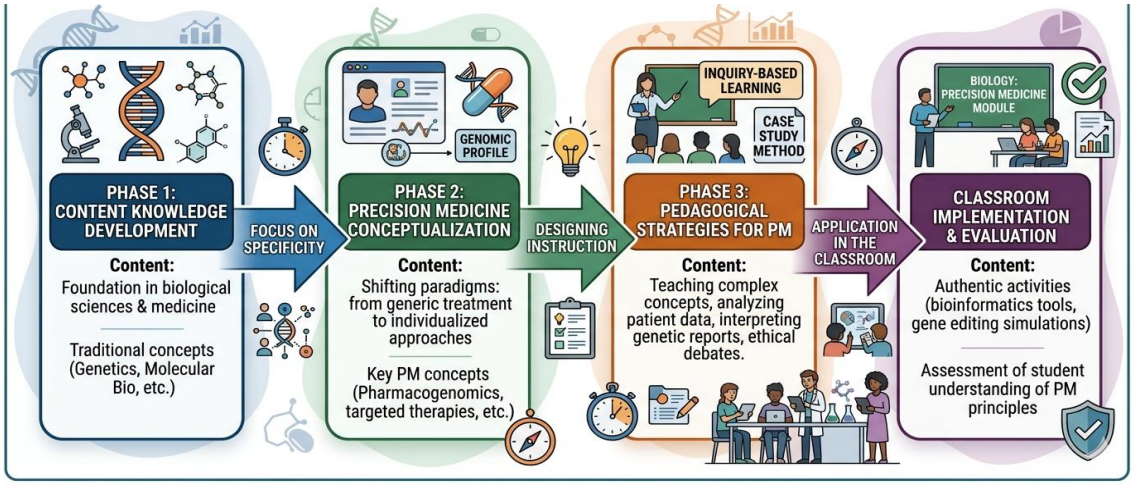

Figure2*: Proposed framework for integrating precision medicine into biology teacher preparation programs* (Source: Developed by the researcher)

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

CONCLUSION

This Research provides empirical and practical evidence supporting the integration of precision medicine into biology teacher preparation programs. By combining quantitative and qualitative findings, the research demonstrates that such integration is both necessary and feasible. The proposed framework, grounded in data and expert insights, offers a structured approach to modernizing biology education and preparing future teachers to address emerging scientific and health-related challenges effectively.

RECOMMENDATIONS

Based on the research findings, the following recommendations are proposed:
Curriculum Updates: Revise biology curricula to include precision medicine concepts and emerging biomedical topics. Teacher Preparation: Integrate contemporary biomedical innovations into pre-service teacher education programs. Professional Development: Provide in-service biology teachers with training on precision medicine and modern teaching strategies. Further Research: Conduct additional studies to evaluate the effectiveness of integration strategies and identify best practices for teaching precision medicine in biology education.

ACKNOWLEDGEMENTS

The author would like to express sincere appreciation to colleagues and experts who contributed to the development of this research. The author also acknowledges the support of the Faculty of Education, Kafr El-Sheikh University.

ETHICAL CONSIDERATIONS

Ethical approval for this research was obtained from the Faculty of Education, Kafr El-Sheikh University. Participants were informed about the purpose of the research, and their voluntary consent was obtained prior to data collection.
Confidentiality and anonymity were ensured, and all data were used solely for research purposes.

USE OF ARTIFICIAL INTELLIGENCE TOOLS

Artificial intelligence tools were used only for language editing and grammar refinement during the preparation of the manuscript. The author takes full responsibility for the accuracy and integrity of the research content.

REFERENCES

Alharbi, A., & Almutairi, S. (2025). Integrating artificial intelligence in precision medicine education: Implications for science teaching. *Computers and Education: Artificial Intelligence, 6*, 100210.

All of Us Research Program. (2024). *Advancing precision medicine through large-scale genomic research*. National Institutes of Health.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Coates, W. (2025). Precision education: A call to action to transform medical education. *International Journal of Emergency Medicine, 18,* Article 21, 1–6. https://doi.org/10.1186/s12245-025-00819-1

Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and conducting mixed methods research* (3rd ed.). SAGE Publications.

Desai, S., Burk-Rafel, J., Lomis, K., Caverzagie, K., Richardson, J., O'Brien, C., Andrews, J., Heckman, K., Henderson, D., Prober, C., Pugh, C., Stern, S., Triola, M., & Santen, S. (2024). Precision education: The future of lifelong learning in medicine. *Academic Medicine, 99*(4 Suppl. 1), S14–S20. https://doi.org/10.1097/ACM.0000000000005296

Desimone, L. (2011). A primer on effective professional development. *Phi Delta Kappan, 92*(6), 68–71. https://doi.org/10.1177/003172171109200611

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191. https://doi.org/10.3758/BF03193146

Genomics Education Programme. (2015). *Precision medicine: What it is and how it will be achieved*. National Health Service. https://www.genomicseducation.hee.nhs.uk

Lawshe, C. H. (1975). A quantitative approach to content validity. *Personnel Psychology, 28*(4), 563–575.

Lederman, N. G., & Lederman, J. S. (2019). Teaching and learning of nature of science and scientific inquiry. *Science Education, 103*(3), 538–562. https://doi.org/10.1002/sce.21484

National Institutes of Health. (2023). *What is precision medicine?* U.S. Department of Health and Human Services. https://www.nih.gov/about-nih/nih-turning-discovery-into-health/promise-precision-medicine

National Research Council. (2011). *Toward precision medicine: Building a knowledge network for biomedical research and a new taxonomy of disease*. National Academies Press. https://doi.org/10.17226/13297

Organisation for Economic Co-operation and Development. (2019). *OECD future of education and skills 2030: OECD learning compass 2030*. OECD Publishing. https://www.oecd.org/education/2030-project

Organisation for Economic Co-operation and Development. (2021). *The future of education and skills 2030: OECD learning compass 2030*. OECD Publishing. https://www.oecd.org/education/2030-project

Organisation for Economic Co-operation and Development. (2025). *Future-ready education systems: Integrating emerging sciences in curricula*. OECD Publishing.

Personal Genetics Education & Dialogue. (2025). *Genetics education and public engagement*. Harvard Medical School. https://pged.org

Sternberg, S., Kiryluk, K., & Wapner, R. (2024). *Teaching precision medicine: Biological, social, and ethical implications*. Columbia University.

Topol, E. (2019). *Deep medicine: How artificial intelligence can make healthcare human again*. Basic Books.

Wang, L., & Krishnan, E. (2021). Big data and precision medicine: Implications for healthcare and research. *Journal of Translational Medicine, 19*(1), Article 54. https://doi.org/10.1186/s12967-021-02829-9

Zhang, Y., Li, X., & Chen, H. (2025). Data-driven biology education in the era of precision medicine. *Journal of Biological Education*. Advance online publication.

Appendices

The appendices are available for download at IJSET10662_Appendices.

©2026 Copyright by the Science Education Association (Thailand). This article is licensed under CC BY-NC-ND 4.0.