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LABORATORY WORK ON X-RAY DIFFRACTION AS A TOOL FOR DEVELOPING RESEARCH COMPETENCIES IN FUTURE PHYSICS TEACHERS

Abstract. This article demonstrates the effectiveness of methodological approaches to developing research competencies in prospective physics teachers. The implementation of advanced pedagogical technologies during laboratory work led to improved learning outcomes. The article presents the case of one master's student who completed a specialized elective course. The course methodology proved to be highly effective, resulting in the student's noticeable growth in research competencies. Subsequently, the student continued independent research activities, applying the acquired skills and competencies.

The paper presents the results of a pedagogical experiment aimed at fostering research competencies in future physics teachers through the integration of the X'Pert PRO X-ray diffractometer into the educational process. The experiment involved students and master's students enrolled in the "Physics," "Physics and Computer Science," and "Physics and Mathematics" academic programs, divided into experimental and control groups. The primary objective was to examine changes in students' research skills following a series of laboratory sessions on X-ray diffraction. The research employed methods of comparison, synthesis, abstraction, and statistical analysis to ensure the reliability of the results. The methodology included lectures, laboratory work, and independent assignments designed to reinforce both theoretical knowledge and practical skills. While the control groups studied theoretical material, the experimental groups completed hands-on laboratory sessions. As a result of the study, methodological foundations were developed to enhance the research competencies of prospective physics teachers, which, according to the analysis, contribute to the effective training of future specialists.

Keywords: physics teacher, laboratory work, methodology, research, X-ray diffraction.

Introduction

It is well established that laboratory-based physics practicum plays a crucial role in developing research competencies in prospective physics teachers. The physics practicum serves as a foundational component for the growth and formation of these competencies.

It is widely recognized that the research competency of a physics teacher plays a vital role in their professional teaching practice. The core professional skills of future educators are formed within the walls of higher education institutions. Therefore, particular attention is given to the methodology of developing research competencies in prospective physics teachers.

Experience has shown that laboratory work, as the practical component, cannot be separated from the theoretical foundation of the physics practicum or its underlying methodology. Thus, emphasis should be placed on a high-quality and effective methodology for conducting the physics practicum.

Modern education requires future physics teachers to possess not only in-depth subject knowledge but also well-developed research competencies essential for effective teaching and for fostering students' interest in science. As is well known, research competencies serve as a foundation for the professional development of educators, enabling them to apply modern teaching methods and introduce innovative approaches into the educational process (Johnson

& Lee, 2023). Moreover, (Johnson & Lee, 2023) emphasize that the development of such competencies should begin during the training of master's students in order to ensure their high level of professional readiness.

Laboratory work focused on studying X-ray diffraction offers unique opportunities for the development of research competencies. Several authors, such as (Imbert Romero et al., 2024), note that such practical activities help students gain a deeper understanding of scientific principles and foster the development of critical thinking. Research from (MIT OpenCourseWare, 2023) highlights the importance of understanding Bragg's law and the Laue and Debye–Scherrer methods, which are widely used for analyzing crystal structures and serve as a foundation for developing research skills in solid-state physics (MIT OpenCourseWare, 2023).

In the modern paradigm of professional education, future physics teachers must possess more than theoretical knowledge; they require well-developed research competencies to lead effectively in contemporary classrooms. X-ray diffraction (XRD) serves as a premier interdisciplinary tool to bridge the gap between fundamental physics, crystallography, and material science.

Recent studies emphasize that transitioning from passive lectures to active, XRD-based experimental modules significantly enhances student engagement. For instance, (Mešić et al., 2021) demonstrate the efficacy of inquiry-based learning through the use of desktop diffractometers. Their research highlights how prospective teachers develop critical analytical skills by interpreting real-world experimental data, navigating complexities such as instrumental broadening and peak overlapping that are often absent in idealized textbook problems.

The digital transformation of laboratory environments has also introduced new pedagogical dimensions. (Kin et al., 2022) argue for the integration of digital twin laboratories in XRD education. This approach allows students to refine their experimental techniques in a high-fidelity virtual environment before operating expensive physical equipment, thereby strengthening their technical literacy and procedural autonomy.

Furthermore, the development of research-oriented mindsets requires a structured didactic progression. According to (Bunaciu et al., 2015) moving from the abstract conceptualization of diffraction laws to the practical characterization of unknown materials allows future educators to build a holistic physical worldview. This competence is vital for their future role in supervising student-led research projects and translating complex physical phenomena into accessible classroom experiments.

At present, most universities are equipped with experimental and analytical instruments such as TEM, SEM, XRF, EPR, NMR, IR spectroscopy, and others. These instruments operate based on various physical principles. For example, TEM and SEM utilize the principles of electron and X-ray diffraction. Although primarily used to address tasks in research projects, their potential for developing students' research skills remains underutilized.

Research from the Paul Scherrer Institute also emphasizes that laboratory experiments involving X-ray diffraction enhance students' critical thinking and practical understanding of crystallographic structures. Working with real experimental setups enables master's students to master advanced techniques and deepen their understanding of atomic structures, thereby contributing to their professional development (Anderson, 2024).

The work of (Bukusheva et al., 2023) emphasizes that practical physics classes are not only a crucial stage in mastering theoretical content but also a foundation for fostering a research-oriented culture among prospective teachers. The study by (Johnson & Lee, 2023) demonstrates that laboratory sessions involving X-ray diffraction enable students to apply scientific methods in practical activities, simulate a real research environment, and enrich their methodological toolkit.

However, as the analysis of available literature shows, educational programs at higher education institutions lack a clear methodology for conducting laboratory work on the topics of "electron diffraction" and "X-ray diffraction."

Moreover, even in universities equipped with specialized instruments and facilities for laboratory experiments, there is often a lack of connection between laboratories and students. This was confirmed through a survey conducted among students and master's students.

Our study (Dalabayev et al., 2025) The main components of a special physics workshop on "X-ray diffraction" are separately disclosed. The theoretical support of the workshop and the complex of laboratory work related directly to the research work are considered, their main goals are analyzed. The paper develops methodological foundations for the formation of scientific research competencies of future physics teachers based on the example of performing a complex of laboratory practical training in X-ray diffraction.

In light of the above, the aim of this study is to demonstrate the effectiveness of implementing a methodological model for enhancing research competencies in prospective physics teachers, using laboratory work on X-ray diffraction as a case study. To achieve this aim, the following objectives were identified, in accordance with the recommendations of (Hattie, 2011):

First, to present the methodological model and its overall structure;

Second, to illustrate the application of the methodological foundations for developing research competencies in prospective physics teachers through the example of one master's student;

Third, to assess the formation and progression of the student's knowledge and demonstrate the implementation of the study's main hypotheses.

Materials and methods

The pedagogical experiment was carried out in three main stages. At the analytical stage, the relevant scientific and methodological literature was analyzed, the research problem was clarified, and existing contradictions in the preparation of future physics teachers were identified. Based on this analysis, the research hypothesis, goals, objectives, and methodological foundations of the study were formulated. At the constructive stage, the developed methodological model aimed at forming the research competencies of future physics teachers was implemented in the educational process. In particular, a specialized course titled "X-ray Diffraction" was introduced, and various forms and methods of teaching, including lectures, laboratory work, independent study, and research projects, were applied. At the feedback stage, the effectiveness of the implemented model was evaluated. Diagnostic tools were used to assess the level of development of research competencies among students, and the obtained results were analyzed to determine the effectiveness of the proposed methodological approach.

To address the research objectives and achieve the stated aim, the pedagogical experiment utilized the following materials: the X'Pert PRO X-ray diffractometer (Figure 1) of the National Research Laboratory for Collective Use at Sarsen Amanzholov East Kazakhstan University and its operator, as well as fourth-year students and first- and second-year master's students enrolled in the "Physics," "Physics and Computer Science," and "Physics and Mathematics" academic programs at Sarsen Amanzholov East Kazakhstan University and Khoja Akhmet Yassawi International Kazakh-Turkish University.

Figure 1.
XPert Diffractometer



Participants in this pedagogical experiment were divided into two groups: an “experimental group” and a “control group”.

For the purpose of conducting the research work systematically, the supervised students and master's students were divided into four groups: A, B, C, and D. To assess the effectiveness of the conducted surveys and the physics practicum, based on the main research design of the groups, the provided educational and instructional materials were classified into parts A and B, C and D, depending on the level of comprehension. (Table 1)

Information about the controlled groups is presented in the table below:

Table 1.
Participant Information

№ Group number	Educational Program Code of the Group	Group Name Used During the Pedagogical Experiment	Number of Students in the Group
1	7M01502	A	12
2	6B01502	B	8
3	6B01502	B	15
4	6B01520	C	20
5	6B01520	C	13
6	7M01520	D	22
			Total Number of Students 90

Six groups participated in the pedagogical experiment. Three of them served as control groups. The groups involved in the experiment were designated as A, B, C, and D. Groups A and B were assigned as the primary control groups; they were limited to working with the educational manual and completing the corresponding assignments. Groups C and D, by contrast, fully completed the physics practicum.

The main objective was to compare the “before-and-after” changes in the research competencies of prospective physics teachers through intergroup comparison.

The following research methods were employed in the study:

- Methods of comparison, synthesis, and abstraction to justify the applicability of the pedagogical experiment method, in accordance with (Prokopets, 2021);

- Empirical methods (observation, surveys, and pedagogical experiment) to examine and confirm the effectiveness of the methodological foundations for developing research

competencies in prospective physics teachers, based on the recommendations of (Ndiokubwayo et al., 2020);

- Statistical methods for collecting and analyzing experimental data and determining the statistical significance of the results obtained in the experimental part of the study (Nghiem-Phú et al., 2022);

- Experimental research methods applied during laboratory work (observation, comparison, modeling, experimentation, and measurement).

The pedagogical experiment was conducted in accordance with the framework proposed by John Hattie (Hattie, 2011), which consists of several key components.

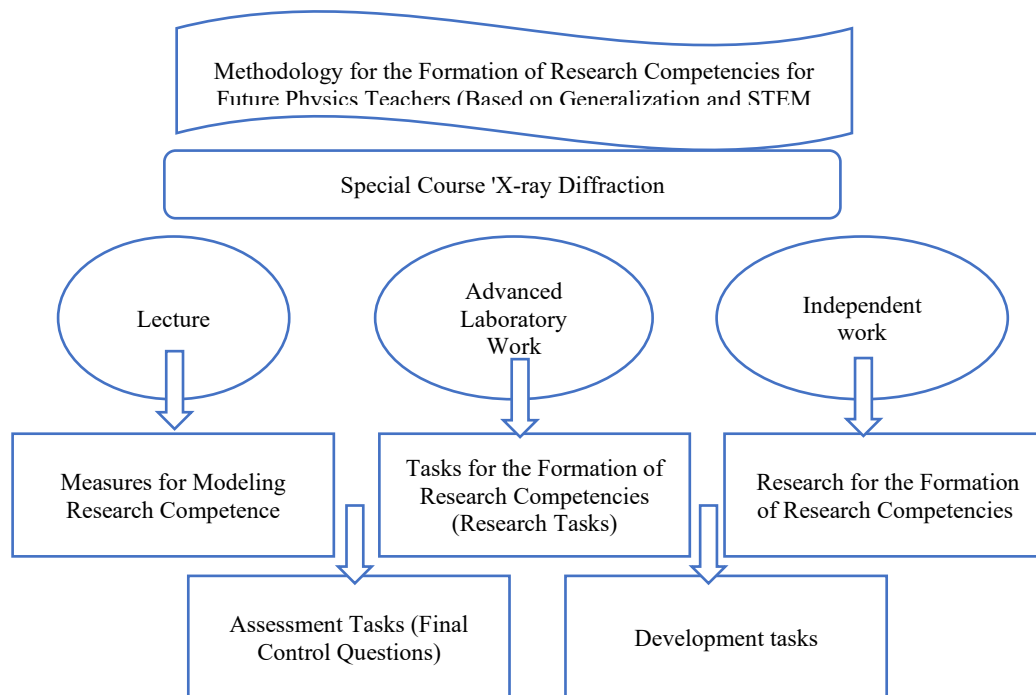
The developed methodological foundations for forming research competencies in prospective physics teachers comprise several core elements, both theoretical and practical. As part of the implementation, educational and instructional materials as well as electronic learning resources were developed. The instructional package includes lectures, practical tasks, and methodological guidelines for the instructor (methodology). The methodological framework for developing research competencies in future physics teachers is considered the theoretical foundation, which consists of lectures, laboratory work, and independent assignments (Figure 2).

The lecture serves as the first stage. It presents the theoretical foundations of the phenomena of diffraction and X-ray diffraction, including all key formulas and terms.

The laboratory work is aimed at developing and strengthening research competencies in prospective physics teachers. It includes three laboratory experiments that are logically interconnected.

The independent work is designed to apply and further reinforce the acquired knowledge and skills through the use of research competencies.

Figure 2.
Model of Methodological Foundations

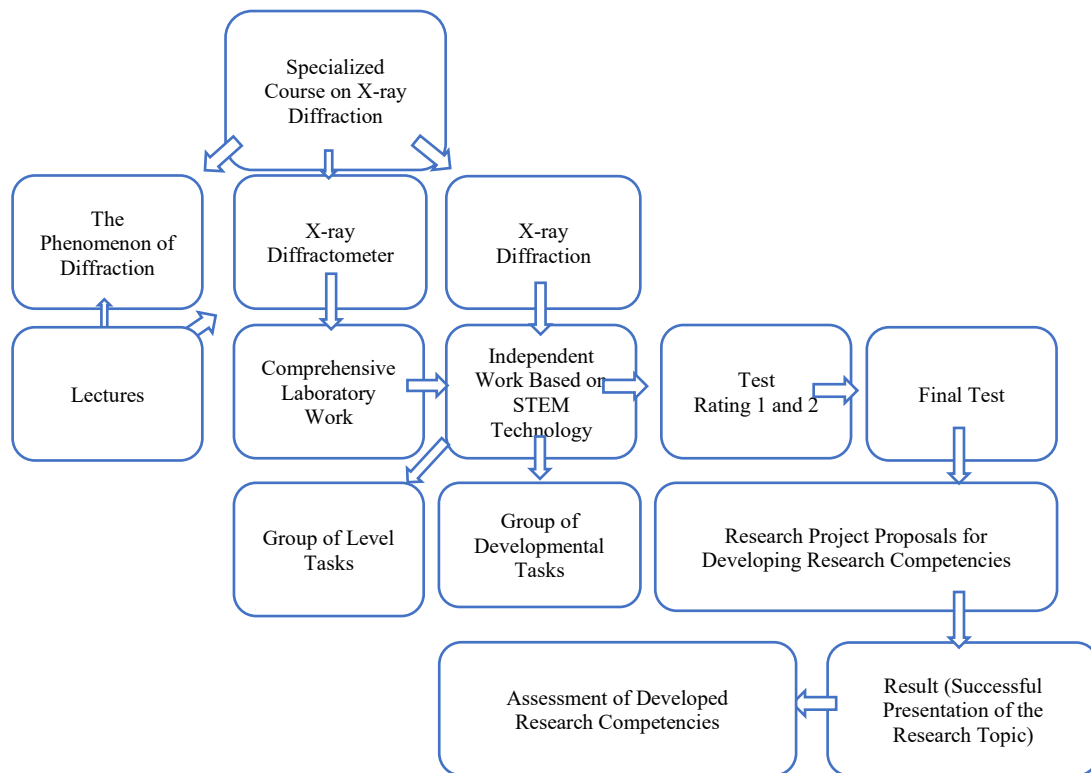


The methodology is implemented as part of a special elective course titled “X-ray Diffraction.” This elective is designed to develop and enhance research competencies in prospective physics teachers (Figure 3).

For future physics teachers, the development of research competencies is critically important. These skills not only enable effective organization of research activities in schools but also foster students' critical thinking, independence, and interest in science. A teacher equipped with well-developed research competencies can actively integrate modern scientific advances into the educational process, adapt teaching materials to current educational goals and students’ needs, and support students in conducting their own research projects.

Thus, the formation and development of research competencies in prospective physics teachers is one of the most essential components of professional training. It ensures high-quality teaching and contributes to the scientific development of students

Figure 3.
Model of the Elective Course



As mentioned above, the educational and methodological complex consists of a textbook, a methodological guide, and an electronic educational resource. The textbook titled "Theoretical Foundations of X-ray Diffraction" was approved by the University Academic Council and received a certificate of entry into the state register of rights to copyright-protected objects under number No. 42606 dated February 5, 2024.

The textbook comprises 10 chapters: 8 of them present the core theoretical material. The remaining 2 chapters cover topics for independent research projects and various reinforcing and developmental tasks. All tasks and exercises are developed using and incorporating key elements of STEM technology.

A teaching and methodological guide entitled “X-ray Diffraction Analysis: A Research Work Complex” was also developed. This guide serves as a continuation of the textbook.

Received a certificate of entry into the state register of rights to copyright-protected objects under number No. 53545 dated January 16, 2025.

The guide consists of three core practical and laboratory assignments. It also includes methodological recommendations for the instructor delivering the course. The guide outlines effective strategies for assessing laboratory work and provides evaluation criteria for various student tasks. In addition to these innovations, the guide offers an assessment sheet template, a student knowledge growth chart, and additional recommendations on writing conclusions and conducting engaging practical sessions.

Results

Research competencies represent a set of knowledge, abilities, and skills necessary for conducting independent scientific work and solving research problems. These competencies are particularly important for future teachers, as they enable not only active participation in research but also the effective organization of students' research activities. Research competencies comprise several key components (Table 1).

Table 1

Structure of Research Competences in Physics Education

Competence Type	Description / Components
Theoretical Competence	1. Mastery of the fundamentals of the scientific method and understanding of key scientific concepts and theories. 2. Understanding the principles and laws of physics, with the ability to systematize and analyze theoretical knowledge. 3. Ability to critically evaluate scientific sources and identify relevant data for research.
Methodological Competence	1. Knowledge and application of research methods (experiments, observation, modeling, mathematical modeling, statistical analysis). 2. Ability to select appropriate methods for specific research problems. 3. Ability to formulate hypotheses and define research aims and objectives.
Practical Competence	1. Ability to organize and conduct experiments, observations, and measurements, and analyze results. 2. Use of specialized equipment, software, and technologies in physics research. 3. Designing and implementing laboratory work and educational projects.
Information Competence	1. Skills in working with scientific and technical sources (databases, journals, monographs). 2. Ability to process, analyze, and interpret data using scientific and statistical tools. 3. Presentation of research results in reports, articles, and presentations.
Analytical Competence	1. Ability to analyze data, identify patterns, and compare with theoretical frameworks. 2. Critical evaluation of research findings, including identification of errors and biases. 3. Ability to draw conclusions and formulate recommendations for further research.
Communicative Competence	1. Ability to present research results effectively in oral and written form. 2. Proficiency in scientific communication (presentations, papers, conferences). 3. Ability to explain complex scientific concepts at different levels of understanding.
Project Competence	1. Ability to plan and organize research projects. 2. Development of research strategy, resource and time allocation, coordination of participants. 3. Ability to anticipate risks and adapt the project to changing conditions.
Reflective Competence	1. Ability to evaluate one's actions and research outcomes. 2. Awareness of strengths and limitations in scientific activity. 3. Openness to feedback and readiness to adjust approaches.

The above-mentioned competencies are developed and strengthened through a structured system of laboratory work, which plays a central role in the formation of research skills among students and master's students. In particular, Laboratory Work No. 3 was designed as a comprehensive task integrating theoretical knowledge, practical application, and analytical thinking.

The procedure of Laboratory Work No. 3 includes several последовательных этапов. First, students familiarize themselves with the theoretical materials related to X-ray diffraction. This is followed by the design of a sample, taking into account the operational procedures of

the device as demonstrated during Laboratory Work No. 1. Subsequently, students record the data generated by the software and perform a detailed analysis of the obtained values.

At the next stage, students carry out calculations using the given formula and compare the results with the software output. Special attention is paid to the comparison and analysis of diffraction patterns (diffractograms), which enables students to interpret experimental results. Based on this analysis, students describe the sample and identify the unknown material through comparison of diffraction patterns. They then provide a detailed description of the unknown sample, formulate conclusions, answer control questions, and present their laboratory work for evaluation.

Within the broader methodological framework aimed at developing research competencies in prospective physics teachers (using X-ray diffraction as an example), the educational process is organized as a последовательная система взаимосвязанных этапов. Initially, students are introduced to the objectives and goals of the elective course “X-ray Diffraction,” followed by an assessment of their prior knowledge. This diagnostic stage ensures alignment between students’ initial preparedness and the course content.

The next stage involves studying the theoretical foundations using specialized literature, such as the textbook “Theoretical Foundations of X-ray Diffraction,” and completing consolidation exercises on key topics, including the phenomena of X-ray diffraction. Practical training is then implemented through a series of laboratory works. Laboratory Work No. 1 focuses on familiarizing students with the operational principles of the X-ray diffractometer, while Laboratory Work No. 2 involves conducting X-ray diffraction analysis of aluminum. Laboratory Work No. 3 extends this experience by requiring students to analyze copper and identify an additional unknown component in the sample.

In addition to laboratory activities, students complete independent assignments incorporating elements of STEM technologies, solve differentiated tasks, and engage in developmental exercises aimed at enhancing higher-order thinking skills. Their progress is monitored through intermediate rating assessments, followed by a final evaluation of their knowledge and competencies.

An important component of the methodology is the inclusion of individual research work. Students are assigned research topics, conduct independent investigations, and present their findings in the form of presentations, thesis defenses, or academic articles. The level of research competency formation is then assessed, and students are encouraged to continue their scientific research activities, ensuring the sustainabilityPoint 1. The goal of the elective course “X-ray Diffraction” (“Рентген сәулесінің дифракциясы”) is to deepen students’ understanding of the phenomenon of X-ray diffraction while developing research competencies in prospective physics teachers.

Point 2. At the beginning of the academic year, before starting the course, master's and bachelor's students completed a diagnostic test on the topic “X-ray Diffraction” and a survey on “Research Competencies.” The average level of subject knowledge among students was 65.5%. The survey results indicated that most students had never visited the university’s Shared Research Laboratory and were unfamiliar with the concept of an X-ray diffractometer. In addition, they experienced difficulty listing the research competencies required of a physics teacher.

Point 3. During the elective course, master's and bachelor's students studied the textbook titled Theoretical Foundations of X-ray Diffraction (Рентген сәулесі дифракциясының теориялық негіздері), which was approved by the University Academic Council. Through the lectures presented in the textbook, students acquired essential theoretical knowledge related to the phenomenon of X-ray diffraction.

Point 4. Upon completion of the theoretical part, master's and bachelor's students completed reinforcement exercises on the topic The Phenomenon of X-ray Diffraction. The

results demonstrated a high level of understanding, with students scoring an average of 95 out of 100 points.

Point 5. To foster and develop research competencies in prospective physics teachers, an instructional-methodological guide titled X-ray Diffraction Analysis: A Set of Research-Based Laboratory Activities was developed in addition to the textbook. The guide includes three laboratory experiments along with a variety of tasks and problems based on STEM technology elements. A step-by-step procedure is provided for each lab, all of which follow a standardized structure from defining the objective to answering control questions.

For instance, Laboratory Work No. 3, titled Identification of a Second Unknown Element Through Diffraction Analysis, aims to determine an unknown element in a mixture using a copper X-ray diffraction sample under the guidance of a research supervisor. Equipment used: X'pert PRO X-ray diffractometer and a copper sample (with impurity).

As a result of the experiment, the students obtained the diffraction patterns (see Figures 4 and 5). The unknown element was identified as cobalt.

Figure 4.
Diffractogram No. 1

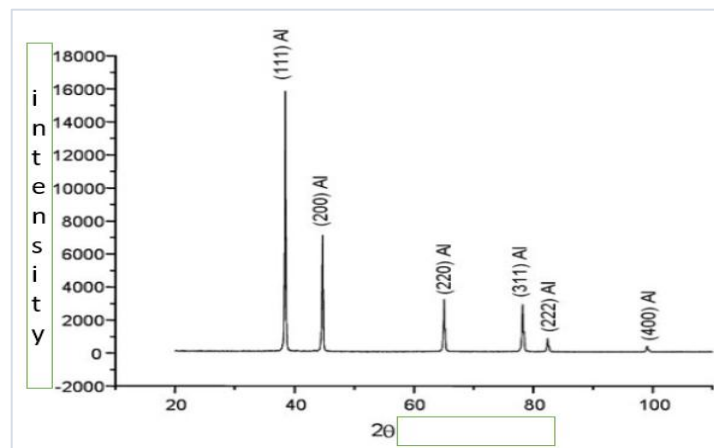
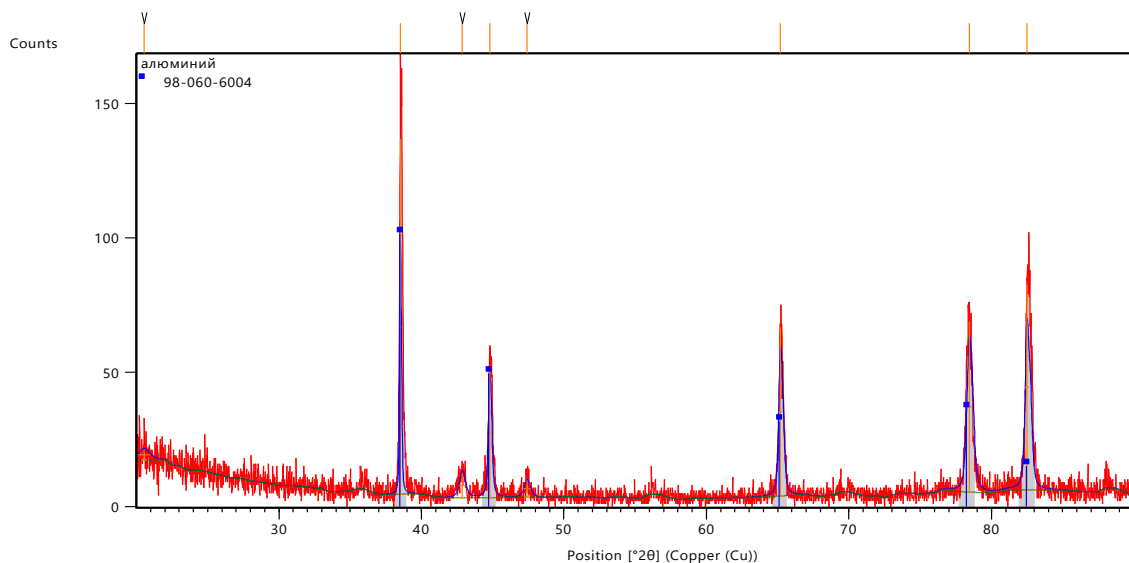


Figure 5.
Diffractogram No. 2



Point 6. Independent assignments based on elements of STEM technologies were completed. These assignments came in various formats. For example, the “Word Cloud” activity aimed to develop and reinforce students’ understanding of physics definitions and laws; “Build the Formula” targeted deeper knowledge of formulas related to the topic and other areas of physics. In addition, a range of test tasks incorporating innovative approaches was used.

Point 7. During the course, special attention was given to solving problems, with a primary focus on using the Bragg–Wulff formula. Differentiated tasks at three levels were provided. By solving each task, master's students would obtain a key word or term. As a result, upon completing the stage, they would collect various definitions of physical laws.

Point 8. Master's and undergraduate students successfully completed the stage involving developmental tasks.

Point 9. According to the plan, master's and undergraduate students completed Rating 1 and Rating 2 assessments. Both were passed as credit-based evaluations.

Point 10. At the end of the main stages of the elective course, a final assessment was conducted to evaluate the level of students’ knowledge. The knowledge quality reached 100%. Thus, it can be concluded that the goal of the course was achieved.

Point 11. To support further independent research activity, topics for research projects were assigned.

Point 12. Master’s and undergraduate students continued working on their projects under the guidance of academic advisors.

Point 13. A master's thesis defense on the topic is planned.

Point 14. An analysis of the results showed that the level of research competency development among students was rated as “excellent.” During interviews with students, positive feedback was received regarding the course and the relevance of the topic.

Point 15. Master’s students plan to pursue doctoral studies in the scientific-pedagogical track, while undergraduate students intend to apply for master's programs.

Discussion

The aim of this study was to demonstrate the effectiveness of a methodological model for developing research competencies in prospective physics teachers through laboratory work on X-ray diffraction. The following tasks were addressed during the course of the research: (1) the development and presentation of the methodological model, (2) the implementation of the proposed methodology with master’s and bachelor’s degree students enrolled in physics and mathematics programs, and (3) the evaluation of the outcomes of the pedagogical experiment in order to analyze changes in the level of knowledge and research skills.

The results of this study, centered on structured laboratory work in X-ray diffraction (XRD), align with the global shift toward research-oriented teacher education. While (Mešić et al., 2021) advocate for the use of desktop XRD units to simplify the experimental process for students, our methodology emphasizes a deeper immersion into the full analytical cycle. Unlike their approach, which focuses on simplified data interpretation, our laboratory framework requires future teachers to master the transition from sample preparation to the final structural analysis, ensuring a more comprehensive development of research competencies.

A significant point of divergence is found in the role of simulation. (Kin et al., 2022) prioritize "digital twin" environments to build procedural knowledge. While virtual labs offer accessibility, our findings suggest that physical interaction with the diffractometer is indispensable for future physics teachers. The tactical experience of aligning samples and troubleshooting real-time hardware issues-aspects often absent in digital twins-provides a level of professional autonomy that prepares educators for real-world laboratory management.

Furthermore, our didactic sequence expands upon the "theory-to-practice" model proposed by (Bunaciu et al., 2015). While they focus on the conceptual transition from diffraction laws to materials science, our work introduces a competency-based assessment at each stage of the lab. This allows for a quantifiable measurement of how a student's ability to hypothesize and verify results evolves through repeated XRD cycles.

In summary, while international trends lean toward digitalization and simplified instrumentation, our methodology reinforces the necessity of "hands-on" experimental physics. This approach ensures that future teachers are not merely users of technology, but researchers capable of designing and implementing complex experiments in their future professional practice.

The results of the pedagogical experiment confirmed the hypothesis that the use of laboratory work contributes to the development of research competencies. Students in the experimental groups demonstrated a higher level of understanding of both the theoretical and practical aspects of X-ray diffraction. These findings are consistent with conclusions drawn in the work of (Prokopets, 2021), which emphasizes the importance of methodological approaches in educational practice, as well as (MIT OpenCourseWare, 2023), which highlights the significance of hands-on experiments in studying complex physical phenomena.

Moreover, our approach aligns with the recommendations of (Ndihokubwayo et al. 2020), who argue that the use of experimental methods in education enhances students' skills in analyzing and synthesizing information. The application of statistical analysis, as suggested in the study by (Nghiem-Phú and Nguyễn, 2022), confirmed the reliability of the obtained results, allowing for an objective evaluation of the method's effectiveness.

Thus, the conducted study contributes to the development of educational technologies aimed at fostering research competencies. However, there remain prospects for further work, including expanding the participant sample, developing additional laboratory activities, and integrating them into teacher training programs. Future research could also explore the impact of digital tools on the development of research skills, which is a relevant issue for modern educational programs.

For example, by applying the acquired knowledge in practice, a novice teacher achieved success in their professional activity. In particular, they prepared prize-winners for a Republican scientific and practical conference. This indicates that the physics teacher developed and enhanced their research competencies and skills gained through the implemented methodology.

For instance, in the 2021–2022 academic year, a 10th-grade student won 2nd place at the district stage of the Republican Science Project Competition in general education subjects with a project titled "The Phenomenon of Deformation in Household Conditions." In the 2022–2023 academic year, another 10th-grade student won 1st place at the district stage of the same competition with a project titled "Supplying Shopping Centers with Electricity Using Piezoelectric Elements," and was recommended for participation at the regional level. In addition, a team of 11th-grade students took 1st place in the district Physics Tournament "Physics Battle," where students from 12 schools participated. In the 2023–2024 academic year, an 11th-grade student won 3rd place at the regional stage of the Republican Science Project Competition and was recommended for the national stage, where they ultimately received 3rd place (awarded with a third-degree diploma, a bronze medal, and the Shakarim Educational Grant from Shakarim University in Semey). Also, in the same academic year, a 10th-grade student took 1st place at the district stage of the competition with a project titled "Development of a Waste Sorting System for Industrial Enterprises," and was recommended for the regional stage. In the 2024–2025 academic year, this student, now in 11th grade, is participating in the regional stage of the competition.

Conclusion

This paper proposes a method aimed at developing research skills in prospective physics teachers through the study of the X-ray diffraction unit within the physics curriculum. A task-based system was designed, including specially selected problems and laboratory activities, all aligned with the goals of the study. The conducted research demonstrated that this system and the methodology for its implementation are indeed effective. Theoretical foundations for preparing future teachers for research activities were identified based on the analysis of psychological-pedagogical and methodological literature on the topic. It was confirmed that the ability to conduct research is a crucial component of professional training for future physics teachers. The importance of STEM education in fostering research competencies was emphasized, and scientifically grounded criteria for assessing the levels of research skill development were established. The proposed model can serve as a reference for other natural science disciplines.

It has been demonstrated that the research skills of physics students as an integral part of their personality, representing a harmonious combination of a persistent drive for scientific inquiry in the field of physics and the ability to apply physical methods in conducting research can be effectively developed through the integration of STEM elements within laboratory practicums focused on X-ray diffraction. The incorporation of such elements into physics laboratory work in general, and into X-ray diffraction practicums in particular, promotes the development of research competencies among physics students, preparing them for independent scientific work in the later stages of their university education. In turn, this contributes to the advancement of research skills in future physics teachers.

During the course of the study, a set of research competencies essential for prospective physics teachers was systematically identified. Based on this framework, a set of criteria for assessing the level of research competence development was established, including: motivation to engage in research activities; interest in working with scientific literature; initiative in identifying and solving research problems; consistency and awareness in the implementation of research stages; ability to conduct competent analysis of research results; capacity for justified evaluation of obtained findings; logical presentation and defense of research outcomes; and readiness to integrate research activities into future professional practice.

Building upon these competencies and evaluation criteria, a methodology for assessing the level of research competence development among prospective physics teachers was developed. The results of the study demonstrate that the implementation of the proposed instructional model based on laboratory work in X-ray diffraction serves as an effective pedagogical tool for enhancing research competencies in both undergraduate and graduate students.

The study yielded the following key findings. First, participants were introduced to the conceptual and methodological framework underpinning the proposed model. Second, the practical implementation of the methodology was carried out in groups of bachelor's and master's degree students, allowing for the validation of its applicability in different educational contexts. Third, a comparative assessment of the dynamics of knowledge quality and research competence development was conducted, which enabled the verification of the main research hypotheses.

The results of the pedagogical experiment confirmed the effectiveness of the proposed methodology. In particular, a statistically significant improvement in academic performance was observed, with an overall increase of 34.5% among both undergraduate and graduate students (see Figure 6). This outcome indicates the high potential of integrating research-oriented laboratory practices into physics teacher education programs.

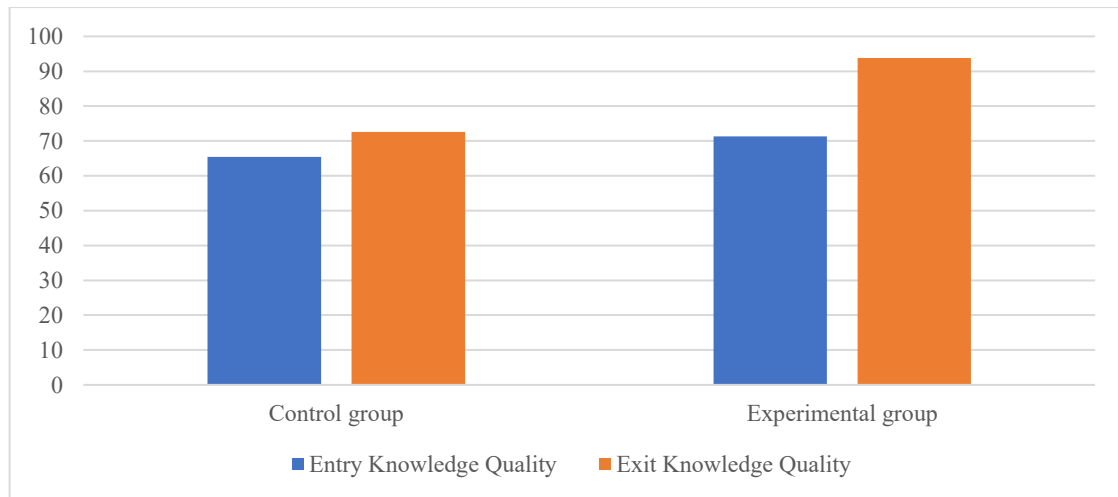


Figure 6. Graph of academic performance quality

Based on the data obtained, we developed a methodological model for fostering research skills in prospective physics teachers using a STEM-based approach. This methodology was successfully integrated into the undergraduate and graduate programs in Physics, Physics and Computer Science, and Physics and Mathematics at S. Amanzholov East Kazakhstan University and Khoja Akhmet Yassawi International Kazakh-Turkish University.

Conflict of Interest Statement

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

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