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EVALUATION OF AN INTERDISCIPLINARY PROJECT-BASED STEM MODEL IN BIOTECHNOLOGY EDUCATION

Abstract. The integration of STEM education into biotechnology is essential for developing research competence, interdisciplinary thinking, and practical problem-solving skills in future biology teachers. However, the implementation of interdisciplinary STEM models supported by experimental research and artificial intelligence remains limited in biotechnology education. This study aimed to develop and evaluate an interdisciplinary STEM project integrating biotechnology, ecology, chemistry, engineering, mathematics, and artificial intelligence within biology teacher education. A mixed-methods approach combining laboratory experimentation, project-based learning, questionnaires, interviews, and statistical analysis was employed. The STEM project was based on investigating the effects of copper, zinc, and cadmium on the growth of *Phaseolus vulgaris*, while students applied artificial intelligence tools, including ChatGPT, Claude AI, Python, and OneCompiler, for data processing, visualization, and scientific interpretation. Educational outcomes showed that 83.3% of participants reported mastering the stages of experimental planning, data collection, and data analysis, while 91.7% reported increased interest in biotechnology after completing the project. Participants also reported improved research competence, interdisciplinary understanding, and confidence in applying scientific methods to environmental problems. The scientific novelty of this study lies in the development of an interdisciplinary STEM model that integrates experimental biotechnology, project-based learning, and artificial intelligence into a unified educational framework. The proposed model contributes to strengthening research-oriented biotechnology education and provides a practical approach for preparing future biology teachers capable of addressing interdisciplinary scientific challenges.

Keywords: STEM education, biotechnology, project-based learning, interdisciplinary learning, research competence, artificial intelligence

Introduction

The modernization of the national education system and the improvement of educational quality have become strategic priorities for ensuring the sustainable development and global competitiveness of Kazakhstan. Head of State Kassym-Jomart Tokayev paid special attention to the national education system in his Address of 1 September. Noting that the education sector is the main indicator of the quality of the nation, the President set out a number of topical tasks facing the education and science system for the further development of the country. One of these tasks is to create favourable conditions for each student, using modern methods, in order to provide comprehensive, high-quality education and to form a competitive, self-aware, spiritually rich, moral and inquisitive personality (Government of the Republic of Kazakhstan, 2021).

Today, the mass development of technology and science brings new demands to the field of education. In particular, the development of biotechnology in close connection with the fields of ecology, medicine, agriculture and industry requires future specialists not only to acquire theoretical knowledge, but also to improve such skills as systematic thinking, the formation of practical skills and research ability. In this regard, the interdisciplinary approach to STEM (Science, Technology, Engineering, Mathematics) is of particular importance.

In biotechnological education, the traditional learning process does not have a positive effect on the practical application of the acquired knowledge and increasing interest in the subject. However, the STEM-based interdisciplinary project-based approach allows students to combine theoretical knowledge and practice and develop analytical thinking skills, directing them to solve a specific problem. With this in mind, we can clearly define the purpose of the study. The purpose of the study is to identify an effective model of interdisciplinary project-based learning in the STEM direction in biotechnological education.

The STEM approach is one of the most effective ways to establish interdisciplinary connections in education. Kelley and Knowles (2016) define STEM as a pedagogical approach that integrates science, technology, engineering, and mathematics to solve real-life problems (Kelley & Knowles, 2016). By connecting theoretical knowledge with practical applications, STEM enriches the educational process and enhances students' scientific literacy and practical skills (Tijani & Adeduyigbe, 2026). Furthermore, in the context of the Fourth Industrial Revolution, STEM has become an important educational approach for developing higher-order competencies, including critical thinking, that meet the demands of modern society (Bybee, 2013).

Beyond improving academic performance, STEM education plays a significant role in developing students' higher-order competencies required for the twenty-first century. Previous studies have shown that participation in interdisciplinary STEM activities enhances problem-solving, critical thinking, creativity, communication, and research skills, which are essential for both professional practice and lifelong learning (AlAli, 2024). These competencies enable students to apply scientific knowledge in unfamiliar situations, collaborate effectively in multidisciplinary teams, and adapt to rapidly changing technological environments. Therefore, STEM education contributes not only to knowledge acquisition but also to the preparation of competitive specialists capable of addressing complex real-world challenges (Sheth & Pathak, 2023).

From a methodological perspective, STEM education is implemented through inquiry-based, problem-based, and project-based learning, enabling students to apply interdisciplinary knowledge to authentic situations. In this approach, teachers act primarily as facilitators who guide students in identifying problems, designing solutions, conducting investigations, and evaluating outcomes rather than simply transmitting knowledge. STEM learning may be organised through the integration of two or more disciplines or through comprehensive projects that combine science, technology, engineering, and mathematics.

Within the STEM framework, each discipline contributes a specific educational function. Science develops students' abilities to observe, analyse, experiment, and explain natural phenomena, often through the investigation of environmental and social issues (Lee & Grapin, 2022). Technology supports the effective use of digital tools, software, and laboratory resources in the learning process (Tulivuori, 2021). Engineering promotes design thinking, modelling, problem-solving, and the development of innovative solutions. Mathematics provides the quantitative foundation for measurement, data analysis, modelling, and the interpretation of research results (Chahine et al., 2020). The successful implementation of interdisciplinary STEM education also depends on teachers' professional competence. Because STEM requires the integration of multiple disciplines, many educators experience difficulties in applying interdisciplinary teaching strategies beyond their primary area of expertise. Therefore, continuous professional development and methodological support are considered essential prerequisites for effective STEM implementation (Polgampala et al., 2017).

Continuous professional development, methodological support, and institutional commitment are recognised as key factors for the successful implementation of interdisciplinary STEM education. These conditions enable teacher educators to confidently integrate STEM concepts into their teaching practice and prepare future biology teachers to apply interdisciplinary approaches effectively in schools (Bakirova, 2023).

Another important challenge in STEM integration is the assessment of students' learning outcomes. Because interdisciplinary STEM learning develops not only subject knowledge but also problem-solving, critical thinking, collaboration, and project skills, traditional assessment methods

are often insufficient. Therefore, innovative assessment approaches capable of evaluating students' ability to apply, analyse, and integrate knowledge in project-based activities have become increasingly important (Chandra et al., 2025).

Contemporary studies also indicate that formative assessment, project-based assessment, portfolios, and authentic performance tasks are more consistent with the objectives of interdisciplinary STEM education than traditional assessment methods. These approaches enable a comprehensive evaluation of students' theoretical knowledge together with their critical thinking, problem-solving abilities, interdisciplinary competence, and practical skills (Bakirova, 2023).

The theoretical foundations of interdisciplinary STEM education have been widely discussed in international literature. Sanders (2008) argues that effective STEM education requires not only the integration of individual disciplines but also their implementation as a unified educational system centred on solving authentic real-world problems. Similarly, Rodríguez et al. (2024) emphasise that project-based learning provides an effective framework for interdisciplinary teaching by promoting critical thinking, creativity, and a deeper understanding of relationships among scientific disciplines.

In Kazakhstan, STEM education has become an important direction in the modernisation of teacher education. Curriculum renewal, the enhancement of practice-oriented learning, and the development of teachers' research competence are identified as key priorities of educational reform (Toybazarova & Nazarova, 2018). Furthermore, university–industry collaboration is essential for supporting innovative STEM programmes, particularly in contexts with limited institutional resources (Jonbekova et al., 2020). Systematically organised laboratory practice provides a strong foundation for research-oriented science education (Balta, 2015). Furthermore, science teachers in Kazakhstan demonstrate a positive readiness to adopt interdisciplinary and innovative teaching approaches (Polatova et al., 2019). Differentiated and project-based learning strategies are effective in developing students' practical competencies (Ibrayeva et al., 2023). Methodological approaches based on STEM integration can also strengthen the professional preparation of future biology teachers (Abdrakhmanova et al., 2025). In addition, project-based learning significantly enhances students' creativity and critical-thinking skills (Lesman et al., 2023). Nevertheless, despite these important contributions, studies specifically devoted to interdisciplinary STEM project models in biotechnology education remain limited in Kazakhstan.

Therefore, this study contributes to the existing literature by proposing and validating an interdisciplinary STEM project model for biotechnology education within the context of higher education in Kazakhstan.

Methods and materials

Project-based learning (PjBL) is a student-centred instructional approach in which learners collaboratively address authentic, real-world problems through interdisciplinary projects. It involves observation, questioning, experimentation, information gathering, analysis, synthesis, and reflection, enabling students to construct knowledge through active participation. By connecting theoretical knowledge with practical experience, PjBL develops problem-solving, critical-thinking, collaboration, and decision-making skills while deepening students' understanding of complex issues (Solomon, 2003; Torres, 2024). This study is designed to identify an effective model of interdisciplinary project-based learning in the STEM direction in biotechnological education. A structural model of STEM project-based learning was developed through a comprehensive literature review. The empirical study involved 24 fourth-year Biology students (Educational Programme 6B01509) from the Kazakh National Women's Teacher Training University. Using stratified randomisation based on gender, academic performance, and previous project experience, participants were assigned to an experimental group ($n = 12$) and a control group ($n = 12$). Baseline equivalence between the groups was confirmed statistically, with no significant differences in age (20.4 ± 1.2 vs. 20.1 ± 1.4 years, $p = 0.521$), GPA (3.62 ± 0.31 vs. 3.65 ± 0.28 , $p = 0.774$), or previous project experience ($p = 0.682$). The equivalence of the control and experimental groups was further confirmed by the pre-test results. The mean pre-test score was 48.7 ± 4.2 in the control

group and 49.1 ± 4.0 in the experimental group, with no statistically significant difference between the groups (independent-samples *t*-test, $t = 0.27$, $p = 0.789$). The experimental group participated in the interdisciplinary STEM project, whereas the control group studied the same content using conventional lecture - and seminar-based instruction. The study employed four groups of research instruments: (1) diagnostic pre- and post-tests assessing six competence domains (biological knowledge, chemistry and biochemistry, mathematical modelling, technological competence, critical thinking, and research skills; maximum score: 100 points per domain); (2) a two-stage structured questionnaire administered via Google Forms, comprising 13 items organised into three thematic sections; (3) semi-structured interviews with five participants (P1-P5); and (4) laboratory measurements of plant biometric parameters. The experimental component was conducted through an interdisciplinary STEM project entitled “Effect of Heavy Metals on Plant Growth”.

The experimental component was conducted through an interdisciplinary STEM project entitled “Effect of Heavy Metals on Plant Growth”. Common bean (*Phaseolus vulgaris*) was selected as the experimental model because of its rapid growth, high sensitivity to heavy metal stress, and suitability for laboratory cultivation. Copper (Cu), zinc (Zn), and cadmium (Cd) were applied at two concentrations (0.01 M and 0.001 M). To evaluate the potential of biological remediation, five *Pseudomonas* strains (1SL - *P. putida*, 2SL - *P. xanthomarina*, 3SL - *P. corrugata*, 4S - *P. fluorescens*, and 5S - *P. putida*) were introduced into the root zone together with the heavy metal solutions.

The experiment was conducted under laboratory conditions using a five-stage interdisciplinary STEM project model (Figure 2).

Stage 1 (Theoretical): Students reviewed the literature on STEM education, project-based learning, and heavy metals, formulated the research question and hypothesis, and became familiar with the digital and artificial intelligence tools used in the project.

Stage 2 (Preparatory): Experimental materials, equipment, and solutions were prepared, student groups were formed, and a baseline questionnaire was administered to assess students' prior knowledge and readiness for the project.

Stage 3 (Experimental): *Phaseolus vulgaris* plants were cultivated, treated with heavy metal solutions, and biometric parameters were measured at predetermined intervals.

Stage 4 (Analytical): Students processed and analysed the experimental data by calculating descriptive statistics, comparing treatment groups, visualising results using Python and Excel, and interpreting the effects of different heavy metals based on experimental findings and published literature.

Stage 5 (Final): Students presented the project results, prepared scientific conclusions, completed the post-test and final questionnaire, and the project outcomes were evaluated using the assessment rubric.

Figure 1

Experimental cultivation and biometric assessment of common bean (*Phaseolus vulgaris*) plants



During the experimental phase, pre-germinated *Phaseolus vulgaris* seeds were cultivated under laboratory conditions and assigned to control and experimental treatments (Figure 1).

Control plants were irrigated with distilled water, whereas experimental plants were exposed to Cu, Zn, and Cd solutions, with selected treatments additionally inoculated with *Pseudomonas* strains. Plant growth was monitored every seven days by measuring stem length, root length, leaf number, and leaf area. All measurements were performed in triplicate and expressed as mean $\pm$ standard deviation ($M \pm SD$), with the results recorded for subsequent statistical analysis (Figure 1).

The interdisciplinary project integrated all four STEM components. Science focused on biotechnology, plant physiology, and heavy metal toxicity; engineering involved experimental design and laboratory procedures; mathematics included biometric measurements, statistical analysis, and data interpretation; while technology incorporated laboratory equipment together with digital and artificial intelligence tools. Digital technologies supported all stages of the project: ChatGPT was used for literature review and scientific writing support, Claude AI for developing an interactive prediction interface, Python for statistical analysis and data visualisation, and OneCompiler for testing and executing Python scripts.

Data were collected through observation, biometric measurements, questionnaires, and semi-structured interviews. Repeated measurements improved data reliability while enabling students to develop research competence, experimental skills, critical thinking, collaborative learning, and data analysis throughout the project.

Quantitative data were analysed using Microsoft Excel and IBM SPSS Statistics. Data normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests, respectively. As the data met the assumptions of normality ($p > 0.05$), differences between groups were analysed using the independent-samples t-test, whereas within-group changes were evaluated using the paired-samples t-test. Descriptive statistics are presented as mean $\pm$ standard deviation ($M \pm SD$), and statistical significance was accepted at ($p < 0.05$).

Qualitative data obtained from the semi-structured interviews were examined using thematic analysis, while open-ended questionnaire responses were evaluated through content analysis (Braun & Clarke, 2006). Interview participants were anonymised (P1-P5), and methodological triangulation was applied to improve the credibility and consistency of the findings.

Quantitative and qualitative data were integrated at the interpretation stage. Diagnostic pre- and post-test results were used to assess changes in students' competence scores, while questionnaire and interview data were used to examine students' self-reported perceptions and experiences. Laboratory data provided the empirical basis for the STEM project activities and were used to contextualise students' data analysis and interpretation. The findings from these data sources were compared and interpreted together to provide a comprehensive assessment of the interdisciplinary STEM learning process.

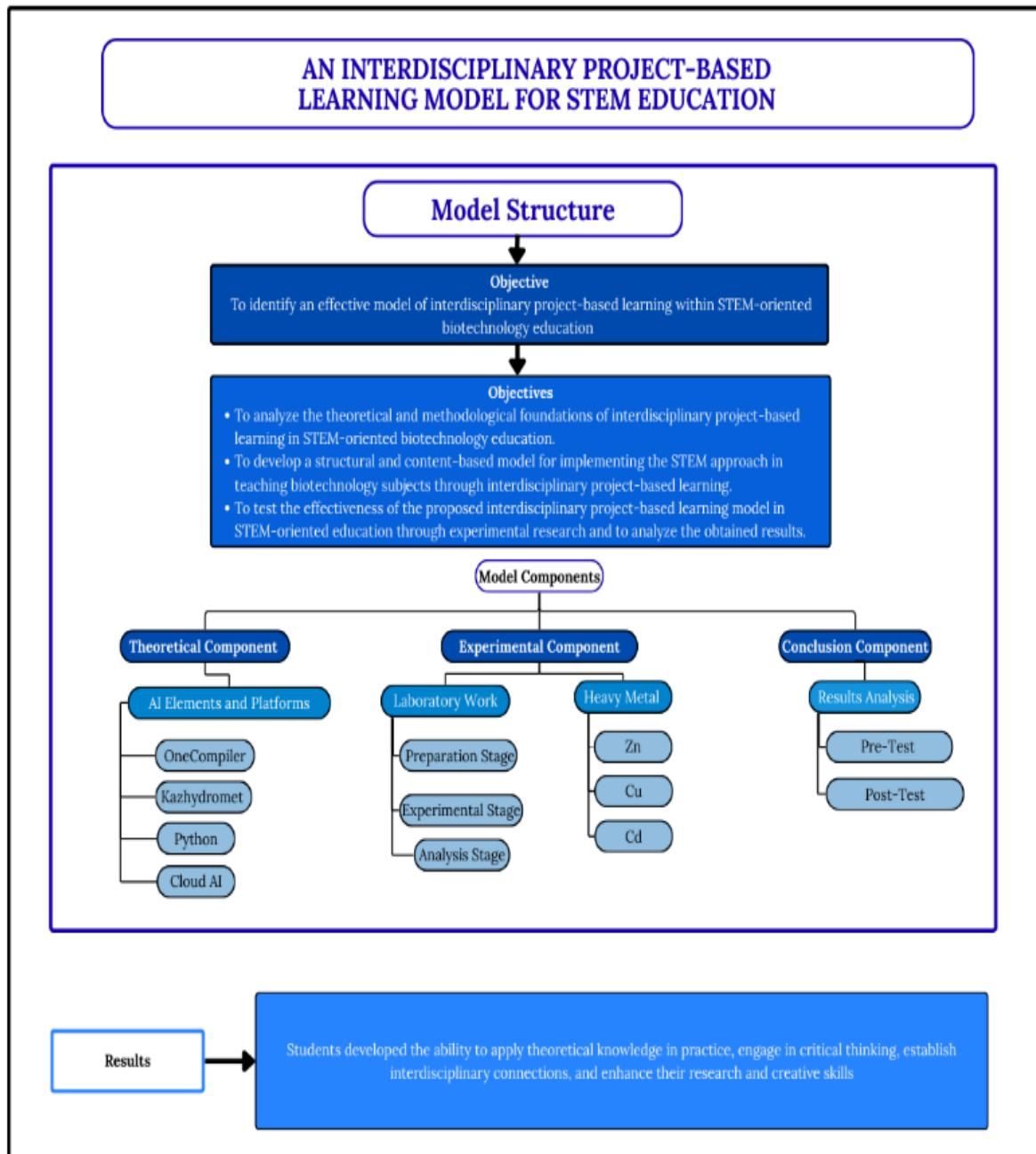
Python and OneCompiler were employed for statistical analysis, programming, and data visualisation. ChatGPT was used to support the literature review, clarify scientific terminology, assist in organising and language-editing the scientific text, and generate and debug Python code used in the project. Within the student STEM project, AI tools were used as supplementary learning and analytical tools. Students used ChatGPT to clarify information related to heavy-metal effects on plants and to support the interpretation of experimental information, while Claude AI was used to develop an interactive interface for predicting plant responses based on biometric indicators. Web references to the AI-based tools and interfaces used in the project are provided in the manuscript. AI-generated information and predictions were not considered experimental evidence and were compared with students' experimental observations, biometric measurements, and relevant scientific literature. The authors subsequently reviewed and verified AI-assisted information, text, and code against the original scientific literature, experimental data, and statistical results. AI tools were not used to generate experimental data or determine the final scientific conclusions.

The effectiveness of the interdisciplinary STEM project was evaluated using quantitative and qualitative data collected throughout the experimental study. The project entitled “Effect of Heavy Metals on Plant Growth” provided students with opportunities to apply theoretical knowledge in a

practical context by integrating biotechnology, ecology, engineering, mathematics, and digital technologies. Students participated in experimental procedures, laboratory measurements, data analysis, and interpretation of the obtained results. The overall structure of the interdisciplinary STEM project model is presented in Figure 2.

Figure 2

Model of interdisciplinary project-based learning in STEM in biotechnological education



Description of the interdisciplinary STEM project model

The proposed interdisciplinary STEM project model was developed to integrate theoretical knowledge with practical laboratory activities in biotechnology education. The model consists of three interconnected components: the theoretical, practical, and evaluation blocks, which collectively support the development of students' research competence, interdisciplinary thinking, and problem-solving skills (Figure 2).

The theoretical block provides the scientific foundation of the project by integrating biotechnology, STEM education, and digital technologies. To support project implementation,

students used several digital and artificial intelligence tools for information retrieval, data processing, statistical analysis, and result visualisation. Environmental data on heavy metal distribution in Kazakhstan were obtained from Kazhydromet. Python and OneCompiler were employed for statistical analysis, programming, and data visualisation, while ChatGPT supported literature review, scientific writing, and Python code generation. Claude AI was used to develop an interactive interface for predicting plant responses based on biometric indicators (<https://kushtar1206-a11y.github.io/mywebsite/>, <https://claude.ai/public/artifacts/bec23a98-45a6-44e8-93c4-f6e3f92f2360>, <https://kushtar1206-a11y.github.io/New-map/> Web references for artificial intelligence tools).

The integration of these digital technologies enabled students to analyse experimental data, visualise research findings, and strengthen their research, analytical, and digital competencies within an interdisciplinary STEM learning environment.

Research Instruments and Assessment Procedure

Three main instruments were used in the study: a diagnostic pre- and post-test, a structured questionnaire, and an assessment rubric. The instruments were developed in accordance with the objectives and competency domains of the interdisciplinary STEM-PBL project “Effect of Heavy Metals on Plant Growth.” The diagnostic test assessed six competency domains: biological knowledge, chemistry and biochemistry, mathematical modelling, technological competences, critical thinking, and research skills. Each domain was assessed on a 100-point scale. Equivalent versions were used for the pre- and post-tests to reduce the effect of memorization. The questionnaire consisted of 13 items organized into three thematic sections and was administered before and after the project to assess students’ perceptions, readiness, research competence, interdisciplinary understanding, and interest in biotechnology. A nine-criterion assessment rubric was used to evaluate students’ project performance. The rubric covered scientific understanding, interdisciplinary integration, experimental and research skills, data analysis, use of STEM tools, scientific communication, and reflection. Each criterion was scored from 1 to 3 points, giving a total possible score of 9–27 points. Scores of 9–14, 15–21, and 22–27 represented low, medium, and high performance levels, respectively. The rubric was applied during and at the end of the project, with students’ performance supported by their laboratory work, reports, presentations, and research results. The instruments were aligned with the project learning objectives and competency domains and were used together with semi-structured interviews and laboratory measurements to provide complementary evidence of students’ learning outcomes.

Research Ethics

The ethical aspects of the study were reviewed by the Scientific Ethics Committee of the Kazakh National Women's Teacher Training University (Protocol No. 4, dated 22 January 2026). The study was conducted in accordance with the relevant ethical principles and requirements for research involving human participants. Before participation, all students were informed about the purpose, content, procedures, expected outcomes, and format of the study. Informed consent was obtained from all participants prior to data collection. Participation was voluntary, and participants were informed of their right to withdraw from the study at any time without academic or other consequences. To ensure confidentiality and anonymity, no personally identifying information was included in the research dataset or reported in the manuscript. Each participant was assigned a unique code, and questionnaire and assessment data were processed using these codes. The collected data were used solely for research purposes and were not disclosed to third parties.

Experimental Block

The interdisciplinary STEM model was implemented through the laboratory project “Effect of Heavy Metals on Plant Growth,” comprising preparation, experimentation, and data analysis. *Phaseolus vulgaris* plants were treated with Cu, Zn, and Cd at 0.01 M and 0.001 M, with selected variants additionally inoculated with *Pseudomonas* strains. The experimental group completed the project, whereas the control group received traditional instruction.

Heavy metal exposure caused concentration-dependent morphological and biometric changes (Table 1), including chlorosis, root damage, growth inhibition, and leaf necrosis. Leaf

area decreased under all treatments and reached its lowest value at 0.01 M Cu ($1.70 \pm 0.09 \text{ cm}^2$ vs. $3.75 \pm 0.19 \text{ cm}^2$ in the control). Root length was the most responsive parameter, decreasing under 0.01 M Cu ($6.5 \pm 0.33 \text{ cm}$) but increasing under 0.01 M Zn ($14.5 \pm 0.73 \text{ cm}$) and 0.001 M Cd ($22.5 \pm 1.13 \text{ cm}$), possibly due to adaptive responses and the influence of *Pseudomonas*. Because the experiment covered only the early growth stage and included three biological replicates, the findings require confirmation in larger and longer-term studies.

Table 1

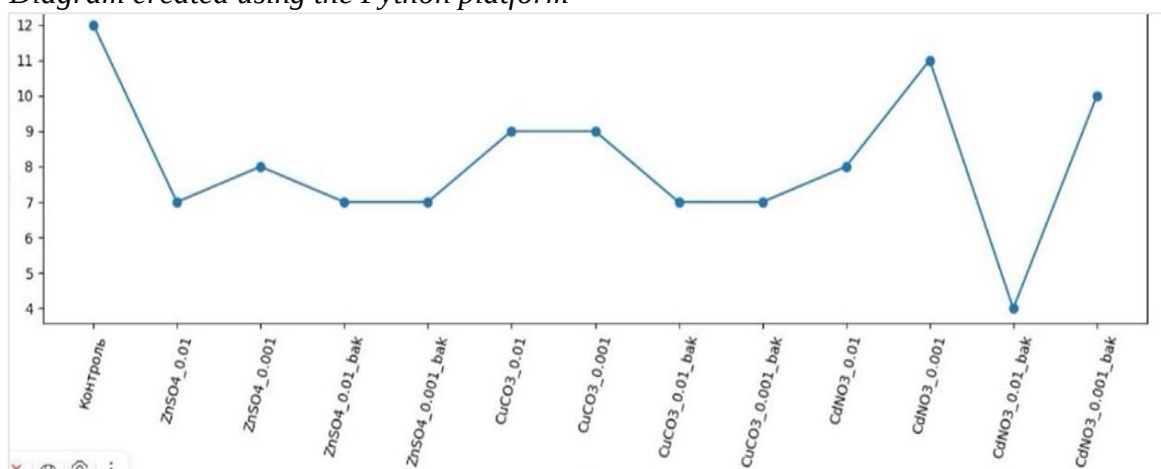
Effect of heavy metals on the biometric parameters of the common bean ($M \pm SD$, $n = 3$)

Growth parameter	Control	Zn 0.01 M	Zn 0.001 M	Cu 0.01 M	Cu 0.001 M	Cd 0.01 M	Cd 0.001 M
Stem length, cm	36 ± 1.80	28 ± 1.40	29 ± 1.45	55 ± 2.75	24.8 ± 1.24	32 ± 1.60	34.5 ± 1.73
Root length, cm	6.9 ± 0.35	14.5 ± 0.73	7.0 ± 0.35	6.5 ± 0.33	21.0 ± 1.05	11.0 ± 0.55	22.5 ± 1.13
Leaf area, cm^2	3.75 ± 0.19	3.5 ± 0.18	2.3 ± 0.12	1.7 ± 0.09	2.75 ± 0.14	3.0 ± 0.15	2.6 ± 0.13
Number of leaves, pcs	5 ± 0.25	8 ± 0.40	3 ± 0.15	8 ± 0.40	5 ± 0.25	6 ± 0.30	5 ± 0.25

A comparative analysis of the experimental results was performed. As part of the interdisciplinary STEM project, students developed a web application that enables online comparison of heavy metal type, concentration, and the corresponding plant growth responses (Figure 3).

Figure 3

Diagram created using the Python platform



Heavy metal exposure affected the growth of *Phaseolus vulgaris* in a concentration-dependent manner. Among the tested metals, copper exhibited the strongest phytotoxicity, reducing root length to $6.5 \pm 0.33 \text{ cm}$ and leaf area to $1.70 \pm 0.09 \text{ cm}^2$, accompanied by chlorosis, vein darkening, and necrotic lesions. Cadmium also inhibited plant growth, particularly at 0.01 M, where root development was markedly reduced ($11.0 \pm 0.55 \text{ cm}$) and chlorosis became evident. In contrast, zinc showed the lowest toxicity at 0.001 M. Although 0.01 M Zn reduced stem growth ($28.0 \pm 1.40 \text{ cm}$ compared with $36.0 \pm 1.80 \text{ cm}$ in the control), it promoted greater root elongation ($14.5 \pm 0.73 \text{ cm}$), suggesting a possible adaptive response to heavy metal stress.

The interdisciplinary STEM project also enhanced students' practical and research competencies. Through laboratory experimentation, data collection, statistical analysis, and collaborative project work, students strengthened their research, teamwork, critical thinking, and scientific communication skills.

Results and Discussion

Before evaluating the effectiveness of the intervention, the initial competence levels of the control and experimental groups were compared. Pre-test results confirmed baseline equivalence between groups, with no significant differences across the six competence domains ($p > 0.05$), indicating similar initial knowledge and skills (Table 2).

Table 2

Pre-test results of the control and experimental groups (points, max = 100)

Competence block	Control group (n = 12), M ± SD	Experimental group (n = 12), M ± SD	t	p
Biological knowledge	52.4 ± 6.1	53.1 ± 5.8	0.32	0.751
Chemistry and biochemistry	49.7 ± 7.3	50.2 ± 7.0	0.19	0.849
Mathematical modelling	44.3 ± 8.2	43.8 ± 8.5	0.17	0.867
Technological competences	47.6 ± 6.8	48.0 ± 6.4	0.17	0.866
Critical thinking	51.2 ± 5.9	51.9 ± 6.2	0.32	0.752
Research skills	46.8 ± 7.1	47.3 ± 7.4	0.19	0.849
Mean over all blocks	48.7 ± 4.2	49.1 ± 4.0	0.27	0.789

In the final block the results of the practical work were analysed. Two types of assessment tools were used: (1) objective diagnostic testing of six competence blocks before and after the project, which made it possible to measure the learning outcomes quantitatively, and (2) an initial and a final questionnaire, which revealed the attitude of the students towards interdisciplinary STEM project learning, the change in their learning motivation and their subjective assessment of the project. The introduction of the test component removes the limitation of an assessment based only on the opinions and the interest of the students.

The final testing was carried out during the last week of the semester using parallel (equivalent) versions of the diagnostic tasks, which excluded the effects of memorisation and practice. The mean gain over all competence blocks in the control group amounted to 8.3 points (+17.0%), which reflects the natural development of professional competence in traditional teaching, whereas in the experimental group it reached 23.6 points (+48.1%), that is 2.8 times more. The difference in the mean gain between the groups was 15.3 points and proved to be statistically highly significant ($t = 11.42$; $p < 0.001$). The greatest differential gain was recorded in the block “research skills” ($\Delta = +17.3$ points) and in the block “mathematical modelling” ($\Delta = +16.3$ points), that is, precisely in those competences that are formed with the greatest difficulty within the traditional lecture and seminar system (Table 3).

Table 3

Comparison of gain scores between the control (CG) and experimental (EG) groups

Competence block	CG post- test M ± SD	EG post- test M ± SD	Gain CG	Gain EG	Δ gain	t	df	p
Biological knowledge	60.3 ± 5.4	74.8 ± 4.9	+7.9	+21.7	+13.8	7.84	22	< .001
Chemistry and biochemistry	57.1 ± 6.2	71.3 ± 5.6	+7.4	+21.1	+13.7	6.97	22	< .001
Mathematical modelling	52.6 ± 7.1	68.4 ± 6.3	+8.3	+24.6	+16.3	7.12	22	< .001
Technological competences	55.9 ± 5.7	72.1 ± 5.1	+8.3	+24.1	+15.8	8.34	22	< .001
Critical thinking	60.4 ± 5.3	76.2 ± 4.7	+9.2	+24.3	+15.1	8.71	22	< .001

Research skills	55.7 ± 6.4	73.5 ± 5.8	+8.9	+26.2	+17.3	7.98	22	< .001
Mean over all blocks	57.0 ± 3.8	72.7 ± 3.2	+8.3	+23.6	+15.3	11.42	22	< .001

Table 3 shows improvements in all six competence domains in both groups. Gain scores ranged from 7.4 to 9.2 points in the control group and from 21.1 to 26.2 points in the experimental group. The largest between-group difference was observed for research skills ($\Delta = 17.3$ points), followed by mathematical modelling ($\Delta = 16.3$) and technological competences ($\Delta = 15.8$), while the smallest difference was observed for chemistry and biochemistry ($\Delta = 13.7$). Across all domains, the mean gain was 8.3 points in the control group and 23.6 points in the experimental group, with a between-group difference of 15.3 points ($t(22) = 11.42, p < .001$).

Table 4

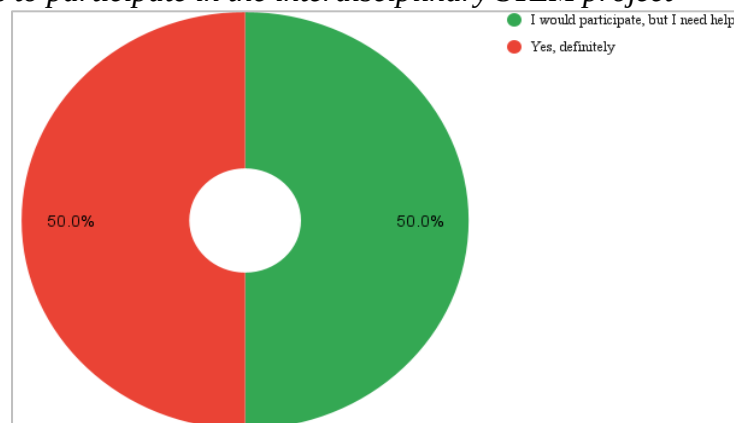
Results of the paired-samples t-test for pre- to post-test changes

Group	Pre-test, M	Post-test, M	Gain	t(11)	p
Control group (all competence domains)	48.7	57.0	+8.3	6.82	< .01
Experimental group (all competence domains)	49.1	72.7	+23.6	18.41	< .001

Table 4 shows statistically significant pre- to post-test improvements in both groups: from 48.7 to 57.0 points in the control group ($t(11) = 6.82, p < .01$) and from 49.1 to 72.7 points in the experimental group ($t(11) = 18.41, p < .001$).

Figure 4

Students' readiness to participate in the interdisciplinary STEM project



The pre-project questionnaire was administered to the 12 students in the experimental group to assess their initial understanding of ecological biotechnology and their readiness to participate in the interdisciplinary STEM project.

The results showed that 83.3% (10/12) of the participants correctly identified ecological biotechnology as an approach to solving environmental problems, whereas 16.7% (2/12) demonstrated incomplete conceptual understanding. Although all students expressed interest in participating in the project, only 50% considered themselves fully prepared, while the remaining 50% reported interest but uncertainty about their readiness (Figure 4). These findings indicate that, before the intervention, students possessed basic theoretical knowledge but lacked confidence in applying interdisciplinary STEM approaches and conducting research activities.

Figure 5

Indicators of mastery of research stages within the framework of a STEM interdisciplinary project

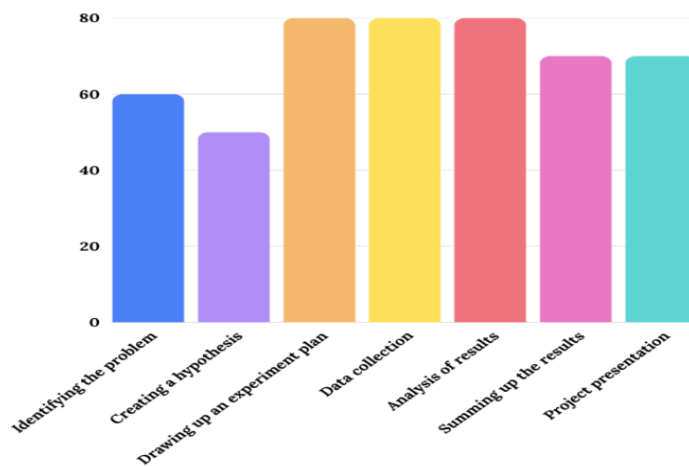


Figure 6
Growth of the research abilities of the participants

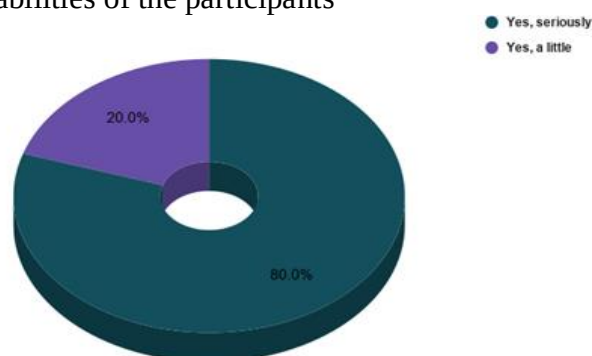


Figure 7
Interdisciplinary Connections

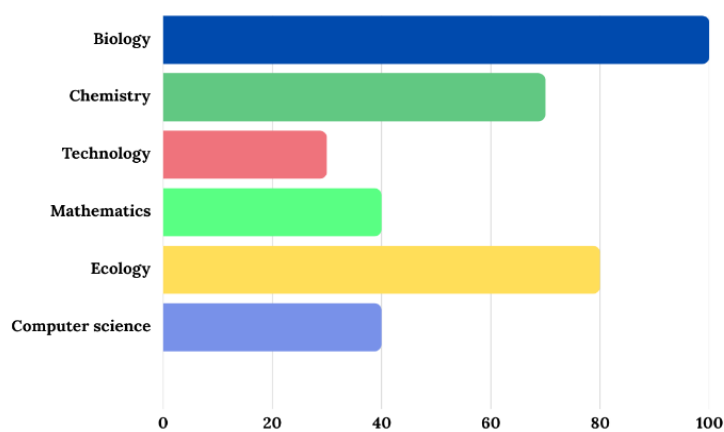
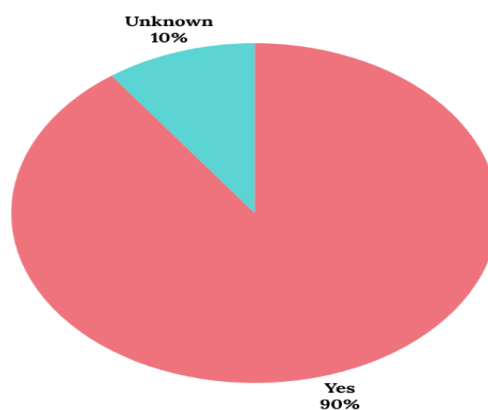


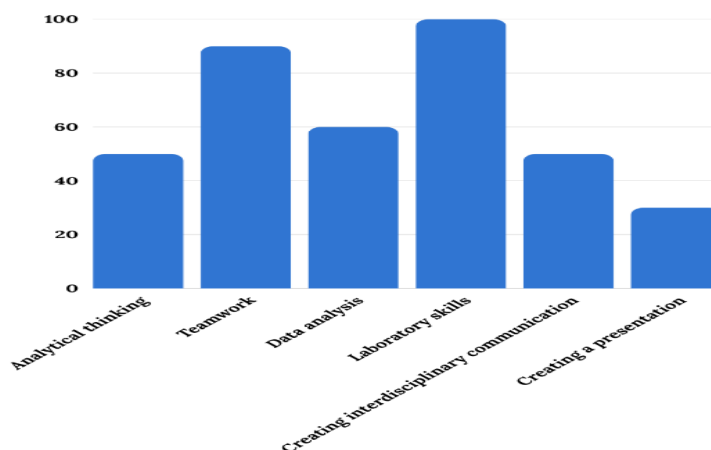
Figure 8
Level of interest of the participants in the subject



Following completion of the project, the questionnaire revealed clear improvements in students' research competence and learning outcomes (Figures 6–10). Most participants (83.3%, 10/12) reported mastering experimental planning, data collection, and data analysis (Figure 5), while all students (100%) indicated improved research competence and 83.3% reported substantial progress (Figure 6).

Students also demonstrated a better understanding of interdisciplinary integration: biology was identified by all participants (100%), followed by ecology (80%) and chemistry (70%), with several students additionally recognising links with mathematics, computer science, and technology (Figure 7). Furthermore, 91.7% reported increased interest in biotechnology after completing the project (Figure 8).

Figure 9
Skills Developed in Participation



The project contributed to the development of laboratory and research skills (100%), teamwork (83.3%), data-analysis skills (66.7%), and analytical thinking together with understanding of interdisciplinary relationships (58.3%) (Figure 9; Table 5). Overall, these findings indicate that the interdisciplinary STEM project effectively strengthened students' practical, analytical, and research competencies.

Table 5
Summary results of the survey of the participants of the STEM project (n = 12)

Indicator	n (of 12)	%
Development of laboratory and research skills	12	100.0
Increased interest in biotechnology	11	91.7
Significant growth of research abilities	10	83.3
Full understanding of the mechanism of the action of heavy metals	10	83.3
STEM integration facilitated the understanding of the material	10	83.3
Development of teamwork skills	10	83.3
Development of data-analysis skills	8	66.7
Correct identification of the most toxic metal (Cu)	8	66.7
Analytical thinking and detailed description of the STEM connection	7	58.3
Mean perceived complexity of the project (out of 5)	—	4.08

The semi-structured interviews (n = 5; P1–P5) supported the quantitative findings. Thematic analysis identified four major themes: (1) integration of theory and practice, (2) development of research competence, (3) strengthening of interdisciplinary thinking, and (4) increased learning motivation. Participants also demonstrated improved understanding of heavy metal toxicity, phytoremediation, and the role of biotechnology in environmental protection. The mean perceived

project complexity was 4.08 ± 0.67 (out of 5), indicating an appropriate cognitive challenge consistent with the zone of proximal development (Vygotsky, 1978).

Qualitative findings from the semi-structured interviews

The semi-structured interviews with five participants (P1–P5) were conducted to further explore students' experiences and perceptions of the interdisciplinary STEM project. Thematic analysis identified four major themes: (1) integration of theory and practice, (2) development of research competence, (3) strengthening of interdisciplinary thinking, and (4) increased learning motivation. The qualitative findings complemented the quantitative questionnaire results and provided additional insight into how students experienced the learning process.

Integration of theory and practice. Participants consistently described the project as an opportunity to connect theoretical knowledge with practical laboratory experience. P1 explained:

“Previously, I considered the effects of heavy metals on plants mainly at the theoretical level. During the project, however, I conducted real experiments and observed how heavy metals affected plant physiology, particularly growth rate and leaf structure. This showed me that understanding knowledge through its application is more important than simply memorising it.” (P1)

Similarly, P3 stated:

“The STEM approach and project-based learning deepened my biotechnology knowledge through practical experience. Studying the response of plants to heavy metals helped me understand the theory more completely.” (P3)

These responses were consistent with the quantitative findings, in which 83.3% of participants (10/12) reported mastering experimental planning, data collection, and data analysis, while 83.3% indicated that STEM integration facilitated their understanding of the learning material. The interview responses therefore provided further evidence that practical experimentation helped students apply theoretical knowledge to the investigation of heavy-metal effects on plants.

Development of research competence. Participants also reported that active involvement in the experimental process contributed to the development of research and analytical skills. P3 described the acquisition of the main stages of scientific inquiry:

“During the experiment, I practically mastered all stages of the scientific method: identifying the problem, formulating a hypothesis, conducting the experiment, and analysing the results. This improved my research abilities and developed my scientific thinking.” (P3)

P4 further emphasised the importance of working with experimental data:

“During the research, I developed skills in collecting, comparing, and analysing data. Comparing the control and experimental groups to determine the effects of heavy metals helped me understand the logic of scientific research. This contributed to the development of my analytical thinking.” (P4)

These qualitative responses corresponded with the questionnaire results, which showed that 100% of participants reported improvement in laboratory and research skills, 83.3% reported significant growth in research abilities, and 66.7% reported development of data-analysis skills. Thus, the interview data further illustrated the practical experiences underlying the reported improvement in research competence.

Strengthening of interdisciplinary thinking. Participants described the integration of several disciplines as an important component of the project. P2 explained how different subject areas contributed to a common research task:

“Interdisciplinary integration clearly demonstrated its contribution to the effectiveness of the research. Biology provided an understanding of the physiological condition of the plant, chemistry was used to determine the concentration of metals, while ecology helped us consider the environmental effects. Combining these areas made the results more complete and comprehensive.” (P2)

Other participants similarly reported using knowledge from chemistry to understand the properties of heavy metals, biology to examine their effects on plants, and ecology to interpret the environmental significance of the findings. These responses were consistent with the questionnaire results: 100% of participants identified biology as relevant to the project, 80% identified ecology,

and 70% identified chemistry, while additional connections with mathematics, computer science, and technology were also recognised. Moreover, 58.3% reported development of analytical thinking and understanding of interdisciplinary relationships.

Increased learning motivation. The interviews also indicated increased interest and active engagement in the learning process. P1 described the difference between project-based and conventional learning:

“Project-based learning significantly increased my interest in the learning process. I was not simply a recipient of ready-made information; I conducted the research myself. This gave me greater motivation.” (P1)

P5 additionally highlighted the development of responsibility through participation in the project:

“The project gave me a sense of responsibility because my work had to produce a real result. This taught me to be more careful and responsible.” (P5)

These qualitative responses complemented the quantitative finding that 91.7% of participants (11/12) reported increased interest in biotechnology after completing the project. The interview data therefore provided contextual evidence for the increased engagement and interest reported in the post-project questionnaire. Overall, the qualitative findings were consistent with the quantitative results and provided a more detailed account of students’ experiences during the interdisciplinary STEM project. Participants described how practical experimentation supported the application of theoretical knowledge, how direct involvement in research strengthened research and analytical skills, how interdisciplinary integration helped connect different areas of knowledge, and how active participation increased their interest and motivation. These findings complement the quantitative evidence presented above and demonstrate convergence between students’ reported experiences and the measured educational outcomes.

Limitations and Future Directions

Although the study demonstrated the effectiveness of the interdisciplinary STEM project, several limitations should be acknowledged. The study was conducted with a relatively small sample ($n = 24$) from a single university, which may limit the generalisability of the findings. In addition, the experimental period was limited to two months and covered only the early growth stage of *Phaseolus vulgaris*. Educational outcomes were assessed using both objective measures and students’ self-assessments; however, the latter were supported through the triangulation of test, questionnaire, and interview data. In future research, we plan to expand the sample by including participants from multiple universities, extend the experiment to cover the complete plant growth cycle, and conduct follow-up assessments to evaluate the long-term sustainability of the learning outcomes.

Conclusion

The present study evaluated an interdisciplinary project-based STEM model in biotechnology education that integrated biology, ecology, chemistry, engineering, mathematics, and artificial intelligence within a project-based learning environment. The model combined theoretical instruction with practical laboratory activities, allowing students to investigate the effects of heavy metals on plant growth and to apply scientific inquiry and interdisciplinary problem-solving approaches. The experimental results showed that copper, zinc, and cadmium affected the biometric characteristics of *Phaseolus vulgaris*, with responses varying according to metal type and concentration. Higher concentrations were associated with greater effects on plant growth, while differences among treatments reflected variations in plant responses to metal stress. The experimental activities provided a context in which students could work with biological data, interpret experimental observations, and relate laboratory findings to environmental biotechnology.

The educational findings indicated increases in competence scores across the assessed domains following participation in the interdisciplinary STEM project. Questionnaire and interview data additionally indicated students’ self-reported perceptions of research competence, interdisciplinary understanding, and confidence in conducting scientific investigations. These self-reported findings

should be interpreted as students' perceptions rather than as independent evidence of competence. The integration of AI tools, including ChatGPT, Claude AI, Python, and OneCompiler, supported selected activities related to information processing, data analysis, visualisation, and interpretation. AI-generated outputs were treated as supplementary resources and were reviewed against experimental observations, scientific literature, and statistical results.

The scientific contribution of the study lies in the development and implementation of an interdisciplinary STEM project that combines experimental biotechnology, project-based learning, computational analysis, and digital and artificial intelligence tools in the preparation of future biology teachers. The model provides a framework for connecting laboratory experimentation with interdisciplinary analysis and project-based learning within biotechnology education.

Overall, the findings provide empirical information on the implementation of an interdisciplinary project-based STEM model in biotechnology education. The results indicate that the model can be used as a framework for integrating experimental biotechnology, interdisciplinary learning, and digital tools into university biology education. However, the findings are limited by the relatively small sample and single-institution setting. Future research should involve larger samples from multiple universities, extend the experimental activities across the complete plant growth cycle, and examine the longer-term educational outcomes of interdisciplinary STEM project-based learning.

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БИОТЕХНОЛОГИЯЛЫҚ БІЛІМ БЕРУДЕГІ ПӘНАРАЛЫҚ ЖОБАЛЫҚ STEM МОДЕЛІН БАҒАЛАУ

Аңдатпа. Болашақ биология мұғалімдерінің зерттеушілік құзыреттілігін, пәнаралық ойлауын және практикалық мәселелерді шешу дағдыларын қалыптастыру үшін STEM білім

беруді биотехнологиямен интеграциялау маңызды. Алайда биотехнологиялық білім беруде эксперименттік зерттеулер мен жасанды интеллект технологияларына негізделген пәнаралық STEM модельдерін қолдану әлі де шектеулі. Бұл зерттеудің мақсаты - биология мұғалімдерін даярлау үдерісінде биотехнология, экология, химия, инженерия, математика және жасанды интеллектті біріктіретін пәнаралық STEM жобасын әзірлеу және бағалау. Зерттеуде зертханалық экспериментті, жобалық оқытуды, сауалнаманы, сұхбатты және статистикалық талдауды біріктіретін аралас әдістер тәсілі қолданылды. STEM жобасы *Phaseolus vulgaris* өсімдігінің өсуіне мыс, мырыш және кадмийдің әсерін зерттеуге негізделді. Жоба барысында студенттер деректерді өңдеу, визуализациялау және ғылыми интерпретациялау үшін ChatGPT, Claude AI, Python және OneCompiler сияқты жасанды интеллект және цифрлық құралдарды қолданды. Білім беру нәтижелері бойынша қатысушылардың 83,3%-ы экспериментті жоспарлау, деректерді жинау және деректерді талдау кезеңдерін меңгергенін хабарлады, ал 91,7%-ы жобаны аяқтағаннан кейін биотехнологияға қызығушылығының артқанын көрсетті. Қатысушылар сондай-ақ зерттеушілік құзыреттіліктің, пәнаралық түсініктің және экологиялық мәселелерді шешуде ғылыми әдістерді қолдануға деген сенімділіктің артқанын хабарлады. Зерттеудің ғылыми жаңалығы эксперименттік биотехнологияны, жобалық оқытуды және жасанды интеллектті біртұтас білім беру шеңберінде біріктіретін пәнаралық STEM моделін әзірлеу мен енгізуде жатыр. Ұсынылған модель зерттеуге бағытталған биотехнологиялық білім беруді дамытуға ықпал етеді және пәнаралық ғылыми мәселелерді шешуге қабілетті болашақ биология мұғалімдерін даярлаудың практикалық тәсілін ұсынады.

Түйін сөздер: STEM білімі, биотехнология, жобалық оқыту, пәнаралық оқыту, зерттеушілік құзыреттілік, жасанды интеллект

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ОЦЕНКА МЕЖДИСЦИПЛИНАРНОЙ ПРОЕКТНОЙ STEM-МОДЕЛИ В БИОТЕХНОЛОГИЧЕСКОМ ОБРАЗОВАНИИ

Аннотация. Интеграция STEM-образования с биотехнологией имеет важное значение для формирования исследовательской компетентности, междисциплинарного мышления и навыков практического решения проблем у будущих учителей биологии. Однако применение междисциплинарных STEM-моделей, основанных на экспериментальных исследованиях и технологиях искусственного интеллекта, в биотехнологическом образовании остается ограниченным. Целью настоящего исследования являлись разработка и оценка междисциплинарного STEM-проекта, интегрирующего биотехнологию, экологию, химию, инженерное дело, математику и искусственный интеллект в подготовке учителей биологии. В исследовании применялся смешанный методический подход, объединяющий лабораторный эксперимент, проектное обучение, анкетирование, интервью и статистический анализ. STEM-проект был основан на изучении влияния меди, цинка и кадмия на рост *Phaseolus vulgaris*. В ходе проекта студенты использовали инструменты искусственного интеллекта и цифровые инструменты, включая ChatGPT, Claude AI, Python и OneCompiler, для обработки данных, визуализации и научной интерпретации результатов. Образовательные результаты показали, что 83,3% участников сообщили об освоении этапов планирования эксперимента, сбора и анализа данных, тогда как 91,7% участников сообщили

о повышении интереса к биотехнологии после завершения проекта. Участники также сообщили о повышении исследовательской компетентности, междисциплинарного понимания и уверенности в применении научных методов для решения экологических проблем. Научная новизна исследования заключается в разработке и реализации междисциплинарной STEM-модели, интегрирующей экспериментальную биотехнологию, проектное обучение и искусственный интеллект в единую образовательную структуру. Предлагаемая модель способствует развитию исследовательски ориентированного биотехнологического образования и представляет практический подход к подготовке будущих учителей биологии, способных решать междисциплинарные научные задачи.

Ключевые слова: STEM-образование, биотехнология, проектное обучение, междисциплинарное обучение, исследовательская компетентность, искусственный интеллект

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