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Scientific and methodological foundations for enhancing the research competencies of future physics teachers using x-ray diffraction as an example

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The main purpose of this article is to develop a model and prepare methodological foundations for forming the research competencies of future physics teachers, demonstrated through the example of X-ray diffraction. The work examines the methodological basis for developing research competencies in prospective physics teachers. The research was carried out using X-ray diffraction, identifying effective ways to introduce research orientation into the teacher training process. During the pedagogical experiment, the authors developed a special STEM-based course, "X-Ray Diffraction," describing its structure and content. The experimental work was conducted at S. Amanzholov East Kazakhstan University and Khoja Ahmed Yassawi International Kazakh-Turkish University. Participants included university lecturers, bachelor's and master's students, and school teachers from East Kazakhstan and Abai regions. The findings showed that the level of research competencies among prospective teachers was insufficient. The proposed methodological model consists of four components: target, structural–content, practical, and diagnostic–result. This model ensures the integration of theoretical knowledge and practical skills, contributing to the formation of research thinking and research culture. The special course includes lectures, laboratory activities, independent work, and research tasks. The developed methodological system improves the professional preparation of future physics teachers, increases interest in research activities, and facilitates the integration of physical experiments into the educational process. A methodological model for developing research competencies through the example of diffraction phenomena was created. A set of laboratory works using an X-ray diffractometer was developed. A pedagogical experiment was conducted to test the hypothesis, and its results were substantiated.

KEYWORDS
laboratory work, methodology, model, pedagogical experiment, physics teachers, scientific research

1 Introduction

Scientific, engineering, and technological fields are rapidly evolving worldwide, making the development of highly competent specialists a national priority. On April 12, 2024, during a meeting of the National Council for Science and Technology, the President of the Republic of Kazakhstan, Kassym-Jomart Tokayev, emphasized the need for specialists with comprehensive competencies to ensure international competitiveness. In line with this, Article 8 of the Law of the Republic of Kazakhstan “On Education” (No. 319-III, July 27, 2007) highlights that state education policy must ensure program competitiveness and support the development of professional competencies among pedagogical personnel.

Improving the quality of teacher preparation is therefore a key focus in Kazakhstan. Rapid technological progress and the integration of innovations present new challenges for physics teachers, particularly in fostering students’ research skills and critical thinking. However, insufficient research competence among pedagogical university students remains a pressing issue. Article 4 of the Law No. 79-VIII (May 6, 2024) “On Amendments and Additions to Certain Legislative Acts in the Field of Science and Education” identifies the development of research skills in specialists as a national priority.

Strategic documents, including the State Program for the Development of Education (2020–2025) and the State Compulsory Standard of Higher and Postgraduate Education (Order No. 2, July 20, 2022), stress the importance of training teachers capable of conducting research and analysis. Despite reforms such as Kazakhstan’s transition to the Bologna system in 2018, current funding and methodological support remain insufficient to fully develop high-level competencies, highlighting the relevance of modern approaches in teacher education to cultivate research skills among future physics teachers.

International research highlights the significance of developing teachers’ research competencies for improving professional development and teaching quality (Dubovicki and Jukić, 2017; Fernández-Batanero et al., 2022; Kin et al., 2022). Research abilities help teachers integrate scientific methodologies into the learning process and cultivate students’ critical and creative thinking (Hattie, 2017; Savery, 2016; Imbert Romero et al., 2024).

In Kazakhstan, the development of research competencies among prospective teachers is an urgent task (Berikkhanova et al., 2023; Bukusheva et al., 2023; Dosymov et al., 2025). Action research and digital learning technologies demonstrate strong potential for enhancing professional competencies (Howard et al., 2021; Nurizinova et al., 2024).

One of the most effective methods for forming research competencies in physics teacher training is integrating concrete physical phenomena and experiments into instruction (Maulana, 2020; Widiyanto et al., 2021; Yilmaz, 2022). X-ray diffraction is especially valuable as it develops theoretical understanding as well as experimental and analytical skills (Bunaciu et al., 2015; Aragón et al., 2019; Mešić et al., 2021). Research shows that X-ray diffraction–based learning assignments promote deep comprehension of physical processes and mastery of scientific methods (Saprudin et al., 2019; Dalabayev et al., 2025). Integrating practical activities with project-based and STEM approaches has proven effective (Selisne et al., 2019; Widiyanto et al., 2021; Qiuhui and Thitinant, 2023). The use of digital resources and virtual laboratories also accelerates the development of research competencies (Freese et al., 2023; Nurizinova et al., 2022; Kozhabekova et al., 2025).

Therefore, developing methodological foundations to enhance the research competencies of future physics teachers using X-ray diffraction is both relevant and effective. This approach fosters research culture, mastery of experimental methods, and deeper understanding of physical laws (Dalabayev et al., 2025; Bunaciu et al., 2015; Aragón et al., 2019; Kurbanbekov et al., 2025).

However, in the available literature, there are no works aimed at solving the above-mentioned issue through the use of existing scientific equipment and devices (Figure 1). Moreover, at present, most universities are equipped with experimental analytical instruments that operate on one or another physical principle. In particular, devices such as X-ray diffraction instruments are based on the principle of diffraction of electronic and X-ray waves. These instruments are mainly used to solve problems within scientific research projects. They are poorly applied in the development of students’ research competencies. Some authors have attempted to use the laws of wave optics and the phenomena of interference and diffraction of waves to develop critical thinking in future physics teachers. The authors noted that the section on wave optics in the general physics course requires further consideration as a model for developing methodological foundations in the training of future physics teachers. Moreover, this leads to an increase in students’ general knowledge level in wave optics.

To address the issue of training future physics teachers and forming their research competencies, the question arises as to which sections of physics should be selected. We chose the diffraction phenomenon as an example for this purpose.

In addition, as shown by the results of the work by Dalabayev et al. (2025), X-ray diffractometry, as one of the most rapidly developing experimental and analytical methods for studying materials, directly influences the formation of research competencies. However, an analysis of the available literature shows that higher education institutions’ educational programs lack methodologies for conducting laboratory work on the topics of “electron diffraction” and “X-ray diffraction.”

In our view, the integration of diffractometers into the educational process using STEM technologies, combined with other innovative teaching approaches, will be effective in developing the research competencies of future physics teachers.

Diffraction is one of the fundamental phenomena of physics, the study of which requires deep understanding and analytical skills. Its application in various scientific fields such as nanotechnology, optics, and materials diagnostics makes it particularly important in the learning process. The use of diffraction in education provides opportunities to integrate theoretical knowledge with practical skills, which contributes to the development of research competencies in future teachers.

Thus, developing methodological foundations aimed at forming the research competence of future physics teachers through the study of the diffraction phenomenon is of particular importance. This research contributes to enhancing teachers’ qualifications, updating educational programs, and integrating scientific achievements into the educational process.

However, during the study it was revealed that there is no interaction between university scientific laboratories and university

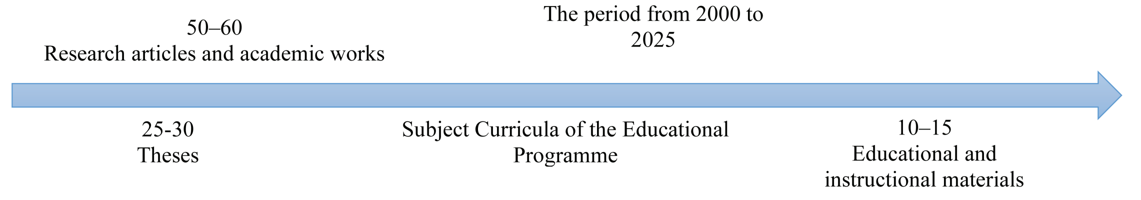

FIGURE 1
Literature review.

students, and many students reported in the survey that they had never visited the laboratories at their institutions. Future physics teachers also struggled to provide a definition of X-ray diffraction. This indicates an insufficient level of knowledge among students in this area. At the search stage, it became clear that future teachers had not mastered the concept of scientific research, the planning of research work, and other fundamental notions. From this, it can be observed that the level of research competence among future physics teachers is low or not formed at all. Thus, the analysis of the main results of the pedagogical experiment made it possible to identify the following issues:

- the absence of a connection between scientific laboratories and students;
- the lack of a system that integrates university-based scientific laboratories into the educational process to engage students in research activities;
- the non-use of available and actively functioning specialized equipment for practical purposes in the educational process;
- the low level of research competence among future physics teachers and the absence of proposed methodological foundations for developing this competence;
- the low level of knowledge among university students in the field of X-ray diffraction, and other related issues.

Thus, these contradictions reveal the existence of an urgent and significant problem. To address these contradictions, the research was titled “Developing methodological foundations for forming the research competence of future physics teachers through the example of the diffraction phenomenon.” Its central problem is to develop a methodology for forming the research competence of future physics teachers and to demonstrate it through the example of X-ray diffraction. The main conclusions and results of this work are presented in the publication by Dalabayev et al. (2025). Recent studies in physics education emphasize the integration of innovative technologies to enhance students’ learning outcomes and research competencies. For instance, B. Kurbanbekov et al. (2025) investigated the impact of virtual reality (VR) technology on students’ understanding of body acceleration, demonstrating significant improvement in conceptual knowledge and engagement. This study highlights the potential of immersive and interactive tools in promoting deep learning and experimental reasoning.

The study also justified why X-ray diffraction was chosen for developing methodological foundations for forming the research competence of future physics teachers. To eliminate the identified shortcomings, one of the main tasks is to study the diffraction phenomenon in depth and implement it using a diffractometer. A review of the literature showed that in the context of scientific-pedagogical research, there are no works that examine X-ray diffraction as an example; existing studies focus either solely on pedagogy or solely on scientific aspects.

The aim of the research is to develop a model and methodological foundations for forming the research competence of future physics teachers and to demonstrate it through the example of an X-ray diffractometer.

The research hypothesis is that if methodological foundations for forming the research competence of future physics teachers are developed, then the research competence of future physics teachers will improve, leading to a higher level of professional preparation among young specialists.

Research objectives:

1. To develop a model of the methodological foundations for forming the research competence of future physics teachers through the example of the diffraction phenomenon.
2. To create a set of laboratory works that develop research competencies using an X-ray diffractometer.
3. To design methodological foundations for forming the research competence of future physics teachers through the example of the diffraction phenomenon.
4. To conduct a pedagogical experiment to test the research hypothesis.

2 Materials and methods

To address the above objectives, a combination of research methods was employed. In addition, the advanced world-class pedagogical experiment methodology proposed by educator-scholar John Hattie was used.

2.1 Theoretical methods

Analysis and study of physical, natural science, philosophical, psychological-pedagogical, scientific-technical, and methodological literature; dissertation research; analysis of educational standards and other methodological documents of higher education institutions; conducting comparisons and identifying analogies; synthesis; systematic analysis; integration; generalization; a systemic approach; modeling pedagogical

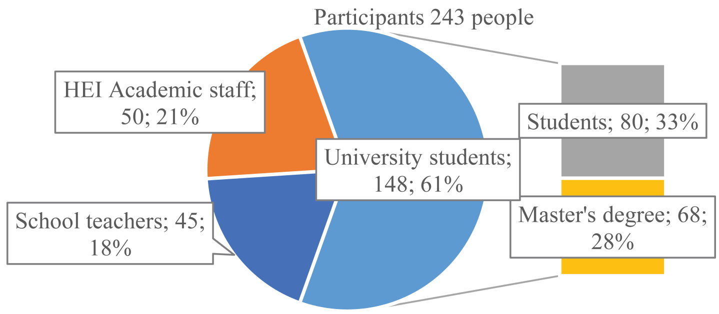

FIGURE 2
Participants of the study.

situations; analyzing innovative pedagogical practice (Hattie, 2017).

2.2 Experimental methods

Observation, interviews, testing, and surveying of physics teachers, students, and university lecturers; expert evaluation of developed materials; conducting a pedagogical experiment (Hattie, 2017).

Research base:

The pedagogical-practical work was conducted at Sarsen Amanzholov East Kazakhstan University and Khoja Akhmet Yassawi International Kazakh-Turkish University, involving university lecturers (50), students, and master's students (148) (Figure 2).

2.3 Additional participants in the pedagogical experiment

The "Orleu" National Center for Professional Development (Professional Development Institute branch for East Kazakhstan Region), School No. 29 in East Kazakhstan Region and School No. 22 in Abai Region.

Research Materials (Tools and Equipment): The study materials included the university's material and technical base, the National Scientific Research Laboratory for Collective Use (NSRLCU), a PANalytical X'Pert Pro X-ray diffractometer, and the operator.

Research—Observation Work The study involved students from the Bachelor's program 6B015 "Teacher Training in Natural Sciences" at Sarsen Amanzholov East Kazakhstan University, including the B010 "Physics Teacher Training" 6B01502 Physics Education program. In addition, master's students from the 7M015 "Teacher Training in Natural Sciences" program, including M011 "Physics Teacher Training" 7M01502 Physics Education program, of the same university participated.

Furthermore, students from the Bachelor's program 6B015 "Teacher Training in Natural Sciences" at Khoja Akhmet Yassawi International Kazakh-Turkish University, including B010 "Physics Teacher Training" 6B01520 Physics Education program, as well as master's students from the 7M015 "Teacher Training in Natural Science" program, including M011 "Physics Teacher Training" 7M01520 Physics Education program, were observed.

3 Research results

The professional development of teachers is implemented within the framework of state programs and strategies, such as the State Program for the Development of Education and Science of the Republic of Kazakhstan, the "Educated Nation" national project, and the Presidential addresses of the Republic of Kazakhstan aimed at modernizing the education system. These documents emphasize the professional development of teaching staff, the development of educational infrastructure, and the integration of international experience, while defining the priorities of teacher training.

Pedagogical higher education institutions in Kazakhstan, relying on state support and introducing modern educational technologies, are creating conditions for training highly qualified teachers capable of contributing to societal development and the future of the country.

In shaping scientific worldview, developing critical thinking, and preparing students to solve complex problems related to contemporary scientific and technological challenges, the natural science and mathematics cycle of subjects, including physics, plays a key role. These subjects provide the fundamental knowledge necessary to understand natural phenomena, develop technologies, and apply them in practice. The role of subjects in the natural science-mathematics cycle can be summarized as follows:

Developing scientific literacy: Natural science subjects help students understand fundamental laws of nature, such as chemical reactions, biological processes, and physical phenomena. This contributes to forming a holistic understanding of the world around us.

Developing mathematical thinking: Mathematics, as a core subject, develops logical and abstract thinking, data analysis, and the ability to make predictions, which are essential in any professional field.

Preparing for modern professions: Subjects within the natural science-mathematics cycle provide foundational knowledge necessary for careers related to engineering, information technology, medicine, ecology, and many other fields.

Forming key competencies: Students learn to design experiments, analyze results, and model situations, which helps develop research skills and the ability to solve practical problems.

The significance of the research was first confirmed through a review and analysis of literature and previous studies, after which the main part of the pedagogical experiment began. Initially, a survey was conducted to determine the level of

TABLE 1 Survey for university teachers.

For university teachers SURVEY *"Dear Colleague! We kindly ask you to provide complete answers to the questions presented below."*						
Teacher's full name:.						
Total number of students:. . .. . of which the number of groups in the Physics major:.						
Please assess how well the skills listed below have been developed in your students using a five-point scale. We kindly ask you to place a " + " sign in the appropriate column.						
No.	**Assessable Research Competency**	**1**	**2**	**3**	**4**	**5**
1	Collection and Systematic Analysis of Scientific Data					
2	Ability to Make Preliminary Hypotheses					
3	Setting Personal Goals for the Research Topic					
4	Defining the Objectives of the Research Work					
5	Defining the Subject and Object of the Research					
6	Ability to Present One's Perspective					
7	Applying Observation or Other Research Methods					
8	Implementing or Organizing the Research Work					
9	Analyzing the Results of Scientific Research Work					
10	Documenting and Presenting the Results of Scientific Research Work According to Requirements					
Thank you for taking the time to respond to the survey!						

TABLE 2 Survey for students and master's students.

Survey for Students and Master's Students *Dear student! Please provide complete answers to the questions below.*		
No	**Question**	**Answer**
1	Provide the definition of the phenomenon of diffraction:	
2	What is the difference between geometric optics and wave optics?	
3	Are you familiar with the concept of X-ray diffraction?	1- Yes 2- No 3- I forgot. If you are familiar with it, please provide the definition:
4	Please present the formula based on Bragg-Wulf theory:	1-2dsinθ = nλ 2-5dsinθ = 2λ 3- I find it difficult to answer
5	In what year did Conrad Röntgen discover the properties of X-rays?	1-1900 2-1895 3-1850
6	Is it necessary to develop the methodological foundations for forming research competencies of future physics teachers using the phenomenon of diffraction as an example?	1-necessary 2-not necessary 3- I find it difficult to answer If necessary, why?
7	Have you been to the National Scientific Laboratory for Collective Use?	1- yes 2-no 3- I have no information about the laboratory if you are, for what purpose
8	Are you familiar with the X-ray diffractometer equipment at the national scientific research laboratory for collective use based at Sarsen Amanzholov East Kazakhstan University?	1-yes 2-no 3- I find it difficult to answer "If you are familiar, could you please describe the structure and working principle of the X-ray diffractometer?"
9	Are you engaged in scientific research activities?	1-I am currently engaged in it. 2-I have not been involved in scientific research activities. 3-There is no demand for scientific research activities. Why have you not been involved in scientific research activities?
10	Did you encounter any known or unknown difficulties during your involvement in scientific research activities?	1- Yes, difficulties arose 2- No, difficulties did not arise. 3- I find it difficult to answer If difficulties arose, what difficulties did you encounter?
Thank you for taking the time to respond to the survey!		

research competencies of future physics teachers, to understand their perspectives on the issue, and to further substantiate the relevance of the topic. The survey addressed general knowledge of the diffraction phenomenon and the concept of research competence (Table 1). Additionally, the connection between university laboratories and students was explored.

The survey for students and master's students is one of the main components of the pedagogical experiment. The survey proved effective in clarifying the research topic and main issues, revealing additional perspectives, and obtaining a critically informed view of the situation. The survey included the following questions and discussions (Table 2).

The survey questions included both open-ended and closed-ended types. For open-ended questions, students and master's students were not limited to selecting only the provided options; they were also able to express their own opinions and explain why they chose a particular option. This approach ensured the academic integrity of the survey and contributed to the overall effectiveness of the study.

The survey addressed the main questions presented in Table 3. To conduct the research systematically, the observed students and master's students were divided into groups A, B, C, and D. Based on the main research plan, the surveys and the effectiveness of the physical practicum were organized according to the acquisition of the proposed educational and methodological materials. Accordingly, the groups were classified as A and B, and C and D. Information about the observed groups is presented in Table 3.

Six groups participated in the pedagogical experiment, with three designated as control groups. The experimental groups were labeled A, B, C, and D. Groups A and B served as the initial control groups, focusing only on mastering the educational materials and completing the assigned tasks. Groups C and D completed the full physical practicum (Table 3).

The primary goal was to compare the groups and assess the development of research competencies in future physics teachers by analyzing the "before and after" changes.

In Table 3, the sections mastered by the initial groups A and B and the control groups C and D, based on the proposed methodological foundations, are presented.

The specialized course in the educational materials, which is a key component of the pedagogical experiment conducted at the end of the study, predominantly covers topics in scientific physics. However, modifications and additions are allowed to adapt these topics toward a scientific–pedagogical orientation.

For example, Topic 1 covers the X-ray diffraction analysis and study of the strength properties of copper; Topic 2 focuses on the X-ray diffraction analysis and study of the strength properties of aluminum; and Topic 3 presents examples of encountering the diffraction phenomenon at home and independent laboratory work for secondary school students.

Initially, students master the theoretical content of the practicum as presented in the educational materials. After mastering the theoretical materials and providing full answers to the control questions, students proceed to developmental tasks aimed at forming and enhancing their research competencies. The quality of these tasks also allows the instructor to evaluate the mastery of the theoretical material. Next follows the set of theoretical assignments.

The survey for university faculty members stands out for its precision. It includes ten evaluation categories. At the end of the survey, all points are totaled and submitted for the statistical processing stage of the pedagogical experiment. This allows for a comprehensive examination of the research topic and helps clarify its direction.

The survey was conducted among students and master's students of Sarsen Amanzholov East Kazakhstan University and Khoja Akhmet Yassawi International Kazakh-Turkish University (148 participants), among university faculty members (50 participants), and among physics teachers from various schools in East Kazakhstan and Abai regions (a total of 54 participants, of which 51 were from general education schools).

TABLE 3 Comparative table.

Completed tasks	Groups A and B	Groups C and D
Mastering the theoretical sections of the educational materials	+	+
Physics dictation	+	+
Word cloud	+	+
Construct formulas	+	+
Physics rebus puzzle	+	+
Mastering the set of laboratory works from the educational and methodological materials	-	+
Laboratory work No 1	-	+
Laboratory work No 2	-	+
Laboratory work No 3	-	+

The results of the survey conducted among physics teachers in general education schools of the Republic of Kazakhstan are shown in Table 4.

In general, the surveys conducted during the research contributed significantly to the study. Among them, the survey administered to physics teachers, as mentioned above, had a substantial impact on guiding the research in the right direction. Physics teachers, drawing on their own experience, provided responses that suggested ways to address other issues in the future and engage with them further. This indicates not only the development of research competencies but also highlights the insufficient level of other competencies. However, it is not possible to address all issues simultaneously. Therefore, it was determined that the formation of research competencies should be prioritized.

Teachers of various ages and with different lengths of teaching experience participated in the survey. This diversity allowed respondents to provide critical answers from multiple perspectives. In this way, the differing viewpoints of experienced teachers and young professionals were clarified. The oldest participant in the survey was a 65-year-old teacher, while the youngest had only 1 year of teaching experience. Respondents included teachers ranging from the standard pedagogical qualification to the "teacher-master" category, and some held academic degrees. This ensured a comprehensive and sufficiently in-depth consideration of the topic.

The research sites served as the primary locations for conducting the pedagogical experiment. The number and quality of university students and master's students (future physics teachers) contributed significantly to the effectiveness of the study. In addition to the research sites, the number of participants in the pedagogical experiment was also sufficient. Educational institutions from several regions of the Republic of Kazakhstan participated. This indicates the importance of the study and the urgency of addressing the issues it examines.

In the first stage of the pedagogical experiment, all bachelor's and master's students were fully involved (Table 5). However, the "pre-test" and "post-test" assessments conducted during the first and third stages of the pedagogical experiment were carried

TABLE 4 Survey for physics teachers of general education institutions.

SURVEY for Physics Teachers of Secondary Schools in Abai Region Purpose: To determine the significance of the topic *"Developing the Methodological Foundations for Forming Research Competencies of Future Physics Teachers Using the Diffraction Phenomenon as an Example."*		
No	Question	Answer
Section 1		
1	Full name	
2	Age (years)	
3	Place of work (School)	
4	Education	
5	Specialty	
6	Academic degree	
7	Academic Title	
8	Qualification category	
9	Teaching experience (years)	
10	Contact phone number	
Section 2		
1	In your opinion, what is the level of preparation of future physics teachers?	1.1() Low 1.2 () Medium 1.3 () High Reason:
2	What factors affect the quality preparation of future physics teachers?	2.1 () Qualified faculty members 2.2 () University material and technical base 2.3 () High-quality and modern elective courses Reason:
3	Which teaching technologies should be used in elective courses (or special courses)?	3.1 () Advanced innovative technologies 3.2 () STEM technologies 3.3 () Traditional teaching technologies Reason:
4	What determines the formation of research competencies of future physics teachers?	4.1 () Quality of the special course 4.2 () Pedagogical approaches 4.3 () Use of active learning methods Reason:
5	What role does laboratory practicum play in the formation of research competencies of future physics teachers?	5.1 () Primary role 5.2 () Secondary role 5.3 () Difficult to answer Reason:
Section 3		
1	In your opinion, is the problem of low research competency levels among future physics teachers significant?	Reason:
2	Do you think the topic *"Developing the Methodological Foundations for Forming Research Competencies of Future Physics Teachers Using the Diffraction Phenomenon as an Example"* is important?	
3	Your suggestions related to the topic above:	
4	In your opinion, what other issues exist in the process of preparing future physics teachers?	
Thank you for taking the time to respond to the survey!		

out only with bachelor's students, as the special course was offered specifically to them. Nevertheless, all master's and bachelor's students (148 participants) took part fully in the survey and discussion processes. This comprehensive involvement had a positive effect on thoroughly addressing and substantiating the research problem.

As shown in the table above, the "control" and "experimental" groups in the pedagogical experiment were each divided into six subgroups (Table 6). This division was made to ensure the full implementation of the pedagogical experiment in this study, following the methodology for conducting pedagogical experiments proposed by Australian educational researcher, Professor John Hattie.

The renowned scholar John Hattie introduced the concept of a "conceptual question" in his proprietary methodology for conducting pedagogical experiments (Hattie, 2017). This concept involves grouping several open and closed questions together to obtain meaningful results. The conceptual questions encompassed all open and closed questions included in the surveys described above. In this study, the pedagogical experiment grouped the questions into three conceptual questions.

The surveys conducted during the pedagogical experiment adhered to the principles of academic integrity and ethical standards. All individuals and organizations participating in the research provided consent for the processing of their information. Additionally, the calculation of experimental error was carried out

TABLE 5 Information about students and master's students.

No group number	Educational program code	Group name in pedagogical experiment	Number of students in groups
1	7M01502	A-1	12
2	6B01502	B-1	8
3	6B01502	B-2	15
4	6B01508 Mathematics - Physics	A-2	18
5	6B01511 Mathematics - Computer science	A-3	21
6	6B01520	C-1	20
7	6B01520	C-2	13
8	7M01520	D-1	22
9	6B01509 Physics - Computer science	C-3	19
Number of participated groups 9			Total number of students 148

TABLE 6 Information about participant groups.

Pedagogical experiment participants	Control group						Experimental group					
Number of participants	72						76					
Groups	1	2	3	4	5	6	1	2	3	4	5	6
Number of students	12	10	11	12	12	15	13	10	13	13	12	12

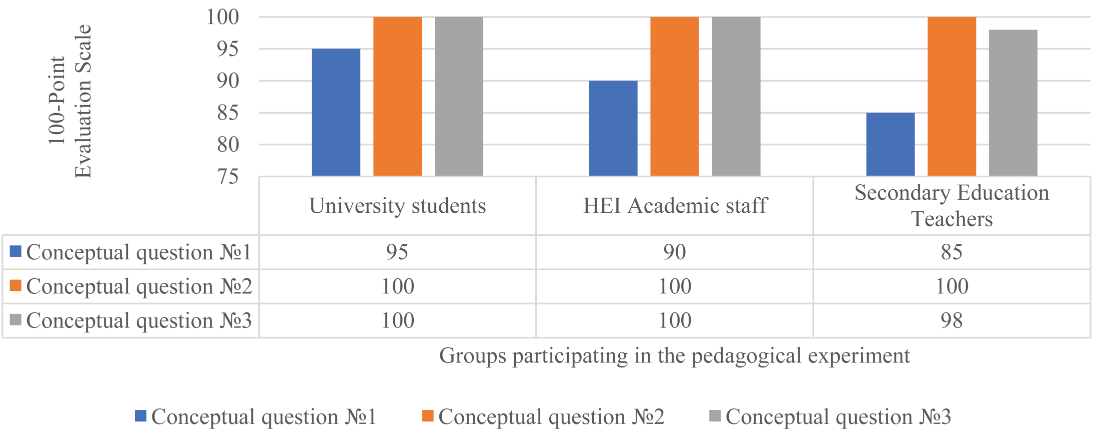

FIGURE 3
General survey results.

in accordance with the methodology proposed by Hattie (2017). By grouping the survey questions based on this approach, the study organized them into three conceptual questions, which allowed for the presentation of the following key results.

Students and master's students responded to the conceptual questions as follows (Figure 3).

For the first conceptual question, 141 respondents stated that physics students experience difficulties in conducting research; 7 respondents found it difficult to answer.

For the second conceptual question, 148 respondents indicated that they do not know the operating principle of an X-ray diffractometer.

For the third conceptual question, all 148 respondents agreed that *"developing the methodological foundations for forming research competencies of future physics teachers using X-ray diffraction as an example"* is a relevant issue.

University lecturers who participated in the pedagogical experiment responded to the main conceptual questions as follows. 45 respondents stated that physics students face problems in research activities; 5 respondents found it difficult to answer. All 50 respondents agreed that the above-mentioned issue can be addressed by introducing an appropriate special course. All 50 respondents also confirmed that *"developing the methodological foundations for forming research competencies of future physics teachers using X-ray diffraction as an example"* is a relevant issue.

Physics teachers from general education schools actively participated in the pedagogical experiment and provided high-quality responses.

20 respondents suggested that modern advanced pedagogical technologies, including STEM education, should be actively used in teaching physics at universities. Regarding the conceptual questions, 38 respondents stated that future physics teachers face difficulties in conducting research; 7 respondents found it difficult to answer. 45 respondents indicated that this issue can be solved by introducing a special course. 45 respondents also agreed that *"developing the methodological foundations for forming research competencies of future physics teachers using X-ray diffraction as an example"* is a relevant issue.

The survey results confirmed a clear demand for this topic and provided valuable recommendations for improving the main model of the proposed methodology.

4 Discussion

Higher education in the Republic of Kazakhstan, encompassing more than 110 institutions, plays a decisive role in training specialists, advancing science and technology, and ensuring socio-economic development. Among these, pedagogical universities are particularly important, as they prepare future teachers whose competencies directly impact the quality of education and upbringing of the younger generation.

The activities of universities are governed by normative legal acts, including the Laws "On Education" and "On Science." According to Article 33 of the Law "On Education," higher education institutions are responsible for preparing qualified personnel, conducting research for innovative development, and training scientific and scientific-pedagogical staff. Article 3 of the Law "On Science" emphasizes the integration of education with scientific activity, fostering research and applied projects.

The State Program "Development of Education and Science in the Republic of Kazakhstan (2020–2025)" prioritizes strengthening scientific infrastructure, supporting university-based research centers, engaging young researchers, and developing academic mobility for students and faculty. Leading universities, such as Nazarbayev University and Al-Farabi Kazakh National University, play a central role in establishing scientific schools and training research personnel.

Pedagogical universities operate within ongoing educational reforms that require innovative approaches to teacher training. Key directions include: (1) formation of professional competencies in pedagogy, subject knowledge, and psychology; (2) integration of digital and interactive teaching technologies; (3) practical teaching experience through pedagogical practicum; (4) development of research skills to implement modern methods; and (5) cultivation of teacher values and ethics, including responsibility, empathy, and leadership.

Thus, pedagogical universities serve as both educational and scientific hubs, preparing highly qualified teachers capable of meeting national and global challenges.

Throughout the research process, the analysis of literature and scientific works remained continuous. In the context of the modern education system, the formation of professional and research competencies among future teachers is one of the essential tasks. In this regard, the methodological model aimed at developing research competencies based on the topic *"Diffraction Phenomenon"* serves as an effective approach.

This methodological model is based on teaching approaches that utilize STEM technologies and is aimed at developing future teachers' research abilities, enhancing their skills in explaining physical phenomena, and applying theoretical knowledge in practice (Figure 4).

In the modern educational system, the requirements for the professional training of future educators are increasing. It is important that they are not limited to subject knowledge alone, but also possess creativity, critical thinking, problem-solving skills, and the ability to conduct scientific research. This methodological guide is designed for the development of physics teachers' research competencies. It is based on widely applicable teaching approaches using STEM technologies and has been developed using the "X-Ray Diffraction" specialized course as an example.

Research competency is a complex attribute that represents a learner's ability to investigate a specific problem, apply scientific methods, analyze results, and draw conclusions. For a future physics teacher, this competency is crucial because it:

- Enables the proper organization and execution of scientific experiments in the teaching process.
- Helps engage students in science and involve them in research activities.
- Teaches critical evaluation of scientific information and its application in lessons.
- Motivates continuous improvement of knowledge and the introduction of innovations.

Brief Structure of the Model The main component of the model, which is applied in the third stage of the pedagogical experiment, is the "X-Ray Diffraction" specialized course.

The "X-Ray Diffraction" specialized course serves as the foundation of the model. This course is aimed at developing future teachers' research competencies.

Components:

1. Lecture: Lectures provide core theoretical knowledge on the physics of X-rays, the phenomenon of diffraction, and methods for studying crystal structures. At this stage:

- The physical nature of X-rays is explained.
- The operating principles of instruments and devices (X-ray diffractometer, goniometer, X-ray sources) are introduced.
- Applications of the method in science and industry are analyzed.

During lectures, modeling activities for research competency development are implemented: formulating hypotheses, defining research objectives, selecting methods, and demonstrating ways to interpret results.

After each lecture, students are given reinforcement tasks (summary control questions, analysis of scientific articles, examination of specific research examples).

Through the modeling activities of research competencies, students acquire theoretical knowledge and are given summary control questions to understand and consolidate it. In

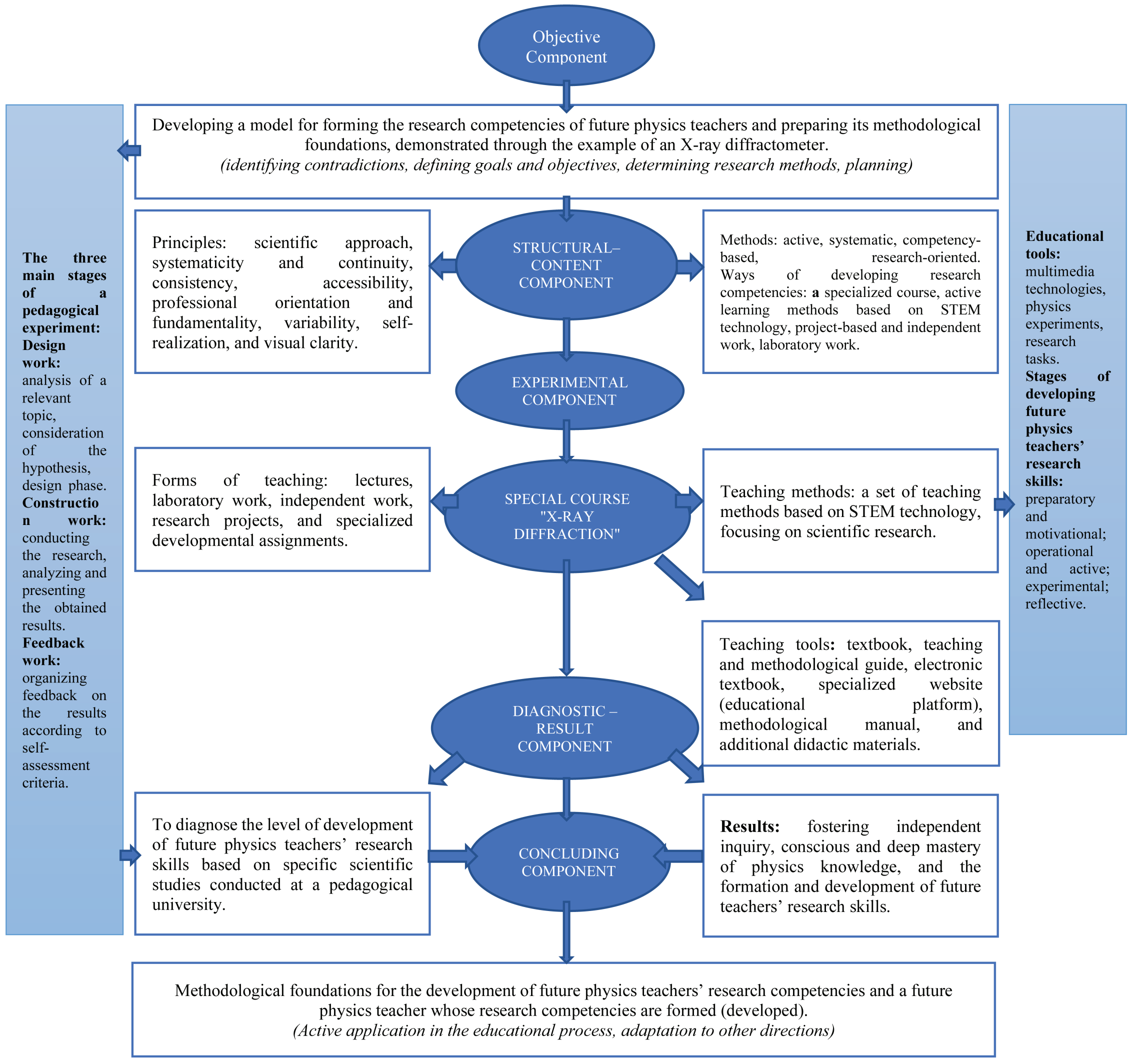

FIGURE 4
Model of the methodology.

this section, students gain the main theoretical knowledge according to the "X-Ray Diffraction" course. During lectures, activities aimed at developing research competencies are conducted, which may include proposing a hypothesis on a specific problem, discussing methods for its validation, and similar exercises.

2. Comprehensive Laboratory Work: The core of the course is laboratory experiments. At this stage, students apply their theoretical knowledge in practice and perform research tasks:

- Planning the experiment;
- Setting up equipment and operating the X-ray diffractometer;
- Recording, processing, and analyzing the obtained data.

Laboratory work is structured as research-type activities: defining the task, selecting the method, identifying sources of error, and comparing results with theoretical predictions. This approach develops analytical thinking skills, enhances the ability to work with experimental data, and provides experience in teamwork.

Special attention is given to the development of research competencies through research-based tasks. In this section, students apply their theoretical knowledge in practice. They investigate the phenomenon of X-ray diffraction, collect and process experimental data. During these activities, "tasks for developing research competencies (research tasks)" are carried out. These tasks are aimed at fostering students' independent research skills.

3. Independent Work: An important part of the course is independent research. At this stage, the student selects the object of study, identifies the problem, and searches for ways to solve it.

During this stage, the student:

- Works with scientific literature, including foreign sources;
- Critically analyzes previous studies;
- Develops and defends an individual scientific project.

Independent work may include small-scale research, designing small experimental setups, and computer modeling of physical processes (using MATLAB, Python, LabVIEW, etc.).

Through developmental tasks, students cultivate independent research skills. They conduct research autonomously and explore creative ways to solve problems. At this stage, they are assigned "research tasks aimed at developing competencies." Here, they apply their acquired knowledge and skills to prepare a small-scale scientific project.

A comprehensive system is used to assess the level of development of students' research competencies:

Summary control questions for testing and consolidating theoretical knowledge.

Reinforcement tasks (summary control questions): These are assessments conducted after lectures and laboratory work. They are designed to evaluate students' theoretical knowledge and practical skills.

At the end of the course, students are given developmental tasks, aimed at deepening their knowledge and improving their research skills. The final assessment consists of the following elements:

- Submission of laboratory reports;
- Defense of research projects;
- Discussion of results and presentation at a scientific seminar.

Developmental tasks: These tasks are aimed at fostering critical thinking and creative problem-solving skills. For example, students may be asked to "propose new applications for X-ray diffraction." During independent work, students are given in-depth tasks aimed at the development of research competencies.

Tasks for Developing Research Competencies (Research Tasks): These are assignments carried out during comprehensive laboratory and independent work, designed to allow a precise assessment of students' research skills. They are aimed at developing practical skills.

Features of the Model: This model, based on a teaching methodology that utilizes STEM technologies, ensures the integration of theory and practice. It prioritizes preparing students for research activities rather than limiting them to theoretical knowledge alone.

Application Results: Implementation of this course allows:

- Integration of interdisciplinary knowledge;
- Development of scientific inquiry skills;
- Enhancement of students' learning motivation;
- Preparation of future physics teachers to apply research methods in schools.

Therefore, the "X-Ray Diffraction" course not only provides knowledge but also lays a solid foundation for the scientific and professional development of future teachers.

This model prepares future physics teachers to:

- Understand and apply scientific research methods;
- Develop research thinking skills;
- Employ effective teaching methods that increase students' interest.

The comprehensive application of the aforementioned approaches allows for a thorough assessment of students' research competencies and helps determine their potential for application in future professional activities. In addition, the evaluation results contribute to refining strategies for developing students' research skills and enhancing the effectiveness of organizing scientific research work.

In comparison, the methodology proposed in the current study for training future physics teachers focuses on developing research competencies through a combination of theoretical instruction, pedagogical practicum, and integration of digital and interactive teaching technologies. While Kurbanbekov et al. (2025) emphasize direct enhancement of student knowledge via VR simulations, our approach prioritizes preparing teachers capable of designing and conducting research-based activities, integrating modern educational tools, and fostering critical thinking among school students.

Both approaches share a common goal: improving the effectiveness of physics education through innovative methods. However, the present methodology extends beyond immediate learning outcomes, aiming to cultivate professional competencies in future teachers, including the ability to implement research-informed teaching practices, evaluate experimental data, and apply digital technologies effectively. By equipping teachers with these competencies, the methodology ensures sustainable improvements in student learning across diverse physics topics, complementing the findings of studies such as Kurbanbekov et al. (2025).

Table 7 presents the main types of assessment for evaluating the level of research competencies of future physics teachers using the specialized course. Each of the completed tasks encompasses all the above-mentioned methods for assessing research competencies. At

TABLE 7 Types of completed work.

Completed work	Groups A and B	Groups C and D
Mastering the theoretical sections of the educational materials	+	+
Physical dictation	+	+
Word cloud	+	+
Construct formulas	+	+
Physics rebus puzzle	+	+
Mastering the set of laboratory works from the educational and methodological materials	-	+
Laboratory work No. 1	-	+
Laboratory work No. 2	-	+
Laboratory work No. 3	-	+

the same time, the laboratory work applies the evaluation methods for laboratory activities included in the proposed methodological foundations.

As shown in Table 7, the proposed methodological foundations were applied to all completed tasks to conduct both external and internal assessments of students' scientific-research competencies (Table 7).

This methodological model is designed to develop students' scientific-research competencies during the instruction of the "X-Ray Diffraction" specialized course. The primary aim of the model is to equip future physics teachers not only with subject knowledge but also with the skills necessary to plan, conduct, and analyze research activities. This process is carried out through the active integration of STEM (Science, Technology, Engineering, Mathematics) technologies.

Structural Components of the Model and Their Implementation The model is presented as a systematic process comprising several stages:

1. Theoretical Block (Lectures): "General Diffraction Phenomenon": At this stage, students acquire theoretical knowledge of the fundamental concepts, laws, and types of diffraction. This knowledge forms the foundation for a deeper understanding of X-ray diffraction. "X-Ray Diffractometer" and "X-Ray Diffraction": Students study the design and operational principles of the X-ray diffractometer, as well as the characteristics of X-ray diffraction and its applications.

2. Practical and Independent Work Block:

Comprehensive Laboratory Work: To consolidate theoretical knowledge in practice, students perform laboratory experiments. At this stage, they acquire skills in operating the X-ray diffractometer, collecting data, and performing initial analysis. STEM-Based Independent Work: This stage represents a distinctive feature of the model. Students carry out tasks aimed at solving real-world problems through the STEM approach. For example, assignments may include determining the crystal structure of a given material or investigating the properties of a new material using X-ray diffraction methods.

3. Monitoring and Assessment Block: Tiered Tasks and Developmental Tasks: These assignments are designed to assess students' subject knowledge and research skills progressively.

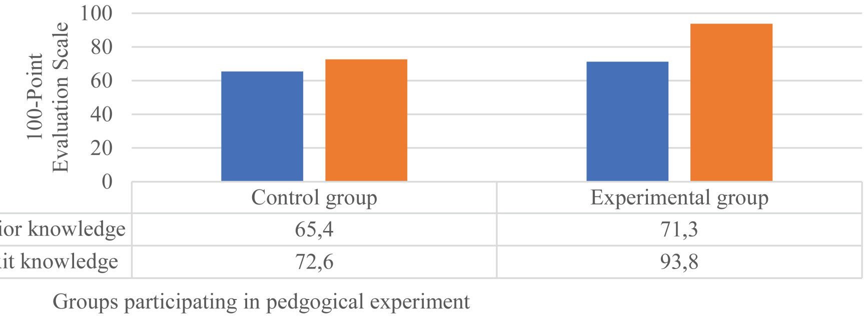

FIGURE 5
Quality of prior and exit knowledge.

TABLE 8 Indicator of knowledge quality.

No.	Information	Control groups	Experimental group
1	Number of participants	72	76
2	Average age	21	22
3	Teaching technology and features	1. Traditional teaching technology (conducting standard laboratory work). 2. Materials and technical base with traditional textbooks. 3. Traditional assignments and tests, etc.	1. STEM-based special course on "X-ray Diffraction" (activating laboratory work using STEM elements). 2. Special educational and methodological materials, developmental tasks, scientific laboratory. 3. Innovative methods for evaluating laboratory work. 4. Tasks to develop research competencies through critical thinking.
4	Prior knowledge quality (X-Ray diffraction)	65.4%	71.3%
5	Exit knowledge quality (X-Ray diffraction)	72.6%	93.8%
6	Change in knowledge quality	Increase 7.2%	Increase 22.5%
7	Final survey of students and master's students to determine the change in research competency levels	145 respondents reported that they understood the overall research work and were already able to conduct independent scientific research. 2 respondents said there were no problems, but noted some difficulties in responding.	

Tiered tasks evaluate the achievement of specific knowledge levels, while developmental tasks aim to foster creative and critical thinking abilities. Tests (Rating 1 and 2): Two rating-based tests are conducted during the course to evaluate students' knowledge at intermediate stages. These tests cover both theoretical and practical questions. Final Test: At the end of the course, a final test is conducted to comprehensively assess students' acquired knowledge and skills.

4. Conclusion and Results Block: Research Projects for Developing Scientific-Research Competencies: At this stage, students prepare a concrete scientific project to demonstrate their research skills. They select a research topic, develop a research plan, formulate a hypothesis, and determine methods for testing it.

Results (Successful Presentation of the Research Topic): As the outcome of the project, students present and defend their research topic before an audience. This allows for the assessment of their ability to explain research results, provide evidence, and draw conclusions.

Assessment of the Formation of Scientific-Research Competencies: At this stage, all student work—including tests, laboratory and independent work, as well as the final research project—is used to provide a final evaluation of the level of development of their scientific-research competencies.

The proposed model, within the framework of the "X-Ray Diffraction" specialized course, allows for the comprehensive and systematic development of future physics teachers' scientific-research competencies. By integrating theoretical knowledge with practical work and combining practical activities with independent research, the model not only deepens students' subject knowledge but also encourages them to engage in independent inquiry, problem-solving, and scientific activities. This model ensures that future educators meet the requirements of modern education.

The initial level of students' scientific-research competencies was determined, and methodological tools for their development were prepared. Baseline indicators were recorded to allow comparison with results obtained in subsequent stages of the experiment (Figure 5).

Special training courses were organized for the teachers and students participating in the experiment, and methodological materials were provided to develop their research competencies.

Results of the Targeted Phase: Based on the data collected during this phase, the effectiveness of the experimental methods was analyzed, and their impact on the development of students' and pupils' research activities was evaluated. In addition, the results obtained from the new teaching approaches were compared with those of the control group, confirming their effectiveness (Table 8).

As a result, using the proposed methodology, the knowledge quality increased by 22.5% (Figure 5). This confirms the main hypothesis.

5 Conclusion

The main objective of the conducted research was to develop a model and methodological foundations for forming the research competencies of future physics teachers, demonstrated using the example of an X-ray diffractometer. During the study, this objective was fully achieved. According to the set tasks, the contradictions that arose in the process of training future physics teachers were resolved.

The following tasks were successfully accomplished during the research:

1. A model of methodological foundations for developing the research competencies of future physics teachers was created, using the example of the diffraction phenomenon.
2. A set of laboratory works aimed at forming research competencies was developed, utilizing the X-ray diffractometer.
3. Methodological foundations for forming the research competencies of future physics teachers were elaborated, based on the diffraction phenomenon.
4. A pedagogical experiment was conducted to test the hypothesis of the study, and its results were substantiated.

The results of the research comply with the requirements of the educational program (EP) code in education. The developed methodological foundations have high scientific and practical significance, and their results can be applied not only in the diffraction section of physics but also in other sections of physics, as well as in other natural science subjects (chemistry, biology, etc.). This study makes a significant contribution to the preparation of future teachers and opens a new direction for enhancing their professional competencies. In addition, it is planned to further transform the model by integrating artificial intelligence (AI) in the future.

Author contributions

MS: Conceptualization, Investigation, Software, Writing – review & editing. TD: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Writing – original draft. MN: Formal analysis, Funding acquisition, Project administration, Resources, Validation, Visualization, Writing – original draft.

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Conflict of interest

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Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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