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STUDY OF THE IMPACT OF INTEGRATING STEM TECHNOLOGY INTO CHEMISTRY TEACHING ON STUDENTS' XXI CENTURY SKILLS

*Toktamys N.B.[1], Shagrayeva B.B.[2], Shertayeva N.T.[3], Bitemirova A.E.[4]
*[1,2,3,4]South Kazakhstan Pedagogical University named after Uzbekali Zhanibekov, Shymkent, Kazakhstan

Abstract. The STEM approach utilizes an integrated, interdisciplinary method to examine scientific and technical concepts within real-world contexts. The student gains the ability to solve several problems and design prototypes for new mechanisms, procedures, and programs within the scope of the installations of this method. This article presents a study investigating the effectiveness of incorporating the STEM approach into 10th-grade chemistry lessons as part of the updated curriculum, specifically examining its impact on student's development of essential 21st-century skills. The study utilised the Cambridge Assessment framework to evaluate student progress in several key areas. This framework provides a robust measure of skills crucial for success in the modern world, including critical thinking, problem-solving, collaboration, communication, and creativity. The research aimed to determine whether applying STEM principles in chemistry education could demonstrably enhance student proficiency in these areas. The findings demonstrated that integrating STEM technology into chemistry classes positively impacted participants' 21st-century skills, such as research, critical thinking, teamwork, and academic performance. Simultaneously, it has been proven that applying STEM teaching increases students' motivation to study science and conduct research in extracurricular activities. Implementing the method will facilitate the establishment of strong connections between schools, society, and the global community, which will enhance STEM literacy and competitiveness in the world economy.

Key words: STEM education, 21st-century skills, problem-solving, critical thinking, integrated lessons, creativity, collaboration, communication, motivation, research skills

Introduction

STEM (Science, Technology, Engineering, and Mathematics) education has gained increasing global attention due to its pivotal role in equipping learners with the competencies required for success in the 21st century. Through the interdisciplinary integration of scientific inquiry, technological innovation, engineering design, and mathematical reasoning, STEM education fosters critical thinking, creativity, and problem-solving skills that are indispensable in today's complex and rapidly changing world. Indeed, according to research by the Bureau of Labor Statistics, growth in STEM occupations is expected to reach 8% by 2029, while global job growth is expected to reach 3.9% [1]. This growth reflects the mounting demand for a workforce capable of understanding and applying scientific and technological principles across diverse contexts [2]. Consequently, STEM education is essential in preparing students for enduring changes in the world by equipping them with the necessary skills to comprehend technological advancements in the 21st century.

STEM education is broadly defined as an interdisciplinary approach that applies knowledge from multiple domains to address real-world challenges. Mobley (2015) describes it as "an educational approach in which interdisciplinary applications are made to solve problems in real life and links to different disciplines are created" [3]. Contemporary research emphasizes that authentic STEM learning experiences are most effective when designed through interdisciplinary and transdisciplinary integration [4]. Such approaches allow students to transfer concepts between domains – such as combining chemistry, physics, and engineering to design a water purification system – thereby deepening conceptual understanding and reinforcing the interconnected nature of scientific inquiry [5].

The incorporation of technology has further expanded the potential of STEM pedagogy. Digital tools, such as virtual laboratories, interactive simulations, and collaborative online environments, enhance engagement and support active, inquiry-driven learning [6-8]. Recent studies have also explored specific applications of STEM technologies in high school chemistry education, demonstrating their capacity to enhance student motivation and performance [9].

Despite this growing body of research, literature still reveals a gap in understanding how STEM-based pedagogies specifically foster 21st-century skills in subject-specific contexts such as chemistry. Much of the existing research remains conceptual or exploratory, with limited empirical evidence on targeted classroom practices that develop such skills. Moreover, while numerous frameworks exist for categorizing 21st-century skills [10-12], there is a lack of consensus on which competencies are most essential for modern learners and how they can be systematically cultivated within STEM disciplines.

In response to these gaps, this study focuses on the development of five core 21st-century skills – problem-solving, critical thinking, creativity and collaboration, teamwork, and research skills – within the context of high school chemistry instruction. These competencies were selected based on their recurring identification in recent educational literature as fundamental to learners' success in both academic and professional environments [10-12].

At the same time, it is important to acknowledge that implementing authentic STEM approaches poses notable challenges. Teachers often face constraints such as limited time, insufficient training, lack of interdisciplinary collaboration, and inadequate access to technological resources. Furthermore, aligning STEM integration with national curricula and assessment systems remains a persistent issue. Recognizing these challenges is critical for ensuring that pedagogical innovations are both practical and sustainable.

Therefore, this paper investigates how STEM-based teaching strategies can effectively nurture 21st-century skills among high school students studying chemistry. It explores instructional techniques – such as STEM-integrated lesson design, interdisciplinary projects, and research-based learning activities – and evaluates their impact through classroom-based assessments. Ultimately, this study aims to contribute to the growing discourse on how STEM education can move beyond theoretical advocacy to achieve measurable outcomes in skill development for modern learners.

Materials and methods

Sample and Participant Selection: A total of 60 students participated in this study, divided into two focus groups of 30 each (Figure 1). The participants were of similar age (16-17 years old) and shared comparable academic performance levels based on previous term grades in chemistry. Both groups studied within identical school settings, under the same curriculum and timetable conditions, to ensure equivalency of learning environments. All students participated voluntarily, and informed consent was obtained from both participants and their parents. Pseudonyms were assigned to maintain confidentiality in all published data.

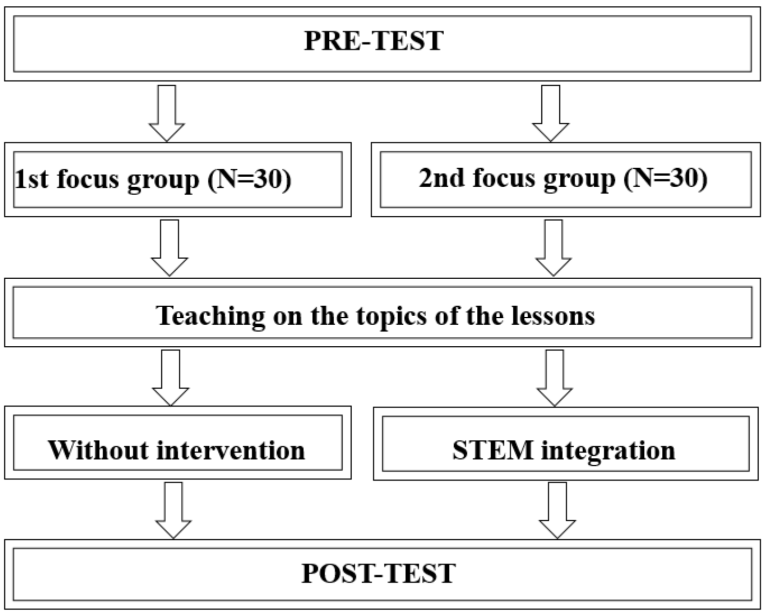

Figure 1 - A quasi-experiment scheme illustrating participant grouping and study design

The research sought to examine how the integration of STEM technologies in the chemistry classroom contributes to the development of twenty-first-century skills such as problem-solving, critical thinking, creativity, collaboration, and research ability.

This quasi-experimental study was conducted at the Nazarbayev Intellectual School of Chemistry and Biology in Turkestan, Kazakhstan, between September

2023 and February 2024. Two instructional approaches were compared:

- Focus Group 1 (Control): Received traditional chemistry instruction based on teacher-led explanations, textbook-based exercises, and standard laboratory demonstrations.
- Focus Group 2 (Experimental): Followed a blended STEM-based model integrating theoretical chemistry lessons with hands-on, interdisciplinary projects and technology-enhanced activities.

Weekly sessions incorporated inquiry-based experiments, digital simulations, and problem-solving workshops aligned with real-world scientific and environmental challenges. Data collection methods included surveys, classroom observations, analysis of students' academic performance, Cambridge Skill Assessment (CSA) results, and evaluation of project-based learning outcomes.

Assessment Frameworks and Instruments

1. Cambridge Skill Assessment (CSA)

The Cambridge Assessment Framework was employed to evaluate three core twenty-first-century skills: critical thinking, collaboration, and creativity [13]. The CSA consisted of multiple-choice items (one point per correct response) and open-ended analytical tasks. The assessment was administered both before and after the intervention to identify skill progression.

2. Project-Based Learning Evaluation

Students in the experimental group engaged in interdisciplinary projects such as:

- Designing eco-friendly chemical synthesis processes,
- Developing prototypes for energy-efficient systems, and
- Investigating heat transfer mechanisms using small-scale calorimeters and convection models.

Project activities adapted resources from Flinn Scientific (Solar Oven STEM Challenge, Small-Scale Calorimeters, Heat Convection of a Gas).

Each project was evaluated using an analytic rubric developed by the research team based on recent STEM education frameworks. The rubric consisted of five domains corresponding to twenty-first-century skills:

Table 1. Analytic rubric

DOMAIN	INDICATORS (EXAMPLES)	EVALUATION SCALE
CRITICAL THINKING	Application of chemical principles, logical reasoning, and problem analysis	1-4 Likert (Low-High)
CREATIVITY	Originality and practicality of design ideas	1-4
COLLABORATION	Quality of teamwork and shared decision-making	1-4
RESEARCH SKILLS	Use of data, evidence, and experimental accuracy	1-4
COMMUNICATION	Clarity of presentation and reflection	1-4

Two independent raters (experienced chemistry teachers) scored the projects. Inter-rater reliability was established (Cohen's $\kappa = 0.86$), ensuring consistency in scoring.

3. Surveys and Questionnaires

Questionnaires were developed to collect students' perceptions regarding the integration of STEM technologies in chemistry. The survey included 20 items: 15 closed-ended statements rated on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree) and 5 open-ended questions exploring students' reflections.

The instrument underwent expert validation by three educators with expertise in STEM pedagogy and psychometrics. A pilot test with 12 non-participating students was conducted to refine item clarity. Cronbach's alpha for internal consistency was $\alpha = 0.89$, indicating strong reliability.

Quantitative survey data were analyzed using SPSS 26.0, applying descriptive statistics (mean, standard deviation) and independent-sample t-tests to detect group differences. Open-ended responses were analyzed thematically using inductive coding to identify patterns related to motivation, perceived benefits, and challenges of STEM-based learning.

Results and discussion

Data Triangulation and Analysis

To strengthen validity, data triangulation was applied by cross-referencing findings from three data sources:

1. Cambridge Skill Assessment results,
2. Project rubric scores, and
3. Survey responses and interviews.

This triangulation enabled a comprehensive understanding of how STEM instruction affected both measurable academic outcomes and subjective learner experiences.

The outcomes of Cambridge (GCSE) assessments were compared between the two focus groups for the same academic term to determine the effect of STEM technology on academic achievement (Table 2).

Table 2. Comparative summary of academic and subject-specific qualifications for the two focus groups

1st focus group (STEM-integrated)	GCSE %	Mark	2nd focus group (Traditional)	GCSE %	Mark
Student 1	87	A	Student 1	69	C
Student 2	86	A	Student 2	60	C
Student 3	77	B	Student 3	66	C
Student 4	86	A	Student 4	79	B
Student 5	52	D	Student 5	71	B
Student 6	85	A	Student 6	60	C
Student 7	84	A	Student 7	86	A
Student 8	90	A*	Student 8	66	C

Student 9	91	A*	Student 9	49	E
Student 10	71	B	Student 10	70	B
Student 11	80	A	Student 11	62	C
Student 12	75	B	Student 12	83	A
Student 13	73	B	Student 13	45	E
Student 14	71	B	Student 14	85	A
Student 15	70	B	Student 15	64	C
Mean ± SD	**78.1 ± 10.8**			**64.2 ± 11.9**	

Initial Knowledge Assessment: Baseline assessments indicated comparable starting points between the two groups, with mean scores of 65% for Group A (STEM-integrated) and 63% for Group B (traditional). This parity ensured that subsequent differences could be attributed primarily to the intervention.

Post-Experiment Outcomes: The comparative data summarized in Table 2 show that the STEM-integrated group achieved a higher mean GCSE score (78.1 ± 10.8) than the traditional group (64.2 ± 11.9). The 14-point difference was statistically significant ($p < 0.01$), confirming the positive impact of STEM integration on academic achievement.

Development of 21st-Century Skills: Beyond cognitive outcomes, Group A demonstrated stronger development in research, communication, and collaboration skills. Evidence of this growth included student participation and recognition in extracurricular activities such as:

✓ "Fire Rescue Robot" – first place in a regional hackathon for innovation in automation.

✓ "Naq VR Syganak" – recognized for educational virtual reality development.

✓ Achievements in national science Olympiads and local research competitions.

These outcomes suggest that sustained engagement in STEM-integrated learning environments can extend academic benefits into applied, real-world contexts.

Critical Considerations: Despite the positive results, several challenges were encountered. Implementing STEM-based instruction required substantial teacher preparation time, access to digital and laboratory resources, and ongoing professional development. Some students initially expressed difficulty adapting to the collaborative and inquiry-based learning format, preferring traditional lecture-based instruction. Addressing these barriers will be essential for large-scale adoption. Moreover, the study's relatively short duration and limited sample size constrain the generalizability of findings.

Implications: The results support the growing body of literature advocating for STEM integration as a means of enhancing chemistry education and fostering transferable 21st-century skills. When balanced with adequate teacher support and institutional resources, this approach has the potential to improve both subject mastery and learner autonomy. Future research could investigate longitudinal impacts and cross-subject scalability to determine the sustainability of these gains.

Conclusion

This study examined the impact of integrating STEM technology into secondary-level chemistry instruction through questionnaires and Cambridge assessment (GCSE) results. The findings demonstrated that students in the STEM-integrated group achieved, on average, a 14% higher performance than their peers in traditional settings. Questionnaire responses indicated that mini-projects and interdisciplinary activities fostered stronger engagement and deeper conceptual understanding. However, a small subset of students showed limited enthusiasm toward research-oriented tasks, suggesting the potential benefit of incorporating creative or artistic elements from the STEAM model to support diverse learner profiles.

Overall, the integration of STEM approaches contributed to improved problem-solving, collaboration, and critical thinking – skills essential for success in the 21st century. The results align with global educational trends emphasizing active, inquiry-based learning. Nevertheless, the study's conclusions should be interpreted within its contextual limitations, including a relatively short intervention period, a single-school setting, and the dependence on available technological resources.

Based on the evidence, the following recommendations are proposed:

1. Gradual and context-sensitive integration: Schools should implement STEM technologies progressively, adapting activities to existing resources and teacher expertise.

2. Professional development: Teachers require sustained training and collaboration opportunities to design effective interdisciplinary lessons and manage project-based learning.

3. Student engagement monitoring: Educators should track correlations between students' extracurricular involvement, academic performance, and social participation to identify those needing additional motivation or alternative learning formats.

Future research could focus on longitudinal studies assessing the durability of STEM-related skills, exploring cross-subject applications, and developing strategies to engage students who are less inclined toward research-based or technical activities.

Funding information

By acknowledging both its strengths and limitations, this study contributes to the growing body of evidence that well-planned STEM integration can enhance chemistry education and better prepare students for future academic and professional challenges.

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ХИМИЯ ПӘНІНЕ STEM ТЕХНОЛОГИЯСЫН КІРІКТІРІП ОҚЫТУДЫҢ ОҚУШЫЛАРДЫҢ XXI ҒАСЫР ДАҒДЫЛАРЫНА ӘСЕРІН ЗЕРТТЕУ

*Тоқтамыс Н.Б.[1], Шаграева Б.Б.[2], Шертаева Н.Т.[3], Битемирова А.Е.[4]
*[1,2,3,4] Өзбекәлі Жәнібеков атындағы Оңтүстік Қазақстан педагогикалық университеті, Шымкент, Қазақстан

Аңдатпа. STEM әдісі ғылыми және техникалық тұжырымдамаларды нақты өмірлік жағдайларда қарастыру үшін кешенді, пәнаралық тәсілді қолданады. Оқушылар осы әдісті қолдану арқылы әртүрлі мәселелерді шешу және жаңа механизмдер, процестер мен бағдарламалардың прототиптерін жасау қабілетін меңгереді. Бұл мақалада жаңартылған оқу бағдарламасы аясында STEM әдісін 10-сыныптағы химия сабақтарына енгізудің тиімділігін зерттеу ұсынылады. Атап айтқанда, оның оқушылардың XXI ғасырдың маңызды дағдыларын дамытуға әсері қарастырылады. Зерттеу барысында оқушылардың негізгі дағдылар бойынша жетістіктерін бағалау үшін Cambridge Assessment құрылымы пайдаланылды. Бұл құрылым қазіргі әлемде табысты болу үшін қажетті дағдыларды, соның ішінде сыни ойлау, мәселелерді шешу, ынтымақтастық, коммуникация және креативтілікті сенімді түрде өлшеуге мүмкіндік береді. Зерттеудің мақсаты – химия пәнін оқытуда STEM қағидаттарын қолдану оқушылардың осы дағдыларын айтарлықтай жақсарта алатынын анықтау болды. Алынған нәтижелер STEM технологияларын химия сабақтарына интеграциялау оқушылардың зерттеушілік қабілеттері, сыни ойлауы, топтық жұмыс дағдылары және академиялық үлгерімі сияқты XXI ғасыр дағдыларына оң әсер ететінін көрсетті. Сонымен қатар, STEM әдістерін қолдану оқушылардың ғылымды оқуға деген ынтасын арттырып, сабақтан тыс ғылыми-зерттеу жұмыстарын жүргізуге қызығушылығын жоғарылататыны дәлелденді. Бұл әдісті енгізу мектептер, қоғам және жаһандық қауымдастық арасындағы байланысты нығайтуға ықпал етеді, нәтижесінде STEM сауаттылығы артып, әлемдік экономикадағы бәсекеге қабілеттілік күшейеді.

Тірек сөздер: STEM білім, 21 ғасыр дағдылары, проблемаларды шешу, сыни тұрғыдан ойлау, кіріктірілген сабақтар, шығармашылық, ынтымақтастық, коммуникация, мотивация, зерттеу дағдылары

ИЗУЧЕНИЕ ВЛИЯНИЯ ИНТЕГРАЦИИ STEM-ТЕХНОЛОГИЙ В ПРЕПОДАВАНИЕ ХИМИИ НА НАВЫКИ УЧЕНИКОВ XXI ВЕКА

*Тоқтамыс Н.Б.[1], Шаграева Б.Б.[2], Шертаева Н.Т.[3], Битемирова А.Е.[4]
*[1,2,3,4] Южно-Казахстанский педагогический университет
имени Өзбекәлі Жәнібеков, Шымкент, Казахстан

Аннотация. Подход STEM использует интегрированный, междисциплинарный метод для изучения научных и технических концепций в реальных условиях. Учащиеся приобретают навыки решения различных проблем и проектирования прототипов новых механизмов, процессов и программ в рамках применения этого метода. В данной статье представлено исследование, посвященное оценке эффективности внедрения STEM-подхода в преподавание химии в 10-х классах в рамках обновленной учебной программы. В частности, изучалось влияние этого подхода на развитие у учеников ключевых навыков XXI века. В ходе исследования использовалась структура оценивания Cambridge Assessment для анализа прогресса учащихся в нескольких ключевых областях. Данная система предлагает надежные критерии оценки навыков, необходимых для успешной адаптации в современном мире, включая критическое мышление, решение проблем, сотрудничество, коммуникацию и креативность. Цель исследования заключалась в том, чтобы определить, способствует ли применение STEM-принципов в обучении химии заметному повышению уровня подготовки учащихся в этих областях. Полученные результаты показали, что интеграция STEM-технологий в преподавание химии положительно влияет на развитие у школьников навыков XXI века, таких как исследовательские способности, критическое мышление, работа в команде и академическая успеваемость. Кроме того, было доказано, что применение STEM-методов способствует повышению мотивации учащихся к изучению науки и проведению научных исследований во внеурочной деятельности. Внедрение данного подхода позволит укрепить связи между школами, обществом и мировым сообществом, что, в свою очередь, повысит уровень STEM-грамотности и конкурентоспособность в глобальной экономике.

Ключевые слова: STEM-образование, навыки XXI века, решение проблем, критическое мышление, интегрированные уроки, креативность, сотрудничество, коммуникация, мотивация, исследовательские навыки

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Information about the authors:

Toktamys N.B. – Doctoral student, South Kazakhstan Pedagogical University named after Uzbekali Zhanibekov, e-mail: nurbolattoktamys0@gmail.com , ORCID: https://orcid.org/0009-0008-0443-6385

Shagrayeva B.B. – Candidate of chemical sciences, docent, South Kazakhstan Pedagogical University named after Uzbekali Zhanibekov, e-mail: bibi-0305@mail.ru

Shertayeva N.T. – Candidate of chemical sciences, docent, South Kazakhstan Pedagogical University named after Uzbekali Zhanibekov, e-mail: nailyaximik@mail.ru

Bitemirova A.E. – Candidate of chemical sciences, docent, South Kazakhstan Pedagogical University named after Uzbekali Zhanibekov, e-mail: bitemirova1960@mail.ru

Авторлар туралы мәлімет:

Тоқтамыс Н.Б. – докторант, Өзбекәлі Жәнібеков атындағы Оңтүстік Қазақстан педагогикалық университеті, e-mail: nurbolattoktamys0@gmail.com , ORCID: https://orcid.org/0009-0008-0443-6385

Шаграева Б.Б. – Химия ғылымдарының кандидаты, доцент, Өзбекәлі Жәнібеков атындағы Оңтүстік Қазақстан педагогикалық университеті, e-mail: bibi-0305@mail.ru

Шертаева Н.Т. – Химия ғылымдарының кандидаты, доцент, Өзбекәлі Жәнібеков атындағы Оңтүстік Қазақстан педагогикалық университеті, e-mail: nailyaximik@mail.ru

Битемирова А.Е. – Химия ғылымдарының кандидаты, доцент, Өзбекәлі Жәнібеков атындағы Оңтүстік Қазақстан педагогикалық университеті, e-mail: bitemirova1960@mail.ru

Информация об авторах:

Тоқтамыс Н.Б. – докторант, Южно-Казахстанский педагогический университет имени Өзбекәлі Жәнібеков, e-mail: nurbolattoktamys0@gmail.com , ORCID: https://orcid.org/0009-0008-0443-6385

Шаграева Б.Б. – Кандидат химических наук, доцент, Южно-Казахстанский педагогический университет имени Өзбекәлі Жәнібеков, e-mail: bibi-0305@mail.ru

Шертаева Н.Т. – Кандидат химических наук, доцент, Южно-Казахстанский педагогический университет имени Өзбекәлі Жәнібеков, e-mail: nailyaximik@mail.ru

Битемирова А.Е. – Кандидат химических наук, доцент, Южно-Казахстанский педагогический университет имени Өзбекәлі Жәнібеков, e-mail: bitemirova1960@mail.ru