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DEVELOPING STEM COMPETENCIES IN PRE-SERVICE PHYSICS TEACHERS: A LONGITUDINAL UNIVERSITY-BASED INTERVENTION STUDY IN KAZAKHSTAN

Abstract. This multi-stage evaluation examines changes in physics teachers' self-assessed STEM competencies following a university-based professional development intervention in Kazakhstan. The study included a diagnostic needs survey (N = 164), course participation by 46 teachers, and complete paired pre-test/post-test data from 25 teachers, who also completed a practice-focused follow-up during the subsequent academic year. At baseline, 63.4% of respondents reported limited STEM understanding and 28.0% reported no familiarity. In the paired subsample, overall self-assessed STEM competence increased from $M = 2.18$ ($SD = 0.71$) to $M = 4.22$ ($SD = 0.58$), $t(24) = -13.78$, $p < .001$. Significant gains were observed in STEM knowledge, lesson planning, interdisciplinary task design, project-based learning, and digital-tool use. During follow-up, all 25 respondents reported implementing STEM projects, averaging 4.2 projects each; satisfaction was $M = 4.36$ ($SD = 0.70$), and 92% would recommend the course. These findings indicate substantial perceived professional growth and reported classroom transfer, but they do not establish causal effects because the study used convenience sampling, self-report measures, and no comparison group.

Keywords: STEM education, teacher competencies, physics teacher preparation, higher education, Kazakhstan

Introduction

STEM (Science, Technology, Engineering, and Mathematics) education has emerged as a strategic priority in contemporary global education systems, recognized by both researchers and policymakers as a key driver of innovation and economic development (Nazarbayev University Graduate School of Education, 2014; World Economic Forum, 2020). By fostering scientific literacy, technological fluency, critical thinking, creativity, and problem-solving skills, STEM-oriented approaches aim to prepare learners for increasingly complex knowledge-based societies (Sirajudin et al., 2021). Central to this paradigm is the integration of disciplinary knowledge with authentic real-world contexts, enabling the practical application of theoretical concepts (Bakytказы et al., 2024).

Within the STEM framework, physics occupies a foundational position, as it provides the conceptual basis for engineering design, technological systems, and scientific modeling (Balta et al., 2024). However, effective STEM integration in physics education depends substantially on teachers' professional competencies, including subject mastery, technological proficiency, and methodological readiness (Nurgaliyeva et al., 2023). Empirical evidence suggests that teachers' STEM competencies significantly influence student engagement, achievement, and career aspirations in STEM-related fields (Clark & Zhang, 2018; Shageeva et al., 2020).

International scholarship increasingly emphasizes multidimensional competency models in STEM teacher preparation (Kurup et al., 2019; Rose et al., 2015). Existing studies identify problem solving, collaboration, technological proficiency, organizational functioning, and integrated pedagogical design as relevant domains. However, subject-specific evidence concerning physics teachers in post-Soviet professional-development settings remains limited. This study addresses that contextual gap while recognizing that self-assessment alone cannot establish observable instructional performance.

In Kazakhstan, educational reforms prioritize teacher development and STEM-oriented pedagogy (Yakavets & Dzhadrina, 2014; Nazarbayev, 2018). However, practicing physics teachers continue to report methodological, organizational, and resource-related barriers to interdisciplinary STEM implementation. Evidence from school practice can therefore inform both in-service professional development and the later design of pre-service physics-teacher curricula.

Addressing this gap, the present study aims to develop and empirically evaluate a structured university-based professional development model for strengthening STEM competencies among physics teachers and to identify implications for pre-service teacher education.

Literature Review

Theoretical frameworks of STEM competencies. International scholarship proposes diverse frameworks for conceptualizing STEM competencies in pre-service teacher education. Berisha and Vula (2021) identify five pedagogical strategies: design-based, project-based, and problem-based learning, collaborative approaches, and inquiry or modeling, as central to competence development. Among these, design-based learning has been identified as particularly effective for interdisciplinary integration (Agudelo Rodríguez et al., 2024). However, while these models provide valuable pedagogical mechanisms, they often lack structured competency assessment frameworks applicable at the university level. Competency structure research further identifies four interrelated domains: problem-solving, collaboration, technological proficiency, and organizational functioning (Rose et al., 2015). Although such multidimensional models offer conceptual clarity, empirical validation in subject-specific teacher education contexts, particularly in physics, remains limited. Studies evaluating STEAM competencies frequently rely on self-assessment instruments and Likert-type scales (Smyrnova-Trybulska et al., 2024), which, while methodologically practical, may not fully capture observable instructional performance.

Pedagogical models and curriculum approaches. University-based teacher education programs increasingly combine multiple pedagogical models to foster STEM integration. Pimthong and Williams (2021) emphasize methodology courses as key platforms for developing integrated instructional design skills. Similarly, Li (2025) proposes innovative curriculum integration strategies through competitive pedagogical formats. Research on creative STEM teacher preparation underscores the importance of aligning theory, practice, and policy dimensions (Milner-Bolotin & Martinović, 2025). Nevertheless, many initiatives remain fragmented, focusing either on isolated instructional techniques or short-term interventions rather than longitudinal competency development. Virtual practicum experiences have also demonstrated effectiveness in enhancing instructional design skills (Wu et al., 2021). However, the scalability and contextual adaptability of such approaches in different higher education systems require further investigation.

Implementation strategies in higher education institutions. At the institutional level, STEM teacher preparation varies significantly in structure and delivery modes. Industry-based immersive placements positively influence professional intentions and instructional practices (Hurley et al., 2023). Comparative analyses based on TALIS-2018 data highlight structural differences in professional development systems across post-Soviet contexts (Chernobay & Tashibaeva, 2020). Recent mixed-methods studies demonstrate that structured STEM courses can enhance teacher self-efficacy (Zhumabay et al., 2024b). Despite these advances, empirical studies integrating theoretical modeling, structured intervention, and longitudinal evaluation within a single university-based framework remain scarce, particularly in Kazakhstan.

Research aim. This study aims to develop and empirically evaluate a structured university-based professional development model for strengthening STEM competencies among physics teachers.

Research objectives: (1) examine baseline levels of STEM awareness and professional needs among physics teachers; (2) develop a theoretically grounded intervention model; (3) evaluate changes in self-assessed STEM competencies from pre-test to post-test; and (4) examine teachers' implementation experience during the following academic year.

Research contribution. The study contributes a contextually adapted five-level model of STEM integration, a structured 80-hour professional-development course, verified pre-test/post-test evidence of change in self-assessed competencies, and follow-up evidence of reported classroom implementation in Kazakhstan. The contribution is empirical and contextual rather than a claim of an entirely original theory or research method.

Methodology

The empirical participants were in-service physics teachers working in secondary schools in Kazakhstan. Their professional needs and implementation experiences were examined to improve continuing professional development and to generate evidence that may inform future pre-service physics-teacher curricula. The empirical intervention itself did not involve pre-service teachers.

The study was situated within a teacher-development continuum linking initial preparation, early-career induction, and continuing professional development. Findings from practicing teachers were treated as indicators of current professional needs, not as direct evidence of the effectiveness of pre-service programmes.

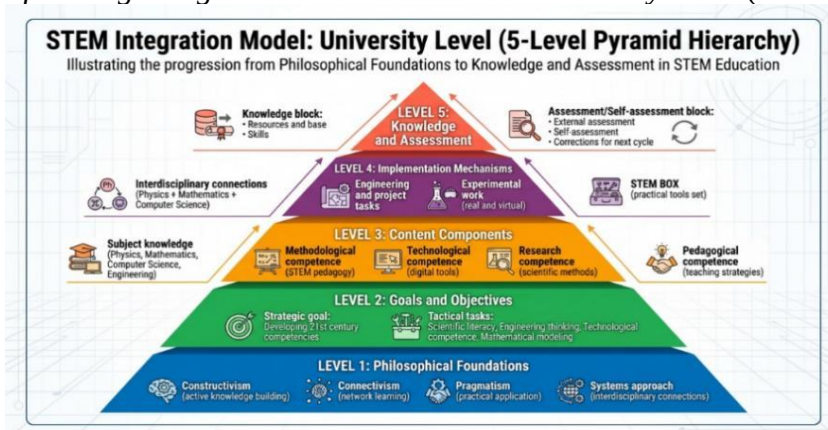
The five-level model was piloted as an organizing framework for the professional-development course. Its potential application in university teacher-education curricula remains a recommendation for future implementation and evaluation rather than a validated outcome of the present study.

The study examined whether a structured STEM course was associated with changes in teachers' self-assessed competencies and how participants reported applying STEM approaches during the following academic year. It did not independently measure student achievement. Accordingly, reported student-progress ratings are interpreted only as teacher perceptions, and no causal pathway from the intervention to student outcomes is claimed.

Research design. The study used a multi-stage quantitative evaluation supplemented by open-ended responses. First, 164 physics teachers completed a diagnostic needs survey. Second, 46 teachers participated in the university-based course "Integrating STEM Elements into Physics Teaching." Third, 25 teachers provided complete paired pre-test/post-test competency data and completed a practice-focused follow-up during the 2024–2025 academic year. The follow-up examined project implementation, barriers, perceived student progress, support, and satisfaction. Convenience sampling and the absence of a comparison group limit causal inference and generalizability.

Figure 1.

A Five-Level Model for Integrating STEM Education at the University Level (Penchev, 2025)



Data collection instruments. The diagnostic survey assessed STEM understanding, conditions required for effective lessons, missing competencies, difficult physics topics, preferred course content, and support needs. The intervention evaluation used five self-rating indicators on a 5-point scale: STEM knowledge, lesson planning, interdisciplinary task design, project-based learning, and digital-tool use. The follow-up questionnaire examined implementation frequency, project activity, barriers, perceived student progress, support, and satisfaction. The questionnaires also contained open-ended prompts about implemented projects and support needs.

The instruments were reviewed for alignment with the study's competency framework and piloted in the local context. Because complete item-level validation evidence and a fully specified measurement model were not available for this report, the five outcomes are treated as self-assessment indicators rather than validated latent subscales. The study therefore reports transparent indicator-level results and identifies further psychometric validation as a priority for future research.

Data analysis. Diagnostic responses were summarized using frequencies and percentages. Paired-samples t-tests were used for pre-test/post-test comparisons among the 25 participants with complete paired data; degrees of freedom were 24. Follow-up ratings are presented descriptively using means, standard deviations, frequencies, and percentages. Earlier omnibus ANOVA comparisons across difficulty categories and school subjects were removed because the same respondents rated multiple categories and participant-level data were unavailable for an appropriate repeated-measures or non-parametric reanalysis. Open-ended responses were used descriptively to identify examples of projects and support needs; no formal intercoder-

reliability claim is made.

The follow-up assessed reported transfer into classroom practice rather than administering the competency scale for a third time. The findings should therefore not be interpreted as a three-wave longitudinal test of sustained competency scores. Attrition is also relevant: 25 of the 46 course participants provided complete paired and follow-up information, and no systematic comparison with non-completers was available.

Ethical considerations. The study received approval from the Ethics Committee of Al-Farabi Kazakh National University. Participants provided informed consent, and confidentiality, anonymity, and the right to withdraw were maintained. The approval reference should be added in the journal submission metadata if required by the target journal.

Results

Teachers' understanding of and preparedness for STEM. The survey results (N=164) showed significant gaps in participants' understanding of STEM: STEM understanding level: – 63.4% (n=104) – limited understanding (general information only) – 28.0% (n=46) – not familiar at all – 8.5% (n=14) – in-depth, analytical-level knowledge. These findings indicate a considerable gap in teachers' knowledge and experience related to STEM education. Many teachers perceive STEM not as a comprehensive pedagogical system but as a set of isolated tasks and projects.

Factors necessary for effective implementation of STEM lessons (Figure 2) – Participation in professional development courses – 43.9% (n=72) – Collaboration and exchange of experience with colleagues – 26.8% (n=44) – Organization of interdisciplinary laboratories – 20.1% (n=33) – Partnership with universities – 6.7% (n=11) – Alignment of STEM activities with the school curriculum – 2.4% (n=4).

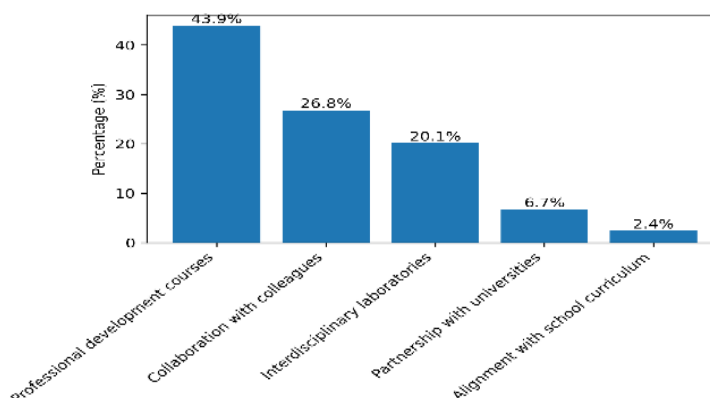
These indicators clearly demonstrate that teachers consider high-quality professional development courses to be the most critical need. In addition to improving their own skills, teachers emphasized the importance of institutional support, including adequate material and technical resources as well as organizational support.

In order to design the course, the competencies lacking for effective STEM integration were identified. These include insufficient methodological preparation – 24% (n=39); limited access to updated scientific information in the natural sciences – 24% (n=39); and effective organization of STEM education at the school level – 52% (n=86).

Difficult topics within the physics curriculum include Astronomy – 49.1% (n=81); Nuclear and Atomic Physics – 37.4% (n=61); Optics – 31.3% (n=51); Hydrodynamics and Wave Phenomena – 28.2% (n=46). These topics are generally considered challenging due to their complexity, lack of visual aids, and limited opportunities for practical activities. In response, the application of STEM strategies such as virtual laboratories (29.4%) and project-based learning (22.7%) can significantly enhance instructional effectiveness.

Figure 2

Factors Necessary for the Effective Implementation of STEM Lessons



Therefore, the course content should cover a broad range, from fundamental STEM concepts to more advanced methodologies and their practical application. Based on the survey data, the course was structured

around three main modules, as presented in Table 1.

To construct the course, an indicator-based analysis was conducted based on the survey responses. The results are presented in Table 1 below.

Table 1.
Indicator-Based Analysis Based on Survey Responses

Evidence area	Survey result	Priority need	Course response
STEM understanding	28.0% no familiarity; 63.4% limited; 8.5% in-depth	Foundational knowledge	Module 1
Missing preparation	50.0% organization; 24.4% methodology; 23.2% scientific updates	Organization and methodology	Modules 1 and 3
Teacher competencies	31.7% critical thinking; 28.7% lifelong learning; 25.0% organization; 22.6% leadership	Methodological development	Module 2
Challenging topics	49.1% astronomy; 37.4% nuclear physics; 31.3% optics; 28.2% waves	Visualization and practical work	Modules 2 and 3
Preferred approaches	29.4% virtual laboratories; 22.7% project learning; 17.8% applied tasks	Digital and project methods	Modules 2 and 3
Support needs	43.9% professional development; 26.8% peer exchange; 20.1% resources	Continuing professional support	All modules

Based on this analysis, the professional development course “Integrating STEM Elements into Physics Teaching” was developed. The course consisted of three main modules (Table 2).

Table 2
Structure and Content of the Professional Development Course

Module	Content
Module 1. Foundations of STEM Education (10 hours)	1.1. Regulatory documents 1.2. STEM: History and development 1.3. Principles of the STEM education system 1.4. STEM teaching practices in the USA 1.5. STEM integration in Kazakhstan: Opportunities and limitations 1.6. STEM teaching methodology: Critical and creative thinking
Module 2. Planning STEM Instruction (30 hours)	2.1. Core principles of STEM instructional planning 2.2. Approaches to applying STEM strategies in physics lessons 2.3. Developing project-based lesson plans 2.4. Specific features of STEM lessons for different grade levels 2.5. Methods of data collection and analysis 2.6. Reflection
Module 3. STEM Box and Resources: Project Development (30 hours)	3.1 STEM Box design and use; 3.2 efficient use of resources; 3.3 interdisciplinary project design; 3.4 project implementation; 3.5 presentation and defence; 3.6 assessment criteria. Final project presentation and assessment: 10 hours.

The course comprised 80 instructional hours: Module 1, Foundations of STEM Education (10 hours); Module 2, Planning STEM Instruction (30 hours); Module 3, STEM Box and Resources (30 hours); and final project presentation and assessment (10 hours). Instruction combined lectures and seminars with practical workshops, project development, virtual laboratories, webinars, Moodle, and Google Classroom. Participants completed a reflective task, a STEM lesson plan, an interdisciplinary project, and a final project presentation evaluated for curriculum alignment, interdisciplinary integration, feasibility, scientific accuracy, use of technology, and assessment design.

The five-level model was developed by adapting Penchev’s (2025) systems framework and related STEM-integration literature to the Kazakhstani professional-development context. It is presented as a

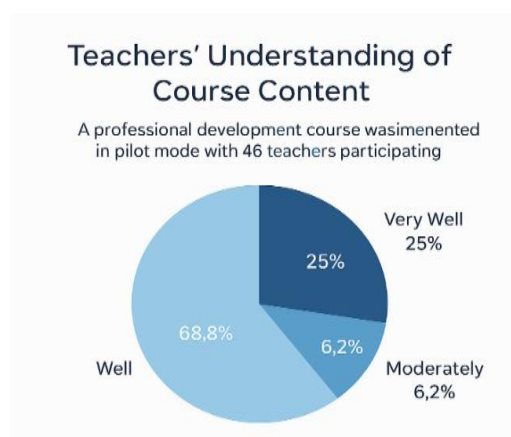
contextual synthesis rather than an entirely original or fully validated framework. The levels comprise philosophical foundations; goals and objectives; content components; implementation mechanisms; and education and assessment.

Results of course implementation. All 46 enrolled teachers completed the course, with an average attendance rate of 96%. Participants produced 46 STEM lesson plans, developed 23 interdisciplinary projects during the course, and participated in practical work with digital simulations, virtual laboratories, and project-based instructional design. The paired analysis reported below uses the 25 teachers for whom complete pre-test and post-test competency scores were available.

Immediate post-course feedback was positive. In the dissertation's course evaluation, perceived usefulness of the content was $M = 4.76$ ($SD = 0.44$), effectiveness of teaching methods was $M = 4.68$ ($SD = 0.48$), quality of learning materials was $M = 4.64$ ($SD = 0.49$), trainer professionalism was $M = 4.84$ ($SD = 0.37$), and overall satisfaction was $M = 4.72$ ($SD = 0.46$), all on a 5-point scale.

Figure 3

Immediate Post-Course Evaluation (Mean Ratings and Standard Deviations)



Participants reported that the course provided practical strategies for integrating STEM into physics instruction. Because these statements are based on self-report, they are interpreted as perceptions of readiness and usefulness rather than objective evidence of teaching mastery or student achievement.

Participants also perceived potential benefits for student engagement and interest in natural sciences. These perceptions were not verified with independent student-level measures and are therefore reported cautiously.

Paired pre-test/post-test comparisons showed statistically significant increases in all five indicators (Table 3). STEM knowledge increased from $M = 2.12$ ($SD = 0.83$) to $M = 4.28$ ($SD = 0.61$), $t(24) = -12.34$; lesson planning from $M = 1.88$ ($SD = 0.73$) to $M = 4.16$ ($SD = 0.69$), $t(24) = -13.45$; interdisciplinary task design from $M = 2.04$ ($SD = 0.79$) to $M = 4.08$ ($SD = 0.70$), $t(24) = -11.89$; project-based learning from $M = 2.32$ ($SD = 0.85$) to $M = 4.24$ ($SD = 0.66$), $t(24) = -10.67$; and digital-tool use from $M = 2.56$ ($SD = 0.92$) to $M = 4.36$ ($SD = 0.64$), $t(24) = -9.23$. Overall STEM competence increased from $M = 2.18$ ($SD = 0.71$) to $M = 4.22$ ($SD = 0.58$), $t(24) = -13.78$. All p values were $< .001$. Figure 4 visualizes the same means and standard deviations.

The follow-up evidence concerned classroom implementation during the subsequent academic year. All 25 respondents reported applying STEM projects, with an average of 4.2 projects per teacher. Reported projects addressed mechanics, electricity and magnetism, thermal physics, optics, and modern physics. The principal implementation difficulties are summarized in Table 4.

Table 3

Pre-Test and Post-Test STEM Competency Scores for Participants with Complete Paired Data (n = 25)

Competency indicator	Pre-test M (SD)	Post-test M (SD)	Mean change	t	p
STEM knowledge	2.12 (0.83)	4.28 (0.61)	+2.16	t(24) = -12.34	< .001
STEM lesson planning	1.88 (0.73)	4.16 (0.69)	+2.28	t(24) = -13.45	< .001
Interdisciplinary task design	2.04 (0.79)	4.08 (0.70)	+2.04	t(24) = -11.89	< .001
Project-based learning	2.32 (0.85)	4.24 (0.66)	+1.92	t(24) = -10.67	< .001
Digital-tool use	2.56 (0.92)	4.36 (0.64)	+1.80	t(24) = -9.23	< .001
Overall STEM competence	2.18 (0.71)	4.22 (0.58)	+2.04	t(24) = -13.78	< .001

Note. Scores were measured on a 5-point scale. Negative t values reflect the pre-test minus post-test direction. Participant-level data were unavailable for computing paired-difference confidence intervals or standardized effect sizes.

Table 4

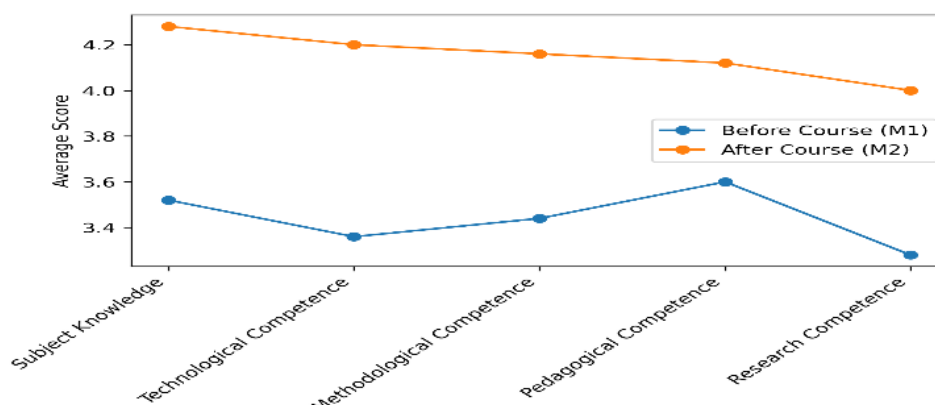
Difficulties Encountered During STEM Project Implementation (5-point scale, n = 25)

Difficulty	M	SD
Time constraints	2.57	1.42
Budget and funding	2.52	1.36
Student preparedness	2.48	1.23
Project assessment	2.44	1.23
Curriculum integration	2.36	1.29
Insufficient equipment	2.32	1.38
Interdisciplinary coordination	2.28	1.21
Insufficient methodological materials	2.24	1.33
Software availability	2.20	1.26
Parent support	2.12	1.17
Administrative support	2.08	1.19
Student grouping	2.00	1.15
Collegial support	1.96	1.10
Safety procedures	1.92	1.08
Internet access	1.87	1.19

Note. Ratings are presented descriptively because the same respondents evaluated all difficulty categories and participant-level data were unavailable for an appropriate repeated-measures analysis. The highest means concerned time constraints (M = 2.57), budget and funding (M = 2.52), student preparedness (M = 2.48), and project assessment (M = 2.44).

Figure 4

Pre-Test and Post-Test Self-Assessed STEM Competencies



During the course, trainees received various types of support in implementing STEM projects (Table 5).

Table 5*Types of Support Received and Their Effectiveness (5-point scale, N = 25)*

Type of support	Mean score	SD
Methodological support	4.24	0.72
Technical support	3.92	0.86
Collegial support	4.12	0.73
Administrative support	3.68	0.91
Financial support	3.44	1.02

At the one-year follow-up ($n = 25$), methodological support received the highest rating ($M = 4.24$, $SD = 0.72$), followed by collegial support ($M = 4.12$, $SD = 0.73$), technical support ($M = 3.92$, $SD = 0.86$), administrative support ($M = 3.68$, $SD = 0.91$), and financial support ($M = 3.44$, $SD = 1.02$). Overall satisfaction was $M = 4.36$ ($SD = 0.70$; 95% CI [4.09, 4.63]); 23 teachers (92%) would recommend the course, and all 25 reported applying acquired knowledge. Strengths included practical orientation (96%), professional support (88%), use of modern technologies (84%), and interdisciplinary integration (80%). Requested improvements included longer duration (52%), additional equipment (44%), and more methodological materials (36%). Perceived student-progress ratings ranged from $M = 3.64$ to 4.10 across six subjects and were highest in informatics ($M = 4.10$, $SD = 0.74$) and physics ($M = 4.00$, $SD = 0.71$). These descriptive ratings reflect teacher perceptions, not independently measured achievement.

Discussion

Baseline needs and intervention relevance. The diagnostic survey ($N = 164$) showed that 63.4% of respondents had only limited STEM understanding and 28.0% had no prior familiarity, while only 8.5% reported in-depth, practice-oriented understanding. Professional development was the most frequently selected condition for effective implementation (43.9%), followed by collaboration and experience exchange (26.8%) and interdisciplinary laboratories or material resources (20.1%). These findings directly informed the course's practical and methodological emphasis.

Intervention-associated change. Complete paired data from 25 teachers showed significant increases in all five self-assessment indicators and in the overall score (all $p < .001$). The largest mean increase occurred in lesson planning (+2.28), followed by STEM knowledge (+2.16), interdisciplinary task design (+2.04), project-based learning (+1.92), and digital-tool use (+1.80). These large changes warrant further confirmation with validated instruments, objective performance measures, and a comparison group.

Theoretical significance of the five-level model. The developed five-level model provides a comprehensive framework for integrating STEM education at the university level. The model synthesizes multiple theoretical approaches. Constructivism and connectivism (Level 1) ensure the principles of active

knowledge construction and networked learning (Suryadi et al., 2023), corresponding with Pimthong and Williams' (2021) concept of constructing integrated STEM education. The competence-oriented approach (Level 3) aligns with the multidimensional competence model proposed by Kurup et al. (2019), integrating subject, methodological, technological, research, and pedagogical competencies. The implementation mechanisms (Level 4) incorporate the five strategies proposed by Berisha and Vula (2021): design-based learning, project-based learning, problem-based learning, collaborative learning, and inquiry/modeling. The Knowledge and Assessment level (Level 5) applies the STEAM competence assessment approach of Smyrnova-Trybulska et al. (2024), combining self-assessment and external evaluation.

Practical implications. The findings suggest that teacher-education and professional-development providers may consider structured STEM components that emphasize practical work, interdisciplinary planning, digital tools, and continuing support. The present evidence does not justify mandatory national adoption without further multi-site evaluation. Extending support over 4–5 months was a participant recommendation rather than an experimentally tested conclusion.

Curriculum-level application. Based on the identified competency gaps and the outcomes of the intervention, a 5 ECTS elective course entitled “Elements of STEM Education in Physics Teaching” was developed for master’s students enrolled in the 7M01501 Physics educational programme. The purpose of the course is to develop students’ professional competencies through the study of the theoretical foundations, core principles, and methodological approaches of STEM education. The course includes project-based approaches to planning and conducting physics lessons and elective courses, methods for designing STEM boxes, and strategies for the effective use of educational resources. The development of this course represents a practical curriculum-level outcome of the study. However, its effectiveness among master’s students has not yet been empirically evaluated; therefore, its implementation and assessment constitute a direction for future research.

School support system. In accordance with the recommendations of Chernobay and Tashibaeva (2020), a comprehensive support system for schools should be established, including provision of technical equipment, a repository of methodological materials, partnership networks (inter-school exchange of experience), and administrative and financial support. Policy-level changes. Consistent with Zhumabay et al. (2024a), STEM education should be integrated into national educational standards, teachers’ workload should be optimized, funding for STEM resources should be increased, and partnerships between universities and schools should be strengthened.

The study has several limitations. Convenience sampling restricts generalizability, and the absence of a comparison group prevents causal attribution. Only 25 of 46 course participants provided complete paired and follow-up data, creating possible attrition bias. Outcomes were predominantly self-reported, and complete psychometric evidence for the indicators was not available. The follow-up did not repeat the competency scale, qualitative responses were not analyzed with independent coders, and student progress was not measured objectively. Difficulty and subject ratings are therefore reported descriptively rather than with an inappropriate independent-groups ANOVA. Future studies should use validated instruments, matched or randomized comparison groups, repeated-measures or non-parametric analyses appropriate to within-participant data, classroom observations, portfolio assessment, objective student outcomes, and transparent preregistered analysis plans.

Conclusion

This study found substantial pre-test/post-test increases in physics teachers’ self-assessed STEM competencies following an 80-hour, practice-oriented professional-development course. Overall competence increased from $M = 2.18$ to $M = 4.22$, $t(24) = -13.78$, $p < .001$. All 25 follow-up respondents reported implementing STEM projects during the subsequent academic year, while methodological and collegial support received the strongest ratings. These findings indicate perceived professional growth and reported classroom transfer, but they do not establish causal effectiveness or objectively verified improvement.

As a curriculum-level application of the findings, a 5 ECTS elective course entitled “Elements of STEM Education in Physics Teaching” was developed for master’s students in the 7M01501 Physics educational programme.

The study offers a contextually adapted framework and preliminary evidence-based recommendations for STEM teacher professional development in Kazakhstan. Further validation is required before broader

claims about effectiveness, student achievement, or transferability can be made.

Future research should extend this work through comparative studies across contexts, qualitative investigations of teacher experiences, and longitudinal tracking of career development. By continuing to build the empirical foundation for STEM teacher education, the research community can support evidence-informed policy and practice that strengthens STEM education systems globally.

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Conflict of Interest Statement

The authors declare no potential conflicts of interest regarding the research, authorship, or publication of this article.

Declaration of the use of AI

The authors declare that artificial intelligence (AI) tools were not used in the preparation of the manuscript text, data analysis, interpretation of the results, or formulation of the conclusions. AI tools were used solely for the generation of one or more visual materials/figures presented in the manuscript. The authors reviewed and verified the generated visual content and assume full responsibility for its accuracy, relevance, and correspondence to the scientific content of the article.

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Author Contributions

All authors contributed equally to all stages of the research, including conceptualization, methodology, data analysis, manuscript preparation, review, and editing. All authors have read and approved the final version of the manuscript.

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