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Integrating STEM Education Methods into Biotechnology Teaching

Abstract

Introduction. This study examines the effectiveness of integrating STEM-based interdisciplinary teaching methods into biotechnology education, with a focus on enhancing student engagement, motivation, and conceptual understanding. A pedagogical experiment was conducted among third-year biology students divided into control and experimental groups. The experimental group was taught through STEM-integrated modules combining theoretical content with laboratory-based tasks, including the analysis of fungi infecting *Daucus carota L.* and pectin extraction from Shantane and Alau carrot varieties. Data collection included pre- and post-tests, classroom observations, and student feedback surveys, supported by multimedia tools and collaborative instructional techniques. *Results.* Findings demonstrated that STEM-integrated lessons significantly improved students' motivation, critical thinking, participation, and academic performance compared to traditional instruction. Students in the experimental group showed deeper conceptual understanding and increased confidence in applying scientific knowledge to real-world contexts. *Scientific novelty.* The study provides empirical evidence on the effectiveness of a newly developed interdisciplinary STEM module specifically designed for biotechnology topics, demonstrating its capacity to enhance 21st-century skills and practical competencies. *Practical significance.* The proposed STEM-based instructional approach and educational materials can be incorporated into higher education curricula to modernize biotechnology teaching, support interdisciplinary learning, and strengthen students' readiness for scientific research and professional practice.

Keywords: STEM education, biotechnology teaching, pectin extraction, interdisciplinary methods, student motivation, practical tasks, multimedia tools, experimental learning.

Introduction. The rapid transformation of science and technology in the twenty-first century has amplified the demand for interdisciplinary approaches in education, particularly in the natural sciences. Traditional subject-centered instruction often results in fragmented knowledge, limiting students' ability to apply scientific concepts in practical contexts. In response, STEM and STEAM education have emerged as effective pedagogical models that integrate science, technology, engineering, and mathematics, providing learners with opportunities to develop critical thinking, creativity, and problem-solving skills required for modern scientific practice.

Biotechnology, as an interdisciplinary field combining biology, chemistry, engineering, and digital technologies, offers a particularly relevant context for implementing STEM-based learning. Teaching topics such as plant pathogens or pectin extraction from Daucus carota L. requires not only theoretical understanding but also the ability to engage in practical experimentation, data analysis, and project-based tasks. However, many students struggle to connect theoretical knowledge with real-world applications, resulting in decreased motivation and limited development of scientific competencies.

Addressing this challenge requires the integration of interactive, practice-oriented, and technologically supported learning environments. Previous research emphasizes that active learning strategies, collaborative methods, and problem-based tasks significantly enhance student engagement and deepen conceptual understanding in the natural sciences. Building on these insights, the present study examines the effectiveness of an interdisciplinary STEM module designed for biotechnology education. The investigation focuses on evaluating how STEM-integrated tasks influence students' motivation, academic performance, and ability to apply scientific knowledge in practice.

Materials and Methods. The methodological framework of the study was structured into three sequential phases to examine the effectiveness of integrating STEM-based interdisciplinary approaches in biotechnology education.

Phase 1 – Determining the research framework.

At the initial stage, the purpose, objectives, subject, and scope of the study were defined. The research focused on evaluating the impact of STEM-integrated modules on students' motivation, academic performance, and practical skills in biotechnology. A theoretical review of international and national literature on STEM/STEAM education and biotechnology teaching was conducted to identify relevant pedagogical principles and instructional strategies.

Phase 2 – Development of STEM-integrated teaching modules.

Based on the theoretical analysis, a set of interdisciplinary modules was designed according to STEM principles. These included: (1) Rules for storing vegetables according to regulatory requirements, (2) Fungi infecting Daucus carota L., and (3) Methods of extracting pectin from carrot varieties Shantane and Alau. The modules incorporated multimedia materials, problem-based tasks, engineering elements, laboratory activities, and collaborative learning methods such as Jigsaw, concept mapping, and interactive lectures.

The participants of the pedagogical experiment were third-year biology students (5B011300 Biology) at Abai Kazakh National Pedagogical University. Students were divided into control and experimental groups. The experimental group studied using STEM-integrated modules, while the control group followed traditional lecture-based instruction.

Phase 3 – Empirical investigation and data collection.

To evaluate the effectiveness of the intervention, several tools were employed: pre-tests and post-tests to measure knowledge acquisition; questionnaires to assess motivation, interest, and confidence; classroom observations to examine engagement; and descriptive–comparative statistical analysis to identify differences between groups. Visual materials, including diagrams, graphs, and student-created videos, were used to support practical tasks. The results were analyzed according to high, medium, and low achievement levels to compare the performance of the control and experimental groups.

Results. The primary objective of this study is to examine the pedagogical features of teaching biotechnology through an integrated STEM approach and to identify effective strategies for incorporating this methodology into university-level biology education. The study seeks to increase students' interest in scientific disciplines, strengthen their confidence in pursuing future professional pathways, and develop key competencies required in the twenty-first century. Additionally, the research aims to provide experimental evidence of the effectiveness of innovative pedagogical technologies in improving learning outcomes in biotechnology.

Research Tasks:

1. To analyze the historical development and conceptual evolution of STEM education.
2. To investigate the theoretical foundations and practical applications of STEM-integrated programs in biology teaching.
3. To develop interdisciplinary modules for biotechnology education and evaluate their pedagogical effectiveness.
4. To design and implement a STEM-based instructional method for teaching the topic of pectin extraction from carrot varieties.
5. To enhance students' academic performance by integrating modern digital tools and interactive instructional methods into biotechnology lessons.

The theoretical background of the study draws on the works of early thinkers who emphasized the interconnected nature of scientific knowledge. According to Yakman

(2019), Descartes was among the first to articulate the idea that all sciences are fundamentally interrelated, arguing that it is more effective to study them collectively rather than in isolation. This philosophical standpoint provides the conceptual foundation for modern STEAM education, where interdisciplinary integration is central to developing holistic scientific understanding.

Historically, scientific disciplines underwent a long period of differentiation beginning in the seventeenth century, leading to a strict separation of research domains. However, since the late 1970s, an opposite tendency toward integration has emerged, driven largely by advancements in biotechnology and the development of synthetic sciences that examine complex interactions within natural and social systems (Sanders, 2008; Vodolazhskaya et al., 2019). These interdisciplinary developments have contributed to the establishment of new high-tech industries and STEM-related professions.

Toffler (1970) predicted that the principal challenge of the twenty-first century would not be the inability to read or write, but the inability to "learn, unlearn, and relearn." He argued that creativity, curiosity, and design thinking would constitute essential skills for the future workforce - a prediction that strongly aligns with the goals of STEM-based pedagogy aimed at fostering adaptability, innovation, and problem-solving competencies among students.

The goals of education evolve continuously in response to societal, economic, and technological transformations. In the current transitional stage, educators are searching for effective pedagogical technologies that correspond to the demands of rapidly changing economic, social, and environmental conditions. One such approach that has gained prominence over the past two decades, particularly within the natural sciences, including biology and geography, is STEM education (Sanders, 2008). This integrative pedagogical model aims to develop key 21st-century competencies by fostering interdisciplinary thinking, technological literacy, and problem-solving skills. Its growing relevance is driven by several global challenges, including the need to enhance national competitiveness, meet the evolving requirements of high-tech labor markets, and address complex social issues through innovative educational solutions (Marr, 2019).

The term STEM education emerged in the United States in the 1990s, initially introduced by bacteriologist Rita Colwell and later adopted by the National Science Foundation (NSF) as a unifying label for science, technology, engineering, and mathematics. Early variations of the acronym, such as SMET and METS, reflected the lack of an established disciplinary order. However, in 2001, Ramaley reorganized the components into the now universally accepted sequence "STEM", which marked the beginning of its widespread incorporation into educational curricula worldwide (Sanders, 2008; Yakman, 2019).

As STEM education developed, various expanded models emerged under the umbrella term STEM+, designed to address additional interdisciplinary needs. The two most common extensions are STEAM, which incorporates the arts, and STREM, which includes robotics. These extensions reflect the growing recognition that creativity, innovation, and design-based thinking significantly enhance learners' ability to achieve deeper, multidimensional learning outcomes (de Vries et al., 2021). In contemporary educational practice, the STEAM model is often considered optimal because it acknowledges the essential role of artistic and creative processes in preparing students for modern professional environments, where aesthetic design, visualization, and creative problem-solving are integral.

The term STEAM education was first introduced at the Rhode Island School of Design (RISD) to emphasize the critical function of art in bridging scientific understanding with creative expression. Below compares the pedagogical characteristics of STEM and STEAM approaches (Table 1).

Table 1

Comparative characteristics of STEM and STEAM approaches in education

Compared features	STEM	STEAM
Goal	Priority in the development of natural sciences, technology, engineering, and mathematics	Mastering the natural sciences in relation to art
Entity	Integration of natural sciences, mathematics, engineering, and technology	Integration of natural sciences, mathematics, engineering, technology, and art
Orientation of educational activity	Development of critical thinking skills through problem-based learning	Development of creative thinking through practice-oriented learning

As part of the pedagogical experiment, an interdisciplinary STEM-based lesson in biotechnology was conducted with third-year students specializing in Biology (5B011300). The lesson focused on the topic "Fungi that infect the plant Daucus carota L." and aimed to introduce students to the main fungal pathogens affecting carrot plants, their biological characteristics, and the diseases they cause. In addition, the lesson sought to develop students' ability to regulate their own learning through active and interactive instructional methods.

The instructional methodology incorporated the Jigsaw technique, interactive lectures, multimedia presentations developed in PowerPoint, and a short educational video on carrot varieties and associated pathogens. Various visual materials were utilized, including a laptop, an interactive whiteboard, handouts, and illustrations of relevant scientists. Interdisciplinary links were established with microbiology, geography, and English language studies to enhance scientific communication skills.

The lesson began with an organizational stage, during which students were assigned to two groups. Using the Jigsaw method, each group examined different sections of the new content and later taught the material to their peers, promoting collaborative learning and mutual responsibility. This activity supported the development of analytical and communicative skills while enabling students to engage actively with scientific content.

Throughout the formative experiment, a comprehensive methodology for integrating modern educational technologies into biology teaching was developed. The biotechnology module consisted of three STEM-oriented topics:

1. Rules for storing vegetables according to regulatory standards,
2. Fungi that infect Daucus carota L.,
3. Methods for extracting pectin from carrot varieties Shantane and Alau.

Each topic employed an interactive demonstration approach supported by a 15 to 20 minute educational video produced using Adobe Premiere Pro CC 2017. The integration of multimedia resources allowed students to visualize biological processes and connect theoretical concepts with practical applications.

A range of innovative digital and interactive tools proved effective in teaching the module, including Quizizz, mind-mapping (associograms), role-playing activities, concept tests, STEM instructional strategies, Jigsaw, Kahoot, Venn diagrams, and critical-thinking technology (STO strategies). These techniques facilitated the development of higher-order thinking skills, increased student motivation, and strengthened their ability to analyze, compare, and synthesize biological information. During the practical sessions, students actively participated in brainstorming activities using the Jigsaw method, where they collaboratively discussed key concepts related to fungal pathogens of Daucus carota L. Instead of visual figures, this stage included a detailed verbal explanation of fungal diseases supported by interactive lecture slides, allowing students to understand the biological mechanisms of infection without relying on static images. Additionally, the educational video illustrating microorganisms relevant to biotechnology lessons was described through narrative commentary, focusing on the structural and functional characteristics of the observed microorganisms. These descriptive explanations ensured that the learning process remained scientifically informative even without the presence of visual figures.

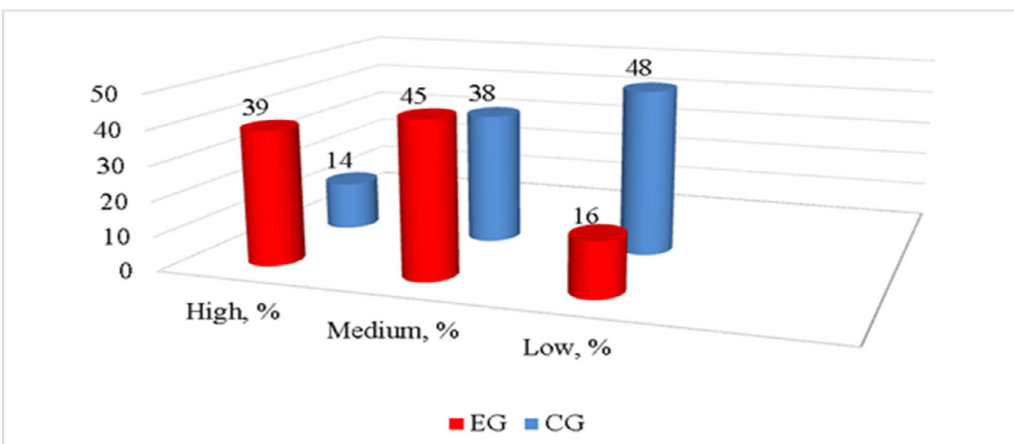
In the validation phase of the lesson, the teacher evaluated the effectiveness of the instructional design using the Interactive Demonstration Lecture Method, originally developed by Dorothy Merrits (Franklin and Marshall College), Robert Walter, and Bob Mack (Clark College). This method combines brief traditional lectures with structured interactive components and is particularly effective for guiding students through complex scientific concepts. It consists of three sequential stages: (1) predicting the outcome of the demonstration, (2) observing and analyzing the demonstration, and (3) reflecting on the results.

During the reflection stage, students were encouraged to engage in metacognitive questioning, responding to prompts such as: "What did I learn from this lesson?" "How can this knowledge be useful to me?" "In what ways can I apply what I have learned?" "Why is this knowledge important?" "How can I develop this knowledge further?", and "What else do I want to explore?" Sharing answers within groups allowed students to consolidate their understanding and co-construct new knowledge based on the learning experience.

Following the implementation of the designed teaching methods across the selected topics, a follow-up survey was administered during the third control stage of the experiment. The results indicated substantial positive changes in students' motivation, engagement, and academic performance. These findings are illustrated in Figure 1, which provides a comparative analysis of achievement levels between the experimental and control groups.

Figure 1

Comparison of student achievement levels in the experimental (EG) and control (CG) groups at the end of the pedagogical experiment



A comparative analysis of student performance revealed substantial improvements in the experimental group (EG) following the implementation of STEM-integrated instructional methods. When comparing the final assessment results with the baseline data collected at the beginning of the experiment, a clear positive shift was observed. The proportion of students demonstrating a high level of achievement increased to 39%, while 45% reached a medium level, and only 16% remained at a low level. In contrast, no meaningful changes were recorded in the control group (CG). By the end of the experiment, the percentage of students achieving a high level remained at 14%, the medium level remained at 38%, and the proportion of students at the low level persisted at 48%. These results indicate that traditional instructional methods used in the control group did not contribute to measurable improvement in student performance, whereas the STEM-based approach used in the experimental group produced significantly better outcomes.

Discussion. The findings of this study demonstrate that the integration of STEM-based instructional methods into biotechnology education significantly enhances student motivation, engagement, and academic performance. These results align with recent empirical studies published in Scopus- and Web of Science-indexed journals, which also report positive effects of interdisciplinary and practice-oriented teaching approaches in the natural sciences. For example, Županec et al., (2022) found that STEM-focused instructional models in biology classes improved conceptual understanding and promoted deeper engagement among primary and secondary school learners. Similar to our results, their study reported a notable increase in the proportion of high-achieving students after the implementation of STEM modules. Likewise, Mims et al. (2025) showed that project-based synthetic biology programs enhanced students' scientific identity, motivation, and ability to apply theoretical knowledge in practical contexts – findings that echo the improved confidence and performance observed in our experimental group.

The present study also corroborates evidence from international research emphasizing the significance of integrating technology-enhanced tools in STEM teaching. Yim et al. (2024) demonstrated that the use of digital platforms such as Kahoot, collaborative learning structures, and creative tasks increased learner participation and supported higher-order thinking. Consistent with their findings, our use of multimedia videos, interactive lectures, and game-based assessments contributed to heightened student engagement and improved learning outcomes.

Despite these similarities, some differences emerge. While previous studies primarily focused on general STEM competence development, our research specifically examined biotechnology topics such as fungal pathogens of Daucus carota L. and pectin extraction from carrot varieties. This provides a novel contribution by demonstrating that STEM integration is effective not only in broad scientific instruction but also in specialized laboratory-based biotechnology modules. Furthermore, compared to studies that rely solely on project-based learning, our approach employed a combination of Jigsaw, interactive demonstration lectures, concept tests, mind maps, and engineering-based problem-solving, offering a more comprehensive instructional framework.

The scientific value of this study lies in its provision of experimental evidence that STEM-integrated pedagogy leads to measurable improvements in academic performance. The shift in the experimental group - from predominantly medium and low achievement levels to 39% high achievement demonstrates the pedagogical efficacy of interdisciplinary, interactive, and technology-supported instruction. Moreover, the decrease in the proportion of low-performing students indicates that the STEM approach supports both advanced and struggling learners, contributing to more equitable learning outcomes.

Another key contribution of this study is its focus on the development of 21st-century competencies. As Rehman et al. (2025) argue, modern STEM programs must cultivate critical thinking, collaboration, creativity, and adaptability to prepare students for rapidly evolving scientific fields. Our findings affirm this claim: students in the experimental group demonstrated increased self-confidence, stronger problem-solving abilities, and greater readiness to apply biotechnology knowledge in real-world and professional contexts. In summary, the comparison with recent international research confirms that the results obtained in this study are scientifically grounded and consistent with global tendencies in STEM education. At the same time, the focus on biotechnology-specific content and the combination of diverse interactive teaching tools contribute new insights to the pedagogical literature and expand the understanding of effective STEM integration in higher education.

Conclusion. The present study provides empirical evidence that integrating STEM-based interdisciplinary pedagogy into biotechnology education yields significant improvements in student learning outcomes. The findings demonstrate that STEM-oriented modules - supported by multimedia resources, engineering-based problem-solving tasks, and collaborative learning structures - enhance learners' conceptual understanding, practical competencies, and motivation to engage with complex biological content. Compared with traditional instruction, students in the experimental group showed higher levels of achievement, greater confidence in applying scientific knowledge, and stronger engagement with biotechnology topics such as fungal pathogens of Daucus carota L. and pectin extraction techniques.

The study's key contribution lies in expanding current STEM education research by demonstrating its effectiveness within discipline-specific biotechnology instruction rather than general science contexts. This adds new insight to existing literature by confirming that interdisciplinary integration is not only pedagogically beneficial but also adaptable to laboratory-oriented, content-intensive modules. Furthermore, the study highlights the importance of linking biological concepts with technological and engineering processes to foster 21st-century skills, including critical thinking, scientific reasoning, creativity, and communication. From a practical standpoint, the developed instructional modules and digital learning resources can be directly incorporated into higher education curricula to modernize biotechnology courses and improve instructional quality. These materials also provide a scalable framework for strengthening STEM competencies among future biology educators. Future research should explore the long-term effects of STEM integration on students' academic trajectories, examine its applicability across broader areas of natural sciences, and develop systematic teacher training programs that ensure sustainable implementation of interdisciplinary pedagogical technologies in higher education. Additionally, large-scale studies involving diverse student populations would further validate the generalizability of these findings.

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