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Methodology for the application of STEM-education technology in the study of physics

Kh.K. Abdrakhmanova[1], K.B. Kudaibergenova*[2]

[1]Zhanibekov University, Shymkent, Kazakhstan
[2]Zhubanov University, Aktobe, Kazakhstan

(E-mail: [1]khabi_kab@mail.ru, [2]kuralai.kasymbekova@gmail.com)

Abstract. This article presents a methodology for applying STEM-education technology in the teaching of physics at pedagogical universities in Kazakhstan. The proposed approach combines the 5E instructional model with project-based learning (PBL) to enhance student engagement, interdisciplinary thinking, and professional competence among prospective physics teachers. A case-based lesson on the topic "Friction: Force of Friction" was developed and piloted with third-year students specialized in physics education. The lesson incorporates real-world problem scenarios, inquiry-based experimentation, and collaborative mini-projects to foster skills in scientific reasoning, critical thinking, and the practical application of physics concepts. Observational data, student reflections, and portfolio assessments indicated increased motivation, deeper conceptual understanding, and the effective integration of STEM components. The study highlights both the pedagogical potential and implementation challenges of STEM in teacher training contexts, including the need for more structured support and curricular integration. The findings contribute to the conceptual framework for modernizing physics education through STEM methodologies and support the systemic development of STEM competencies in future educators.

Keywords: STEM-education, Project-Based Learning (PBL), Physics teaching, 5E instructional model, teacher training

Introduction

The rapid transformations brought about by the Fourth Industrial Revolution demand a rethinking of educational paradigms worldwide. As industries become increasingly automated and digitized, there is a growing necessity for graduates to possess not only subject-specific knowledge but also a new set of skills such as critical thinking, creativity, collaboration, and adaptability (Schwab, 2016). Traditional models of teaching, particularly in the natural sciences, often emphasize memorization over application, thereby limiting students' ability to solve real-world problems and innovate in complex contexts (Reinholz, White & Andrews, 2021). In

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this regard, physics education holds untapped potential: as a foundational science, it equips learners with the analytical tools needed to understand natural phenomena and technological systems. However, without appropriate pedagogical frameworks that emphasize inquiry, interdisciplinarity, and project-based learning, the transformative power of physics education remains underutilized (Bybee, 2013; Holubova, 2008).

STEM education offers a comprehensive solution to address these new educational challenges. By integrating science, technology, engineering, and mathematics into a unified framework, STEM encourages learners to apply knowledge to solve authentic, often open-ended problems (Diep et al., 2023; Krajcik & Delen, 2017). Within physics education, STEM promotes deeper conceptual understanding and learner engagement by connecting theory with practice through experimentation, modeling, and technological applications (Widya et al., 2019; Renard, 2023). Research also shows that approaches such as project-based learning (PBL) and inquiry-based instruction help build essential 21st-century skills like communication, collaboration, and scientific reasoning (Attard, Berger & Mackenzie, 2021; Faif Pasani & Amelia, 2023). In addition, STEM methodologies align with constructivist and sociocultural theories of learning, fostering active and meaningful participation in knowledge construction (Beyerlein & Crystal, 2016).

Despite its strategic importance, STEM education in Kazakhstan remains in an early phase of systemic implementation. While pioneering institutions such as BINOM, Quantum STEM schools, and selected universities have launched pilot programs, the country lacks a unified national strategy, teacher training system, and curricular frameworks to effectively scale STEM initiatives (Karaev, Bejsembaev & Mazbaev, 2022; Bragina, 2024). Recent studies in Kazakhstani pedagogical universities reveal that both in-service and prospective teachers often experience challenges in integrating interdisciplinary content, applying inquiry-based methodologies, and designing authentic STEM learning environments (Abdrakhmanova, Ķudaibergenova & Yamak, 2022; Abdrakhmanova & Kudaibergenova, 2023). Moreover, while schools are increasingly equipped with modern laboratories and digital tools, there is a shortage of methodological support and practice-oriented training modules that prepare teachers to implement STEM in physics teaching contexts (Moiseenko, Temirova & Mataev, 2023; Abdrakhmanova et al., 2025).

This article aims to develop and present a methodology for applying STEM education principles in the teaching of physics within Kazakhstan's pedagogical universities. The proposed methodology combines project-based learning with the 5E instructional model to promote meaningful engagement, critical thinking, and practical skill development among future physics teachers. The article provides a case-based lesson on the topic “Friction: Force of Friction” as a practical example of STEM integration in a physics course. It also outlines the expected outcomes of this methodology and emphasizes its relevance for forming STEM competencies aligned with national and global educational priorities (Abdrakhmanova et al., 2024).

Literature review

The progressive integration of STEM (Science, Technology, Engineering, and Mathematics) into physics education represents a transformative response to the evolving demands of modern global education in the 21st century. In recent decades, an expanding body of research has emphasized the necessity of interdisciplinary pedagogies, inquiry-based methods, and real-world contextualization in teacher education. These approaches are not only aligned with the dynamic nature of STEM careers but also address long-standing limitations of traditional content-based instruction in physics. This literature review critically examines both seminal and recent international contributions to STEM education with a focus on their relevance to physics teacher preparation. The aim is to assess their scholarly impact and identify persisting gaps, particularly in contexts such as Kazakhstan, where systemic STEM integration is still emerging.

Seminal Contributions: From Pedagogical Reform to Inquiry-Driven Models

The theoretical backbone of STEM education is closely tied to constructivist and experiential learning paradigms, where learners actively construct meaning through engagement and application. Among the most influential contributions is the 5E instructional model developed by Bybee and the BSCS (Biological Sciences Curriculum Study) team, which organizes learning into five phases: Engage, Explore, Explain, Elaborate, and Evaluate. Originally proposed for science education broadly, the model has been successfully adapted for STEM integration due to its emphasis on discovery, reflection, and conceptual reinforcement (Bybee et al., 2006). The strength of the 5E framework lies in its ability to transform passive learning environments into interactive ones, fostering analytical reasoning and collaborative inquiry. Alger (Alger, 2012) demonstrated that students engaged in 5E-structured lessons exhibit more profound comprehension of scientific concepts and improved retention, particularly when the model is used in conjunction with an inquiry-based approach and hands-on activities. Despite its wide use, initial applications of the model focused more on general science rather than on subject-specific domains like physics, underscoring a gap in domain-focused instructional refinement.

Simultaneously, project-based learning (PBL) emerged as a compatible pedagogical innovation aligned with STEM objectives. Hmelo-Silver (Hmelo-Silver, 2004) provided an early synthesis of PBL research, highlighting its capacity to cultivate critical thinking, autonomy, and collaborative skills. Later, Hasni et al. (Hasni et al., 2016) reinforced its value in science education by demonstrating that authentic project experiences enhance learners' motivation and deepen interdisciplinary understanding. While these foundational works establish the pedagogical logic for STEM-based reform, their direct applicability to physics teacher training was not the central focus, creating a need for context-specific adaptation in later research.

Recent Developments: Embedding STEM in Physics Instruction

In the last decade, educational researchers have made significant strides in localizing STEM models within subject-specific contexts, particularly in physics education. A notable contribution comes from Krajcik and Delen (Krajcik and Delen, 2017), who advocate for the use of "driving questions" and societal relevance to anchor learning in meaningful contexts. Their work, grounded in the Next Generation Science Standards (NGSS), illustrates how STEM principles can be used to restructure physics and science learning around real-world challenges, enhancing both relevance and engagement.

Rifandi and Rahmi (Rifandi and Rahmi, 2019) highlight the integration of modern technologies, such as Logger Pro video loggers and simulation tools like PhET, within STEM-based physics instruction. These tools, used in physics modules, enhance students' conceptual understanding through data analysis and hands-on experimentation. Their findings point out that students benefit from blended physical-digital environments where they can visualize abstract phenomena like motion or energy transfer through real-time data collection. Similarly, Subramaniam et al. (Subramaniam et al., 2023) examine how design-thinking frameworks help students to blend scientific reasoning with engineering practices for deeper cognition. The authors suggest that engaging students in authentic engineering design tasks fosters the development of STEM Ways of Thinking (SWoT), including design thinking, conceptual understanding (physics concepts, mathematical constructs), and metacognitive reflection.

Digital innovation is another theme in contemporary STEM education literature. Juškaite (Juškaite, 2019) explored virtual experimentation platforms in physics education. According to the author, when learners engage in virtual labs - adjusting parameters, simulating experiments, and receiving instant feedback - they tend to exhibit enhanced curiosity, a deeper understanding of concepts, and stronger inquiry-based skills. These findings align with the growing consensus that digital tools must be integral, not peripheral, to STEM methodology, especially in contexts where physical laboratory access is limited.

STEM Competency Development and Teacher Preparedness

A parallel line of inquiry in recent scholarship considers approaches to STEM competencies being developed among pre-service teachers. Wang et al. (Wang et al., 2011) note that engineering integration into science classrooms is often hindered by insufficient exposure during teacher preparation. For physics educators, this challenge is particularly pronounced due to the abstract and mathematical nature of the course. Therefore, equipping teacher candidates with opportunities to engage in authentic STEM learning, such as designing prototypes or conducting extended investigations, has been shown to enhance both subject mastery and pedagogical readiness.

Research by Attard, Berger, and Mackenzie (Attard, Berger & Mackenzie, 2021) reveals that while many teachers express enthusiasm for interdisciplinary instruction, they often lack the methodological knowledge and confidence to implement STEM effectively. This study also highlights a broader issue echoed in the literature on pre-service STEM teacher preparation: though motivation exists, knowledge and practical readiness are often missing, creating a clear call for scaffolded, structured training modules on STEM approaches embedded in teacher education.

Rodríguez et al. (Rodríguez et al., 2024) conducted a meta-synthesis examining global approaches to STEM teacher education, uncovering both similarities and differences in how these programs are put into practice. Although active learning methods are widely embraced, the extent to which interdisciplinary elements are integrated—and the long-term stability of these initiatives—differs significantly across regions. Their analysis underscores the need for clearly defined conceptual models and consistent institutional backing to avoid fragmented or surface-level implementation of STEM education.

Research Gaps and Implications for Emerging Systems

While international literature provides a strong foundation for STEM integration in physics teacher training, several research gaps remain unresolved, many of which are highly relevant for countries like Kazakhstan. *The first gap* is related with *the bridging theory and practice:* numerous teacher preparation programs find it challenging to offer real-world STEM teaching experiences that accurately reflect the theoretical frameworks discussed in academic courses. *The second gap is continuity and long-term educational research:* while short-term learning gains have been well-documented, few studies evaluate the sustained impact of STEM instruction on teacher identity, instructional innovation, and long-term student achievement. The third gap is disciplinary specificity: there remains a need for more advanced expansion of STEM instruction to physics subfields, such as optics, thermodynamics, or electromagnetism, ensuring that interdisciplinary approaches do not dilute scientific rigor. *One more gap concerns assessment and evaluation models:* despite the emphasis on formative learning, there is limited development of assessment tools tailored to interdisciplinary and competency-based instruction in STEM.

As one way of addressing these research gaps, this study proposes the 5E+PBL approach. It is expected to support the development of STEM competencies and facilitate the integration of STEM methodologies into physics teacher training in Kazakhstan and similar educational settings.

Methods and Materials

Research Design

This study employed a research design to develop, implement, and evaluate a STEM-integrated physics lesson for prospective teachers. The focus was on testing a prototype lesson that integrated interdisciplinary STEM elements through project-based and inquiry-oriented instruction. The approach involves iterative development, implementation, and refinement of a pedagogical tool.

Participants and Context

The study was conducted at Zhubanov University (Aktobe, Kazakhstan) during the 2024–2025 academic year. Participants included third-year bachelor's students majoring in the specialty "Training of a Physics Teacher." A total of 23 students participated in the piloting phase of the STEM lesson as part of their course "Methods of teaching physics". The institutional setting was selected due to its focus on preparing subject-specialist teachers and its growing interest in implementing innovative educational technologies such as STEM.

Instructional Framework

The developed lesson was based on the topic of mechanics, *"Friction: Force of Friction,"* drawn from the physics curriculum. The instructional model followed the **5E framework** (Engage, Explore, Explain, Elaborate, Evaluate), with an emphasis on real-life problem-solving. The lesson was implemented as a **mini-project** based on a case study about walking on icy surfaces, providing a meaningful and practical context for students.

Description of the Integrated Lesson "Friction: Force of Friction"

The lesson "Friction: Force of Friction" was designed as a case-based project that integrates the 5E instructional model with project-based learning (PBL). It centers on a realistic winter scenario in Astana, where students analyze why certain individuals slip on icy surfaces while others do not, based on the material and texture of their footwear soles. The lesson follows the five phases of the 5E model:

Engage: Students solve riddles to identify sole and surface materials (e.g., rubber, polyurethane, wood, carpet). QR codes reveal clues about the physics topic.

Explore: In teams, students conduct experiments using a dynamometer to measure friction forces between different soles and surfaces. They collect and analyze data.

Explain: A mini-lecture on frictional force is provided, and students interpret results, discussing factors that affect slipping.

Elaborate: Students work in teams to develop mini-projects based on real-life friction-related problems (e.g., safe footwear for icy conditions).

Evaluate: Students complete practical tasks, solve physics problems, and present group portfolios to demonstrate conceptual understanding and real-world application.

Table 1. Materials and Tools Used in the Lesson

Item	Purpose
Dynamometer	To measure the frictional force on different surfaces
Sample soles (4 materials)	Plastic, rubber, vulcanized rubber, polyurethane
Test surfaces	Carpet, wood, laminate, ice (or simulated surface)
QR codes and riddles	To engage students and introduce the lesson context
Graph paper/software	For plotting the friction force vs. surface/material
Lab worksheets	For recording observations and measurements

Table 2. Sample Evaluation Rubric for Student Mini-Projects

Criteria	Excellent (16-20 pts)	Good (11-15 pts)	Satisfactory (6-10 pts)	Needs Improvement (1-5 pts)
Scientific reasoning	Clear, well-developed hypothesis; accurate use of physics concepts and terminology	Mostly accurate reasoning with minor conceptual errors	Basic understanding with some misconceptions	Incomplete or flawed scientific logic
Data analysis and interpretation	Correct data collection and interpretation; appropriate use of graphs or tables	Minor errors in data analysis; visual representation included	Data collected but analysis is basic or inconsistent	Data missing or interpretation incorrect
Creativity and problem-solving	Innovative solution with strong real-life relevance; critical thinking evident	Clear and logical problem-solving with moderate originality	Functional but lacks creativity; conventional thinking	Weak or unclear solution; minimal effort
Teamwork and collaboration	Active contribution from all members; excellent coordination	Mostly balanced participation; some collaboration challenges	Uneven participation; coordination is limited	Little or no collaboration; dominant or absent members

Presentation and reflection	Highly organized, clear visuals, and deep reflection on learning	Well-structured with clear ideas; some reflective insight	Basic structure; reflection lacks depth	Poorly organized; no evidence of reflection

Total Score (out of 100):
• **90-100 pts = A** (Excellent)
• **75-89 pts = B** (Good)
• **60-74 pts = C** (Satisfactory)
• **Below 60 pts = D** (Needs Improvement)

This combination of structured activities, physical tools, and formative assessment helps ensure that the lesson not only builds physics content knowledge but also develops interdisciplinary competencies essential for STEM teaching.

Instruments and Tools

To evaluate the effectiveness of the developed lesson and students' engagement with STEM-based learning, the following data collection tools were employed:

• Observation protocols were used during lessons to assess students' collaboration, inquiry behaviors, and engagement with the learning tasks;

• Reflective journals were maintained by both students and the instructor to capture subjective experiences, challenges, and perceived learning outcomes;

• Reviews of student mini-projects allowed for the assessment of competencies such as scientific reasoning, problem-solving, and the ability to integrate STEM concepts;

• Questionnaires were conducted after the lesson to gather feedback on the clarity, relevance, and perceived effectiveness of the instructional design.

These instruments were selected to provide both formative and summative insights into the impact of the STEM lesson on the development of teaching-related competencies among prospective physics teachers.

Results and Discussion

The implementation of the integrated STEM lesson *"Friction: Force of Friction"* provided valuable insights into the effectiveness of combining project-based learning (PBL) and the 5E instructional model in preparing prospective physics teachers. The results are presented according to the main focus areas of the study: student engagement, STEM-competency development, lesson effectiveness, and pedagogical implications.

Student Engagement and Active Participation

Observational data and reflective journals showed a high level of student engagement during the lesson activities. The initial "Engage" phase using riddles and QR codes sparked curiosity and encouraged collaboration. Students were excited to find clues and work with real materials like shoe soles and surfaces. According to their journal entries, they perceived the lesson as "dynamic," "hands-on," and "different from traditional lectures." This supports previous findings that real-life scenarios and active experimentation enhance motivation and create meaningful learning contexts in STEM education (Attard, Berger & Mackenzie, 2021; Krajcik & Delen, 2017).

Development of STEM Competencies

Assessments of mini-projects and teacher observations revealed noticeable growth in STEM-related competencies:

• Students formulated hypotheses and tested predictions using physical measurements with dynamometers.

• They interpreted data on frictional forces and related them to real-life situations.

• The teams used knowledge from different subjects, combining physics with simple engineering, surface design, and math.

The elaboration phase, involving real-world problem-solving tasks (e.g., footwear design, improving comfort, and moving safely at home), demonstrated the students' ability to transfer theoretical knowledge to practical contexts. These outcomes align with the goals of STEM education: to cultivate critical thinking, creativity, and design-based reasoning (Bybee, 2013; Diep et al., 2023).

Lesson Effectiveness and Student Feedback

According to post-lesson questionnaires 91 % of participants rated the lesson as "useful" or "very useful" for their future teaching practice. Students valued the structured yet flexible format of the 5E model, especially the "Explore" and "Elaborate" phases, which promoted autonomy and creativity. However, some students (about 15%) reported difficulties with:

• Interpreting friction coefficient values,

• Making graphs and comparing variables,

• Using experimental results to make engineering decisions.

These challenges suggest that more scaffolding or integration with mathematics and engineering thinking may be required to support full STEM integration, especially for learners with limited experience with interdisciplinary activities.

Pedagogical Implications

The pilot program confirmed that combining PBL with the 5E model offers a coherent and effective structure for STEM lessons in teacher training programs. This approach encourages future teachers to experiment, reflect, and design lessons based on inquiry and real-world situations. However, several practical constraints emerged:

• Time limitations restricted the depth of student elaboration and discussion.

• Lesson preparation was resource-intensive (requiring materials, surfaces, and lab support).

• Not all students were familiar with collaborative learning or learning through exploration, indicating the need for gradual practice with STEM teaching methods in different subjects.

These findings match earlier research showing that STEM is just starting to be used in Kazakhstani universities (Abdrakhmanova et al., 2025; Karaev, Bejsembaev & Mazbaev, 2022), emphasizing the need for systemic support, modular training, and the gradual inclusion of STEM methods in physics and other science didactics.

Summary of Findings

The STEM-integrated lesson *"Friction: Force of Friction"* enhanced student engagement, deepened scientific understanding, and promoted the acquisition of interdisciplinary teaching competencies. The use of the 5E-PBL approach provided structure and flexibility, while the real-world case stimulated inquiry and relevance. The methodology demonstrates potential for broader application in physics teacher training and highlights areas for improvement, including mathematical support and instructional time management.

Future research should focus on long-term tracking of STEM competence development during teaching practice and explore how similar models can be adapted for other topics in the physics curriculum.

Conclusion

This study presented a methodology for integrating STEM-education technologies into the teaching of physics at pedagogical universities through a lesson designed around the topic "Friction: Force of Friction." Using project-based learning and the 5E model, the approach helped future teachers develop scientific thinking, problem-solving skills, and the ability to apply knowledge in real-life situations. Students responded positively and showed improved engagement and understanding. Despite these successes, several challenges were identified, including time constraints, uneven student familiarity with STEM-based formats, and the need for more structured mathematical support. These insights suggest that the integration of STEM in physics teacher education requires systematic implementation, including curricular alignment, professional development for instructors, and access to appropriate resources. Overall, the method shows promise for wider use in teacher training and supports the development of modern, interdisciplinary physics education in Kazakhstan. Further research and wider application across topics and institutions will help refine and validate this approach, ultimately supporting the development of a modern, competency-based educational system aligned with global standards.

Gratitude and conflict of interest

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Contribution of the authors

In writing the research article, all authors contributed equally. Each author played an identical role in the collection, analysis, and summarization of the data.

Kh.K. Abdrakhmanova wrote the sections: methods and materials, results and discussions, handled data revision, verification of accuracy, and approved the final version of the article for publication.

K.B. Kudaibergenova was responsible for searching for information, collecting and analyzing literature, conducting the experiment, gathering the experimental data, corresponding author.

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Х.К. Абдрахманова[1], Қ.Б. Кудайбергенова*[2],
[1]Өзбекәлі Жәнібеков атындағы Оңтүстік Қазақстан педагогикалық университеті, Шымкент қ., Қазақстан
[2]Қ. Жұбанов атындағы Ақтөбе өңірлік университеті, Ақтөбе қ., Қазақстан

STEM-білім беру технологиясын физиканы оқыту саласында қолдану әдістемесі

Аңдатпа. Бұл мақалада Қазақстанның педагогикалық жоғары оқу орындарында физиканы оқыту үдерісінде STEM-білім беру технологиясын қолдану әдістемесі ұсынылады. Ұсынылған тәсіл 5E үлгісін жобалық оқытумен (PBL) ұштастыра отырып, болашақ физика пәні мұғалімдерінің оқу үдерісіне белсенді қатысуын, пәнаралық ойлауын және кәсіби құзыреттіліктерін дамытуға бағытталған. Зерттеу аясында «Үйкеліс: үйкеліс күші» тақырыбы бойынша кейс-сабақ әзірленіп, физика мамандығының үшінші курс студенттерімен сынақтан өткізілді. Сабақ шынайы өмірлік жағдаяттарды, зерттеуге негізделген тәжірибелерді және бірлескен шағын жобаларды қамти отырып, ғылыми ойлау, сыни пайымдау және физикалық ұғымдарды практикалық қолдану дағдыларын дамытуға ықпал етеді. Бақылау мәліметтері, студенттердің рефлексиялары және портфолиолық бағалау нәтижелері студенттердің оқу мотивациясының артқанын, тақырыпты тереңірек түсінгенін және STEM компоненттерінің тиімді біріктірілгенін көрсетті. Зерттеуде STEM-тәсілдің педагогикалық әлеуеті мен оны мұғалімнің даярлау үдерісіне енгізудегі қиындықтары, атап айтқанда, құрылымдалған қолдаудың және оқу бағдарламасына кіріктірудің қажеттілігі атап өтіледі. Бұл зерттеу STEM әдістемесі арқылы физиканы оқытуды жаңғыртудың тұжырымдамалық негізін қалыптастыруға және болашақ мұғалімдердің STEM құзыреттіліктерін жүйелі дамытуға үлес қосады.

Түйін сөздер: STEM-білім беру, жобаға негізделген оқыту, физиканы оқыту, 5E оқыту моделі, мұғалімдерді даярлау

Х.К. Абдрахманова[1], К.Б. Кудайбергенова*[2]
[1]Южно-Казахстанский педагогический университет имени Озбекали Жанибеков, г. Шымкент, Казахстан
[2]Актюбинский региональный университет имени К. Жубанова, г. Актобе, Казахстан

Методология применения технологии STEM-образования при изучении физики

Аннотация. В данной статье представлена методика применения технологии STEM-образования в процессе преподавания физики в педагогических университетах Казахстана. Предложенный подход объединяет модель обучения 5E с проектно-ориентированным обучением (PBL) для повышения учебной мотивации студентов, развития междисциплинарного мышления и формирования профессиональных компетенций у будущих учителей физики. Был разработан и апробирован учебный кейс по теме «Трение. Сила трения» для студентов третьего курса физико-математических специальностей. Урок включает в себя реальные проблемные ситуации, исследовательские эксперименты и совместные мини-проекты, направленные на развитие навыков научного мышления, критического анализа и практического применения физических понятий. Анализ наблюдений, рефлексии и портфолио студентов свидетельствуют о повышении учебной мотивации, более глубоком усвоении содержания и успешной интеграции компонентов STEM. Исследование отражает не только высокий педагогический потенциал STEM-подхода в системе подготовки учителей, но и указывает на ряд затруднений при его внедрении, в частности, на необходимость более структурированной поддержки и интеграции в учебные программы. Результаты исследования вносят вклад в концептуальное обоснование модернизации преподавания физики с использованием STEM-методологии и способствуют системному развитию STEM-компетенций у будущих учителей.

Ключевые слова: STEM-образование, проектно-ориентированное обучение, преподавание физики, модель обучения 5E, подготовка учителей

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Information about the authors:

Abdrakhmanova Kh.K. – Candidate of Chemical Sciences, Associate Professor, Department of Physics, Zhanibekov University, Baitursynov Street 13, 160000, Shymkent, Kazakhstan

Kudaibergenova K.B. – corresponding author, assistant lecturer, Department of Physics, Zhubanov University, Aliya Moldagulova Avenue 34, 030000, Aktobe, Kazakhstan

Авторлар туралы мәліметтер:

Абдрахманова Х.К. – химия ғылымдарының кандидаты, физика кафедрасының доцент м.а., Өзбекәлі Жәнібеков атындағы Оңтүстік Қазақстан педагогикалық университеті, Байтұрсынов көшесі, 13, 160000, Шымкент, Қазақстан

Кудайбергенова Қ.Б. – хат-хабар авторы, физика кафедрасының ассистент лекторы, К.Жұбанов атындағы Ақтөбе өңірлік университеті, А.Молдағұлова даңғылы, 34, 030000, Ақтөбе, Қазақстан

Сведения об авторах:

Абдрахманова Х.К. – кандидат химических наук, и.о.доцента кафедры «Физика», Южно-Казахстанский педагогический университет имени Озбекали Жанибекова, ул. Байтурсынова, 13,160000, г.Шымкент, Казахстан

Кудайбергенова К.Б. – автор для корреспонденции, лектор-ассистент кафедры «Физика» Актюбинского регионального университета им. К. Жубанова, буль. А.Молдагулова, 34, 030000, г.Актобе, Казахстан