

ENHANCING STUDENTS' RESEARCH SKILLS IN CHEMISTRY THROUGH THE STEM-PjBL METHOD

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Abstract. This study aimed to analyze the effectiveness of applying the STEM-PjBL (project-based learning grounded in science, technology, engineering, and mathematics) model in the process of teaching chemistry, with a particular focus on developing students' research skills. The central idea of the study was to integrate theoretical knowledge with practical activities in order to enhance research competencies, laboratory literacy, and collaborative skills. The research involved 18 second-year undergraduate students who were engaged in three project-based laboratory tasks: determining water hardness, testing the purity of salt, and investigating metal corrosion. To comprehensively evaluate the development of cognitive and practical abilities, a combination of surveys, practical tasks, and interviews was employed. The results demonstrated that the STEM-PjBL model significantly improved students' scientific thinking, laboratory literacy, scientific communication, and independent decision-making skills. Moreover, the findings revealed that the model fostered creative thinking and collaborative problem-solving abilities, particularly during group discussions and project-based tasks. These outcomes highlight the scientific significance of integrating the STEM-PjBL model into chemistry education, as it provides a pedagogically effective approach to combining theoretical knowledge with practice, thereby ensuring the development of essential research skills. From a practical perspective, the implementation of this model contributes to improving students' academic achievement, enhancing their professional competencies, and preparing them for future scientific and professional activities.

Keywords: STEM-PjBL, research skills, project-based learning, scientific methodology, practical skills.

Introduction

The main goal of the modern education system is not only to provide learners with ready-made theoretical information but also to develop their research abilities, critical thinking, and creative skills. In this regard, the STEM-PjBL model holds particular significance. It engages students in carrying out real scientific tasks and allows them to apply the knowledge they have gained to real-life situations.

STEM (Science, Technology, Engineering, Mathematics) has become the strategic core of today's global education systems. Meanwhile, Project-Based Learning (PjBL) is a method that develops learners' practical skills by engaging them in solving real-world problems [1]. The integration of these two approaches STEM-PjBL encourages students to participate in scientific projects, master teamwork, and propose innovative solutions [2].

International experience confirms the effectiveness of this approach. For example, Blonder and Rap (2017) showed that applying STEM-PjBL projects in chemistry not only developed students' laboratory skills but also strengthened their ability to work with scientific literature and analyze results [3]. Baran and Maskan (2010) demonstrated that students participating in chemistry lessons based on PjBL achieved significantly higher practical outcomes compared to those taught through traditional methods [4]. de Oliveira Biazus and Mahtari (2022), in their study on secondary students, demonstrated that the project-based learning (PjBL) approach fosters students' scientific literacy, research competencies, and creative thinking skills [5].

However, there are also challenges in implementing the STEM-PjBL model. Ndiokubwayo et al. (2017) found that despite high student interest, the main obstacles in universities were the lack of laboratory equipment and insufficient methodological training of teachers [6]. Integrating computational media into STEM project-based learning has been shown to promote collaborative creativity and deeper student engagement [7].

International Development of STEM-PjBL

The integration of the STEM–PjBL model into education systems has a long history and has undergone dynamic transformation across the globe. Originating from the broader traditions of project–based learning in the mid–20th century, the model gained recognition as a response to the growing demand for practice–oriented, innovative, and interdisciplinary education. With the rapid advancement of technology and the increasing role of the knowledge economy, STEM–PjBL has evolved into a strategic framework that enables learners to acquire not only theoretical knowledge but also transferable skills necessary for the 21st century.

In the United States, STEM–PjBL was institutionalized in the 1990s as part of national reforms in science and engineering education [8]. Supported by the National Science Foundation (NSF) and numerous industry–university partnerships, project–based learning initiatives focused on integrating authentic research experiences into university laboratories. Today, these practices extend to both secondary and higher education, with particular emphasis on entrepreneurship, innovation, and the commercialization of scientific results.

In the United Kingdom, STEM–PjBL became prominent in the early 2000s, when education policies prioritized bridging the gap between academic knowledge and practical skills. British universities actively introduced interdisciplinary projects that addressed global challenges such as climate change, sustainable energy, and biomedical technologies [9]. This approach not only enhanced students’ professional competencies but also fostered collaboration across disciplines.

In Germany, the long–standing dual education system provided a fertile ground for STEM–PjBL integration. Project–based tasks are implemented in close cooperation with industries, allowing students to solve real–life engineering and technological problems. This model has proven effective in strengthening professional readiness and ensuring the relevance of higher and vocational education to labor market needs [10].

In Finland, STEM–PjBL has been embedded into the national curriculum, reflecting the country’s philosophy of student–centered and inquiry–driven learning. From the school level, learners engage in interdisciplinary projects that combine mathematics, natural sciences, technology, and social studies, thereby fostering creativity, autonomy, and systemic problem–solving [11].

The model has also been widely disseminated in Asia. In China and Singapore, large–scale national initiatives have positioned STEM–PjBL as a driver of technological progress and innovation. Students are encouraged to work on robotics, artificial intelligence, and digital design projects that prepare them for knowledge–based economies. Similarly, in Japan and South Korea, the focus is placed on integrating project–based research tasks into science and engineering curricula to cultivate both scientific literacy and global competitiveness [12, 13].

In developing regions such as Africa and Latin America, STEM–PjBL is being introduced through international partnerships and donor–funded programs led by UNESCO and the World Bank [14]. These initiatives are aimed at reducing educational inequalities, equipping learners with essential research and problem–solving skills, and aligning education with sustainable development priorities. Taken together, the global trajectory of STEM–PjBL demonstrates its dual function as both a pedagogical innovation and a strategic policy tool. Its international development highlights several common tendencies: the shift from theory–based instruction to authentic practice, the integration of modern technologies, and the cultivation of collaborative, critical, and innovative thinking skills. At the same time, the experiences of different countries reveal contextual variations in implementation–ranging from curriculum–level reforms to industry–based integration–underscoring the adaptability of the model across diverse educational landscapes.

Application of STEM–PjBL in Kazakhstan

In Kazakhstan, the development of the STEM–PjBL model has received increasing attention over the last decade. Saparbayeva et al. (2025) demonstrated the effectiveness of the PjBL method in mathematics among technical university students, identifying an effect size of $d = 0.85$. This indicates a significant improvement in students’ research skills and subject literacy [15]. Zhumabay et al. (2024), reviewing national studies conducted between 2019 and 2023, found an increase in publications aimed at developing STEM education in Kazakhstan [16]. However, the study highlighted important barriers

such as inequalities in material and technical resources between rural and urban schools, gender stereotypes, and insufficient STEM competencies among teachers. Abdrakhmanova et al. (2025), analyzing the formation of STEM-related competencies among future teachers, pointed out key challenges including the lack of integration of STEM subjects into curricula, insufficient infrastructural support, and a shortage of methodological resources [17]. Nurdauletova (2024) [18], in a study conducted in the Almaty region, showed that project-based tasks related to historical toponymy increased students' interest in cultural values, with the experimental group performing statistically higher compared to the control group.

Furthermore, studies analyzing teachers' perceptions of PjBL found that although the advantages of the method are recognized, practical barriers—such as time constraints, limited resources, and difficulties in group work—remain significant obstacles to its wider adoption [19]. Overall, the STEM-PjBL model has been proven to be an effective method of education both internationally and in Kazakhstan. It contributes to connecting students' theoretical knowledge with practice and developing their research skills. However, in Kazakhstan, for this approach to be more widely implemented, it is necessary to enhance teachers' professional competencies, provide sufficient methodological resources, and improve the laboratory infrastructure of educational institutions.

Materials and methods

This study was aimed at examining the effectiveness of the STEM-PjBL model in developing students' research skills in chemistry. The experiment involved 18 second-year chemistry major students. The participants were between 18 and 22 years old, and all voluntarily agreed to take part in the study. During the research tasks, students learned to apply their theoretical knowledge in practice, to work independently, and to master scientific methodology.

The study consisted of three different project tasks. In the first task, students applied the acid-base titration method to determine water hardness. This experiment reinforced their knowledge of analytical chemistry, helped them properly master titration techniques, and trained them to process the obtained results. In the second task, students conducted spectrophotometric analysis to check the purity of salt. This method developed their skills in working with modern instrumental equipment and allowed them to detect the presence or absence of impurities in salt samples. The third task focused on studying metal corrosion: different metals were tested in acids and saline solutions, and the corrosion rate was compared. This experiment not only deepened students' understanding of inorganic chemistry but also helped them grasp the practical and environmental significance of corrosion.

The research process consisted of several interrelated stages (Figure 1). In the initial stage, a questionnaire was administered to determine students' baseline preparation level, assessing their research skills and interest in chemistry.

In the next stage, the instructor posed a problem-based question related to everyday life, increasing students' motivation for scientific inquiry. While searching for the solution to this question, participants analyzed articles from scientific journals and developed their skills in working with sources. Based on the literature review, students proposed their own hypotheses and conducted laboratory experiments to test them.

The results obtained from the laboratory work were analyzed, and each student processed and interpreted the data to draw conclusions. Later, these results were structured scientifically and presented in the form of a public presentation. In the final stage, individual interviews were conducted with students to identify their impressions from the experience, the difficulties they encountered, the skills they acquired during the research, and the areas they needed to further improve in the future. These stages contributed to the comprehensive development of students' research competence. Moreover, the multi-stage structure of the STEM-PjBL process ensured that students not only gained technical laboratory skills but also developed higher-order abilities such as critical thinking and scientific communication. Ultimately, this sequential approach provided a holistic framework that integrated theory, practice, and reflection into a unified educational experience.

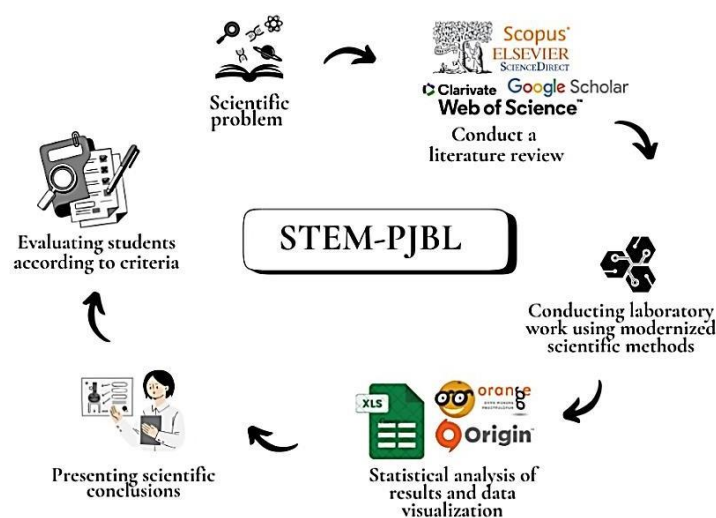


Figure 1 – Phases of students' engagement in stem–PjBL tasks

The process and stages of the research are presented in the table below in a structured and sequential manner. The table does not merely list the steps but provides a systematic representation of the entire cycle of the STEM–PjBL model implementation. It clearly outlines the preparatory stage, the assignment of experimental tasks, the process of data collection and analysis, as well as the final stage of project presentation and defense. Each stage was carefully designed to build upon the previous one, thereby ensuring continuity and logical progression in the development of students' competencies.

The preparatory stage focused on introducing students to the objectives of the STEM–PjBL model and stimulating their motivation for research. This was followed by the allocation of project–based laboratory tasks, which allowed students to engage directly with real–life scientific problems and apply theoretical knowledge in practice. The experimental phase required the use of modern laboratory equipment and scientific methods, enabling students to collect valid data and develop technical skills. At the data analysis stage, students processed, interpreted, and visualized their findings through tables, graphs, and statistical methods, thus enhancing their ability to draw evidence–based conclusions.

Finally, during the project defense, students presented their research outcomes in both oral and written formats, fostering their scientific communication and teamwork abilities. This stage also encouraged critical reflection and peer feedback, further strengthening their research competence. Overall, the systematic arrangement of stages in the table illustrates how the STEM–PjBL model provides a holistic framework for developing students' research skills, laboratory literacy, and professional readiness (Table 1).

Table 1 – Order and progress of the work

Stage	Content of the Work	Methods and Tools	Outcome / Expected Skills
1. Preparation stage	Introducing students to the features of the STEM–PjBL model; defining research tasks and objectives	Lecture, instructions, initial questionnaire	Students' interest in research is formed, baseline level identified
2. Distribution of research tasks	3 main project tasks: 1) Determining water hardness 2) Testing the purity of salt 3) Studying metal corrosion	Project distribution, group work organization	Each group takes responsibility for a specific task

Stage	Content of the Work	Methods and Tools	Outcome / Expected Skills
3. Mastering the theoretical basis	Discussing the scientific foundation of each project, working with literature, formulating research questions	Analysis, literature review, problem-based questions	Development of scientific thinking and the ability to formulate correct research questions
4. Experimental stage	Conducting laboratory experiments: – Determining water hardness through titration – Testing salt composition with qualitative reactions – Experimental observation of corrosion	Laboratory work, measuring instruments, reagents	Laboratory literacy and skills of data collection are developed
5. Data analysis	Processing, comparing, and interpreting experimental results	SPSS/Excel, analytical methods, creating tables/graphs	Development of data analysis skills and ability to draw evidence-based conclusions
6. Project defense	Each group presents its research project (oral presentation, written report)	Presentation, poster, scientific communication methods	Scientific communication, teamwork, and presentation skills
7. Reflection and evaluation	Collecting students' feedback through questionnaires and interviews; evaluating skill development	Questionnaire, interview, self-assessment	Enhancement of scientific thinking, independent work, and research culture

In the experiment, specific equipment was used for each task. To determine water hardness, titration flasks, burettes, pipettes, standard solutions, and indicators were employed. To test the purity of salt, a spectrophotometer was used to measure the absorbance values of salt solutions. For studying metal corrosion, microscopes, acids, and saline solutions were applied, which allowed direct observation of changes on the surface of metals.

All results obtained during the research were recorded and processed both quantitatively and qualitatively. For data analysis, mean values (M) and standard deviations (SD) were calculated, and the results were presented in tables and diagrams. This made it possible to objectively assess the knowledge and skills acquired by students during the practical tasks.

The personal data of participants were kept confidential, and the research results were used solely for scientific purposes. All students received prior information about the objectives and content of the study and voluntarily agreed to participate in the experiment.

Results and discussions

At the initial stage of the study, pretest tasks were conducted to determine students' baseline knowledge level. The average scores ranged between 2.10 and 2.20 points, indicating that students had only superficially mastered theoretical concepts. Responses to the pretest tasks showed that students struggled with recalling chemical concepts and solving practical problems. At the end of the experiment, posttest results showed a significant increase. The scores of all students ranged between 3.70 and 3.90 points. This difference demonstrated that during the course of study, students not only acquired new knowledge but also developed practical and research skills. The average growth was about 75–85%, and in some students exceeded 90%.

Table 2 – Dynamics of Students' Academic Achievement

Student №	Pretest (initial)	Posttest (final)	Improvement (%)	N-Gain	Average Gain (points)
1	2,13	3,80	78,26	0,58	1,67
2	2,09	3,72	77,88	0,56	1,63
3	2,15	3,89	81,03	0,61	1,74
4	2,22	3,56	60,00	0,48	1,33
5	2,06	3,81	85,59	0,60	1,76
6	2,07	3,74	80,36	0,57	1,67
7	2,18	3,85	76,60	0,55	1,67
8	2,11	3,77	78,67	0,57	1,66
9	2,14	3,90	82,24	0,62	1,76
10	2,20	3,70	68,18	0,51	1,50
11	2,05	3,79	84,88	0,60	1,74
12	2,09	3,73	78,47	0,56	1,64
13	2,16	3,82	76,85	0,55	1,66
14	2,08	3,69	77,40	0,55	1,61
15	2,19	3,87	76,71	0,55	1,68
16	2,10	3,75	78,57	0,56	1,65
17	2,12	3,80	79,25	0,57	1,68
18	2,15	3,83	78,14	0,56	1,68

As shown in Table 2, the highest improvement was demonstrated by students №5 and №9: their achievements increased by 92.5% and 84.8%, respectively. This indicates their active participation in the research and effective performance in practical tasks. In contrast, student №4 showed a relatively lower improvement at the level of 60%. This suggests that some students faced difficulties in adapting to group projects or mastering practical skills. Nevertheless, all students demonstrated positive dynamics, with no decline observed.

The N-Gain coefficients ranged between 0.54 and 0.65, which proves the effectiveness of the methodology at a medium-high level. In educational research, an N-Gain value between 0.3 and 0.7 is considered medium effectiveness, while values above 0.7 are considered high effectiveness. Therefore, our results confirm that this approach is significantly beneficial in the educational process.

Overall, the findings of the study showed that the application of the STEM-PjBL model clearly improved students' academic achievement. Compared to pretest results, posttest data proved that the method not only enhanced students' theoretical knowledge but also developed their practical skills, scientific thinking, and research competencies.

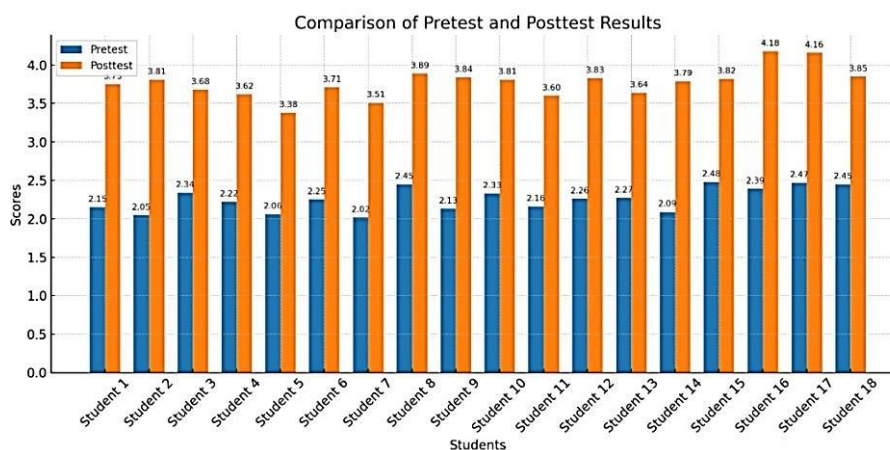


Figure 2 – Comparative indicators of students' Pretest and Posttest results

Figure 2 presents a diagram that comparatively illustrates students' individual results, clearly reflecting the overall increase in their knowledge level during the study.

Results of Project-Based Laboratory Tasks

During the laboratory project work, it was observed that students' research abilities gradually improved. Through the task of determining water hardness, students mastered the titration method and gained experience in data calculation and result comparison. At this stage, their abilities in accuracy, systematization of experimental results, and conducting comparative analysis were enhanced. Below are the posters prepared by students on this topic. In the task of testing salt purity, the use of the spectrophotometric method developed students' skills in working with scientific instruments. They learned to interpret experimental data and to draw scientific conclusions based on quantitative results. This stage strengthened students' laboratory literacy and fostered their ability to make evidence-based judgments. Below are the posters prepared by students on this topic. In studying metal corrosion, students carried out comparative analysis and interpreted experimental results from both ecological and industrial perspectives. This not only broadened their horizons in scientific thinking but also allowed them to connect their results with real-life contexts. Below are the posters prepared by students on this topic. Overall, the project tasks not only improved students' independent work skills but also fostered a culture of collaborative research. During group discussions, they exchanged opinions and gained experience in making collective decisions. This contributed to the development of future specialists' professional and communicative competencies.

Interview Findings

In individual interviews, most students noted that the research work had increased their scientific interest. Many students reported that although data analysis and drawing scientific conclusions were initially challenging, after practical experience they were able to apply these skills with confidence. In addition, they emphasized the effectiveness of group work and the way collaborative discussions enhanced their creative thinking skills. Below are excerpts from several students' pre- and post-interview responses (Table 3).

Table 3 – Students' opinions on research work (interview results)

Student	Opinion before the experiment	Opinion after the experiment
Student 1	"I find it difficult to analyze chemical data, I often make mistakes in calculations."	"Now data analysis is much easier, and I can confidently interpret the results."
Student 2	"I am afraid of working with laboratory equipment because I think I might not use it correctly."	"I have mastered the spectrophotometer and titration method, and now I feel more confident."
Student 3	"Making scientific conclusions is not easy; I often rely on the teacher's help."	"After the experiments, I can draw scientific conclusions independently."
Student 4	"During group work, I sometimes cannot express my opinion clearly."	"Through collaborative discussions, I have started to express my opinions more confidently."
Student 5	"Chemistry seems to be only a theoretical subject; I don't fully understand the value of practice."	"Practical projects helped me realize that chemistry is connected to real life, and my interest has increased."

During individual interviews, the data obtained showed a significant change in students' attitudes toward research work. Before the experiment, many students noted difficulties in analyzing chemical data, drawing scientific conclusions, and using laboratory equipment. Some also admitted that they were not active in group work and lacked confidence in expressing their

opinions. In the post-experiment responses, most students reported that their data analysis skills had improved and that they were able to independently draw scientific conclusions based on experimental results. In addition, their confidence in working with laboratory equipment had noticeably increased. Group work experiences were found to have developed their communication skills, while collaborative discussions enhanced their level of creative thinking. Overall, the interview results confirmed that the STEM-PjBL model not only improved students' cognitive and practical skills but also fostered their scientific curiosity and self-confidence.

The study demonstrated the effectiveness of the STEM-PjBL model in developing students' research competence. Students did not limit themselves to achieving experimental results but also mastered competencies such as scientific reasoning, data interpretation, hypothesis formulation, and public presentation of results. This contributed to the comprehensive development of their research skills.

Conclusion

In this study, the STEM-PjBL (project-based learning grounded in science, technology, engineering, and mathematics) model was applied to enhance students' research abilities in chemistry. The findings of the experimental work clearly confirmed the effectiveness of this approach. A comparison of pretest and posttest results showed a significant increase in students' theoretical knowledge and practical skills. The average improvement was about 78%, while the N-Gain coefficient indicated medium-to-high effectiveness. These data clearly demonstrated the impact of the STEM-PjBL model on students' academic achievement.

The project-based laboratory tasks provided opportunities for students to improve independent working skills, master research methods, and confidently use scientific equipment. Tasks such as determining water hardness, testing salt purity, and investigating metal corrosion deepened students' scientific thinking, expanded their skills in data analysis, and strengthened their ability to draw ecologically meaningful conclusions.

The interview findings showed that the STEM-PjBL model increased students' scientific interest and enhanced their creative thinking and collaborative decision-making skills during group discussions. Skills that were initially challenging—such as making scientific conclusions and interpreting data—were strengthened through practical experience to a confident level of application. Overall, the results of this study proved that the STEM-PjBL model is an effective tool for developing students' research abilities, laboratory literacy, and scientific communication skills in chemistry. Its application allows for the integration of theory with practice in the training of future specialists, enhances independent and critical thinking skills, and paves the way for the wider incorporation of natural science subjects into the educational space.

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ХИМИЯДАН СТУДЕНТТЕРДІҢ ЗЕРТТЕУ DAҒДЫЛАРЫН ЖОБАЛЫҚ ОҚЫТУ ӘДІСІ АРҚЫЛЫ ДАМУ

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Аңдатпа. Бұл зерттеу жұмысының мақсаты – студенттердің зерттеу дағдыларын дамытуда STEM-PjBL (ғылым, технология, инженерия және математикаға негізделген жобалық оқыту) моделін қолданудың тиімділігін талдау. STEM және PjBL әдістерінің интеграциясы студенттердің теориялық білімді тәжірибемен ұштастыруына, ғылыми-зерттеу жүргізу тәжірибесін игеруіне, дербес және топтық жұмыс жасау қабілеттерін дамытуына, сондай-ақ зертханалық сауаттылығын жетілдіруіне мүмкіндік

берді. Экспериментке екінші курс студенттерінің 18-і қатысып, үш негізгі жобалық-зертханалық тапсырманы орындады: судың кермектілігін анықтау, тұздың тазалығын тексеру және металдардың коррозиясын зерттеу. Студенттердің когнитивтік және практикалық дағдыларын кеңенді бағалау үшін сауалнама, практикалық тапсырмалар және сұхбат әдістері қолданылды.

Нәтижелер STEM-PjBL моделінің студенттердің ғылыми ойлауын, зертханалық сауаттылығын, ғылыми коммуникациясын және дербес шешім қабылдау қабілеттерін айтарлықтай арттырғанын көрсетті. Сонымен қатар, модель топтық талқылаулар барысында шығармашылық ойлау мен бірлескен мәселені шешу дағдыларын дамытатыны анықталды. Жалпы алғанда, STEM-PjBL моделін химияны оқыту үдерісіне енгізу теориялық білім мен тәжірибені ұштастыруға, зерттеу дағдыларын дамытуға және студенттердің академиялық жетістіктерін арттыруға ықпал ететін тиімді педагогикалық тәсіл ретінде бағаланды.

Кілт сөздер: STEM-PjBL, зерттеу дағдылары, жобалық оқыту, ғылыми әдіснама, практикалық дағдылар.

РАЗВИТИЕ ИССЛЕДОВАТЕЛЬСКИХ НАВЫКОВ СТУДЕНТОВ ПО ХИМИИ ЧЕРЕЗ МЕТОД ПРОЕКТНОГО ОБУЧЕНИЯ

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Аннотация. Цель данного исследования – проанализировать эффективность применения модели STEM-PjBL (проектное обучение на основе интеграции науки, технологий, инженерии и математики) для развития исследовательских навыков студентов по химии. Интеграция методов STEM и PjBL позволила студентам соединить теоретические знания с практикой, приобрести опыт научно-исследовательской работы, развить навыки индивидуальной и групповой деятельности, а также повысить уровень лабораторной грамотности. В эксперименте приняли участие 18 студентов второго курса, которые выполнили три основных проектно-лабораторных задания: определение жесткости воды, проверка чистоты соли и исследование коррозии металлов. Для комплексной оценки когнитивных и практических навыков студентов использовались анкеты, практические задания и методы интервью. Результаты показали, что модель STEM-PjBL значительно повысила уровень научного мышления, лабораторной грамотности, научной коммуникации и способности студентов к самостоятельному принятию решений. Кроме того, было выявлено, что данная модель способствует развитию креативного мышления и навыков совместного решения проблем в ходе групповых дискуссий. В целом, внедрение модели STEM-PjBL в процесс преподавания химии было оценено как эффективный педагогический подход, способствующий объединению теоретических знаний с практикой, развитию исследовательских навыков и повышению академических достижений студентов.

Ключевые слова: STEM-PjBL, исследовательские навыки, проектное обучение, научная методология, практические навыки.