Pedagogical environments for the formation of research competence in students within practice-oriented chemistry education

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ABSTRACT

Despite the importance of research competence in modern chemical education, traditional instructional methods often fail to sufficiently prepare students for independent scientific inquiry and professional growth, creating a gap between theoretical knowledge and practical application. The research aimed to experimentally validate a multifaceted system of pedagogical environments (research-focused, metacognitive-digital, and motivational) designed to foster research competence in chemistry students through practice-oriented learning. The research design of the research was a 30-week longitudinal pedagogical experiment utilizing a quasi-experimental design with pre- and post-test assessments. The sample comprised of 325 third- and fourth-year future chemistry teachers (experimental group (EG)=165; control group (CG)=160) from a national university in Kazakhstan. Statistical analysis (Pearson χ^2 test) confirmed significant growth in the EG across all competence criteria, with the proportion of students reaching "high-level" research proficiency increasing from 10.9% to 38.8%. The key implication is integrating structured pedagogical environments into teacher-training curricula effectively bridges the gap between theoretical knowledge and practical inquiry, providing a scalable framework for modernizing science, technology, engineering and mathematics (STEM) education.

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1. INTRODUCTION

In the modern educational space, one of the main trends in the development of higher chemical education is the reorientation of the educational process towards preparing students for scientific and research activities that meet the challenges of scientific and technological progress and the demands of the labor market [1]. The formation of research competence, which we define as an integrative personality characteristic, manifested in the willingness and ability to independently initiate, plan, implement and evaluate the research process in the field of chemistry based on a practice-oriented approach, using methods of scientific cognition, critical thinking, experimental modeling and digital technologies, is of particular importance in the context of practically oriented training. The emphasis is shifted from the reproduction of ready-made knowledge to the acquisition of experience in active cognition, experimentation, and interpretation of results.

We conducted this study because, despite the clear necessity of research-oriented education, traditional chemistry instruction often prioritizes “cookbook” laboratory manuals where students simply follow pre-defined steps to reach a known result. This approach fails to foster true research skills, such as experimental modeling, hypothesis testing, and the ability to interpret unexpected chemical phenomena. The relevance of the study is due to the urgent need to transform chemistry laboratories from spaces of passive imitation into special educational environments that mirror actual scientific inquiry. Current pedagogical tools in chemistry frequently remain abstract, focusing on theoretical calculations while failing to bridge the gap between classroom instruction and the practical demands of modern chemical laboratories.

The issue of the formation of students’ competences, in particular research competence, in the context of educational approaches based on competencies, activities and practice is actively discussed in modern scientific discourse [2]–[4]. However, the pedagogical environments that enable the effective application of these approaches within the rigorous and resource-intensive process of studying chemistry remain insufficiently specified. Our research is relevant to the field as it addresses this specific chemical education gap by providing a structured framework that moves beyond basic laboratory skills. To solve the problem of student passivity and low engagement in research, our model introduces a three-pronged intervention: i) research-focused settings that simulate authentic laboratory challenges; ii) digital-metacognitive tools that allow students to simulate and reflect on complex chemical reactions; and iii) motivational support that connects chemical theory to real-world professional problems. Unlike existing models that focus only on manual laboratory techniques, this system integrates the cognitive and reflective components necessary for a chemist to independently plan and evaluate an original research process.

Given the scientific and theoretical significance of the problem, as well as the practical need for the formation of research competence in chemistry students, it is important to conduct a comprehensive study of the pedagogical environments that ensure its effectiveness. To guide this investigation and address the identified gaps in traditional instruction, this study is centered on the following main research question: what specific pedagogical environments, when integrated into a practice-oriented chemistry curriculum, are most effective for fostering the multidimensional structural components of students’ research competence?

So, the scientific novelty of this research is explicitly manifested in the development and experimental validation of a unique, multifaceted system of pedagogical environments specifically designed to foster research competence in chemistry students through a practice-oriented learning. Unlike existing approaches, this system is innovative in its synergistic integration of cognitive, digital-metacognitive, and motivational components to create conditions for active scientific inquiry within professional training. Furthermore, this study contributes an original, structured model for embedding research activities directly into the higher education chemistry curriculum, providing new empirical evidence of its effectiveness that has not been previously documented in this specific context.

Beyond its pedagogical utility, the significance of this study is rooted in its alignment with global educational goals, specifically the United Nations Sustainable Development Goal 4 [5] (SDG 4: quality education). By developing research competencies, this study directly supports target 4.3 (equal access to affordable quality higher education) and target 4.4, which aims to substantially increase the number of youth with relevant technical and vocational skills for employment and entrepreneurship. At the national level, this research contributes to the “Concept for the Development of Higher Education and Science in the Republic of Kazakhstan for 2023-2029,” [6] which prioritizes the transition to a research-intensive educational model and the modernization of educational infrastructure to foster a knowledge-based economy. By proposing a practice-oriented framework, the study offers a concrete mechanism for curriculum reform, moving away from traditional instruction toward competency-based learning as mandated by the 2024 Law on Science and Technology Policy. Ultimately, this research is significant for enhancing student outcomes, including critical thinking, scientific literacy, and professional adaptability, ensuring that graduates are prepared for the demands of the global high-tech labor market.

The significance of this study is rooted in its ability to provide a practical solution to the persistent gap between academic theory and laboratory practice. For students, this research is significant as it transforms the learning experience from passive procedural imitation to autonomous scientific inquiry, directly enhancing their professional readiness and adaptability. For educators and university administrators, the study offers a validated, scalable framework of three pedagogical environments that can be integrated into existing curricula to modernize chemistry training without requiring entirely new infrastructure. At the policy level, adoption of this model encourages a shift from content-heavy evaluation toward competency-based validation of learning. By implementing these research-driven environments, institutions can move beyond traditional “cookbook” laboratory instruction toward a practice-oriented paradigm that ensures graduates are capable of addressing complex, real-world scientific challenges in the global labor market.

In the context of the transformation of higher education, the problem of forming research competence of students, especially in the process of professional training of future experts in the natural sciences, is becoming increasingly relevant. So, there are numerous studies exploring different aspects of forming research competence. The investigation by Ješková *et al.* [7] emphasizes that the formation of research competence should be gradual and accompanied by pedagogical support for the academic self-development of students. The research draw attention to the importance of mentoring and research seminars in the development of research skills. However, unlike our study, the work does not consider specialized approaches to the formation of research competence, especially in chemistry education, and does not have a practice-oriented teaching vector.

Popova [8] analyzed the effectiveness of inquiry-based learning (IBL) for developing students' scientific thinking in the natural sciences. They emphasize the importance of problem-based teaching, hypothetical modeling, and empirical analysis as tools for developing research autonomy. Conversely, in our investigation, researchers do not pay sufficient attention to the operational-active and reflective components, which are key elements of research competence in our model. García-Holgado and García-Peñalvo [9] emphasizes the effectiveness of the science, technology, engineering, and mathematics (STEM) approach in forming research competence through the integration of chemistry with other disciplines. The authors paid particular attention to teamwork, digital technologies, and real-world projects. In contrast to our work, the emphasis shifts to the interdisciplinary nature of research, while our attention is focused on the intra-subject structure of chemistry research activity and the methodological support for research competence formation.

Rivas *et al.* [10] analyze the role of metacognitive strategies in IBL. They argue that the development of planning, self-monitoring, and self-assessment skills has a direct impact on students' research. Distinct from our study, where the reflective component operates in conjunction with the motivational-value and operational-active components, in this study, the consideration of reflection is isolated, without systematic integration into the educational model of chemical research. Previous studies [11], [12] emphasize the digital delivery of research activities in chemistry. The use of virtual laboratories, online simulations, and remote experimentation platforms significantly expand students' access to research experiences. However, unlike our model, which is based on a pedagogical synthesis of content, methodological, and motivational support, the authors of these studies focus primarily on the instrumental aspects of implementing IBL.

OECD TALIS [13] reports and UNESCO analytical reviews [14] show that a practice-oriented pedagogical approach, which provides a link between educational content and the real professional settings, is a decisive factor in the formation of research competence. In contrast to the general strategic vision of international organizations, our study specifies the implementation of a practice-oriented approach within the framework of chemistry study, taking into account pedagogical environments, motivational mechanisms and the structural organization of competencies. In summary, while the scientific literature presents various methodological guidelines, it lacks a holistic, integrative pedagogical model specifically designed for the formation of research competence within chemistry education based on practically oriented learning. This study was undertaken specifically to offer a data-driven solution to the challenge of low research engagement among undergraduates, providing a comprehensive, original pedagogical framework that is currently absent from the chemical education literature.

So, the aim of the article is to experimentally validate a multifaceted system of pedagogical environments (research-focused, metacognitive-digital, and motivational) designed to foster research competence in chemistry students through practice-oriented learning. The realization of the set purpose involves the development and testing of a system of pedagogical influences aimed at activating cognitive activity, developing scientific thinking and forming a stable motivation for independent scientific research. In order to achieve this purpose, the following tasks were identified in the study: i) to define the terms "pedagogical environments" and "research competence"; ii) to find out essential structural elements of students' research competence in practice-oriented study of chemistry in higher education institutions; iii) to substantiate the pedagogical environments for the formation of research competence in future chemists in the conditions of practical-oriented study of chemistry; iv) to verify experimentally the effectiveness of pedagogical environments for the formation of research competence; and v) to propose recommendations for the successful formation of research competence of chemistry students during practical-oriented study of chemistry. Solving these tasks will allow us to identify the impact of scientifically substantiated pedagogical environments that will contribute to the modernization of chemistry education based on research activity, as well as to improving the quality of professional training of future specialists.

2. METHOD
2.1. Theoretical framework and mapping of outcomes
The conceptual framework of this study relies on a synthesis of four interrelated theoretical dimensions that align with professional, pedagogical, and technical education (PPTE) outcomes in chemistry. These approaches guide the pedagogical design and implementation of pedagogical environments conducive to the formation of research competence and map onto specific structural outcomes as:
- Competency-based approach: this dimension prioritizes the development of students' ability to apply integrated knowledge, skills, and attitudes to solve scientific problems. It maps onto the cognitive and technical mastery outcomes, ensuring students possess the foundational "know-how" required for professional chemical inquiry
- Practice-oriented approach: this approach connects learning with real-world applications and professional settings. It maps onto operational-activity outcomes, where students demonstrate applied proficiency in laboratory techniques, experimental modelling, and the ability to address industrial or social challenges through chemistry;
- Metacognition: this dimension focuses on the internalization of scientific thinking and the self-regulation of research activities. It maps onto reflective and pedagogical outcomes, fostering the student's ability to autonomously monitor, evaluate, and adjust their cognitive strategies during complex chemical investigations
- Motivation: this pillar addresses the formation of internal interest and the personal significance of scientific research. It maps onto motivational-value outcomes, which ensure sustained professional engagement, ethical awareness, and a committed research identity in the future specialist. By integrating these four dimensions, the proposed pedagogical environments act as dynamic systems that bridge the gap between theoretical instruction and the multifaceted demands of modern chemical laboratories.

2.2. Research design and general methods
To achieve the research purpose and tasks, we employed a comprehensive approach combining theoretical and empirical methods. First, theoretical methods included analysis, synthesis, and generalization of scientific literature to clarify the definitions of key terms used in the study, identify and describe the structural components (motivational-value, cognitive, operational-activity, and reflective) of students' research competence. This phase further justified the selection and structure of pedagogical environments necessary for the formation of research competence in practice-oriented chemistry education. Secondly, empirical methods were used to test the effectiveness of the proposed pedagogical environments through a longitudinal pedagogical experiment utilizing a quasi-experimental design. This involved the systematic implementation of three designed pedagogical environments (research-focused, metacognitive-digital, and motivational) to foster research competence. The approach is rooted in a synthesis of competency-based and practice-oriented methodologies, aimed at moving students from passive learning to active scientific inquiry. Lastly, statistical methods were employed to analyze the data obtained from the experiment. Using Microsoft Excel's built-in tools, we applied the Pearson χ^2 test to determine the statistical significance of the differences between the control group (CG) and experimental group (EG) research competence levels at the beginning and end of the study. This statistical validation allowed us to rigorously confirm or refute the null hypothesis regarding the effectiveness of the developed pedagogical environments.

2.3. Study participants
To address the stated research purpose, a longitudinal pedagogical experiment was conducted at the Faculty of Natural Sciences and Geography of Abai Kazakh National Pedagogical University (Almaty, Kazakhstan). The context of implementation continued during the standard academic year (2024/25) over a period of two academic semesters (30 weeks), where students were enrolled in specialized courses such as chemical synthesis and physical methods of chemical research. Participants in the study comprised 325 third- and fourth-year students, aged 19-21 years. This specific age group was chosen because these students possess the foundational theoretical knowledge necessary to transition into independent research.

These participants were allocated into two distinct groups: an EG consisting of 165 students and a CG with 160 students. Participant selection utilized a cluster sampling method, where entire academic cohorts, rather than individual students, served as the units of research to maintain the ecological validity of the classroom environment. The demographics of the participants were as: the gender distribution within the EG was 58.17% male and 41.82% female. The CG, matched for age, exhibited a gender distribution of 54.12% male and 45.87% female participants. For the EG, specifically designed pedagogical environments were systematically implemented during both classroom instruction and practical internships. Instruction for the CG proceeded using traditional lecture-and-tutorial formats without the intentional incorporation of the aforementioned pedagogical environments. All participating students received comprehensive information regarding the study's parameters and provided their informed consent prior to engagement.

2.4. Research instruments and scales

To ensure transparency and allow for replication, we utilized a specific set of tools mapped directly to the four structural components of research competence. Table 1 provides a comprehensive mapping of each instrument to its corresponding competence component and the specific behavioral indicators measured.

Table 1. Mapping of research instruments to competence components and indicators

Instrument	Competence component	Specific indicators measured
"Interest and motivation" questionnaire [15]	Motivational-value	Sustained cognitive interest in chemistry research; awareness of professional value; internal motivation; academic autonomy.
"Concept inventory" [16] (25-item MCQ)	Cognitive	Mastery of scientific research methods; knowledge of fundamental chemical laws; ability to connect theory to practical professional cases.
Practical laboratory task (standardized 0–100 rubric)	Operational-activity	Independent experiment planning; compliance with safety/precision protocols; statistical processing of results; presentation of findings.
"MARSI/MAI test" [17] (52 items) and a researcher portfolio	Reflective	Ability to evaluate self-activities; error identification and correction; use of self-assessment methods; consistency in research journaling.

Thus, as illustrated in Table 1, motivational-value criterion was measured via the "interest and motivation" questionnaire [15]. A sample item from this scale includes: "To what extent do you feel that conducting independent chemical experiments is essential for your future career?" (rated on a 5-point Likert scale from 'not at all' to 'extremely'); cognitive criterion was assessed through a "concept inventory" [16]. This instrument consists of 25 multiple-choice questions focusing on core chemical principles and research methodology, with a Cronbach's α=0.82 in the current study, indicating high internal consistency; operational-activity criterion was evaluated through a practical laboratory task with a structured standardized rubric (0–100 points). A sample task required students to "develop and execute a titration plan to determine the concentration of an unknown active substance," with the rubric scoring students on technical precision, safety protocols, and data recording; reflective criterion: measured using the "MARSI/MAI test" [17] and a researcher portfolio. The metacognitive awareness inventory (MAI) includes 52 items, such as: "I ask myself if I have considered all options when solving a research problem."

2.5. Organization of the study

During the investigation, it was hypothesized that the efficiency of forming research competence in chemistry students during practical-oriented study of chemistry would increase if educators cultivate this competence purposefully applying specially designed pedagogical environments, which we understand as factors of the educational process that are purposefully created and institutionally substantiated and that contribute to the systematic formation of research competence of chemistry students in a practice-oriented education. Having analyzed modern research and personal educational experience, we decided to examine the pedagogical environments that form a holistic system that allow for the formation of research competence not only as a set of skills, but as a sustainable personal and professional education of the student. These pedagogical environments are the following: i) organization of a learning setting focused on student research activity; ii) using metacognitive and digital tools for reflection and self-regulation of student research activity; and iii) motivational support for student research activity through personally meaningful and practice-oriented tasks.

To ensure a rigorous assessment of this hypothesis, we first identified the four structural components of research competence that served as our evaluation criteria: i) motivational-value component reveals a stable interest in research activities; the desire to have thorough knowledge of chemistry, which is a prerequisite for the successful completion of experimental tasks, the formation of a person's worldview and motivation for self-development and self-improvement [18]; ii) cognitive component includes general scientific knowledge (mastery of general scientific research methods), general natural knowledge (knowledge of natural sciences and methods of their research) and chemical knowledge (knowledge of chemical elements, substances, transformations of substances, methods of research in chemistry), which are formed in the process of mastering educational material comprehensively and systematically in the conditions of an educational process focused on the integration of theoretical and practical components [19]; iii) operational-activity component involves the ability of students to use the acquired skills and abilities with maximum benefit. In the process of educational research, students master the methods of planning and conducting scientific experiments, critical analysis of results, and the presentation of research results in the form of course and qualification papers, which contributes to the development of skills of independent scientific cognition. The knowledge obtained in the process of studying chemistry serves as a necessary tool for gaining subjective research experience [20]; and iv) reflective component of research competence is aimed at analyzing the results of student's own activities, recognizing possible consequences, and taking corrective actions based on the experience gained [21]. These criteria and their specific indicators are illustrated in Figure 1.

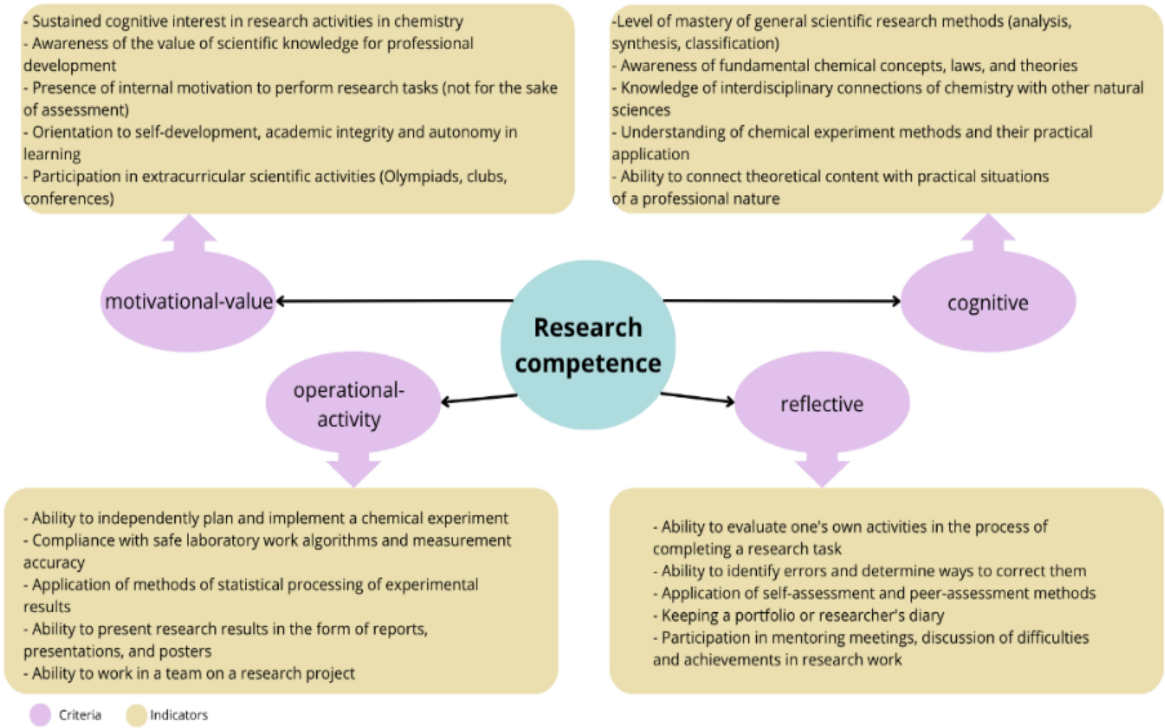

Figure 1. Structural elements of students' research competence

To judge the research hypothesis, a pedagogical experiment comprising three stages was conducted as:

a. Statement stage (weeks 1-2): students in both groups were assessed using the instruments described in Section 2.2 to establish their foundational baseline. Initial diagnostic assessments indicated a notable lack of formed research competence among a significant proportion of students in both groups. Data were anonymized and coded for statistical tracking.
b. Formative stage (weeks 3-28): to ensure internal validity, both groups were taught by the same faculty members and utilized identical laboratory equipment and reagents. The intervention was applied to the EG through three specific pedagogical environments:

Environment 1: "organization of a learning setting focused on research activity" is one of the key pedagogical environments for the formation of research competence in practice-oriented study of chemistry. Such an environment involves creating an atmosphere of academic freedom, scientific research, interaction and personal responsibility of the student for the results of his knowledge. The formative stage involved specific activities within each environment. To implement this environment, problem-based learning methods, research tasks, educational projects, as well as case analysis methods were used. Research laboratory practical classes were introduced in the classes, where students not only repeated standard experiments, but also modified them, formulated their own hypotheses and tested them on the basis of experimental data. This approach developed critical thinking and scientific analysis skills. In addition, micro-research was organized in the format of mini-projects. A key activity was the "water quality project," where students had to formulate a hypothesis regarding local water hardness and modify standard EDTA titration methods to account for specific local mineral variations. These tasks contributed to the formation of interdisciplinary connections and understanding of the applied value of chemical knowledge. In addition, exercises on hypothesis formation, interpretation of scientific texts, formulation of research questions, as well as reflective sessions after completing each block of tasks were actively used. At the end of the classes, discussions of the results were organized in small groups, which stimulated the development of argumentation, analysis and mutual learning. The learning environment organized in this way was designed not only to stimulate research interest, but also to lay the foundations for independent scientific activity, which is the basis of the professional competence of the future specialist.

Environment 2: "using metacognitive and digital tools for reflection and self-regulation of student research activity" is aimed at developing students' ability to meaningfully control their own cognitive process, set research goals, evaluate results, and adjust actions during scientific research. This allows for the formation of a reflective and self-regulatory component of research competence, which is critically important in the context of practice-oriented chemistry education. In the classroom, this environment was implemented through teaching methods that stimulate metacognition: self-observation, self-assessment, and asking questions about a student's own actions. For example, we implemented digital reflective blogging. Using Trello or Notion, students completed the "I am a researcher" exercise, requiring them to log not just data, but "failure analyses", i.e., discussions of why an experiment failed, what corrective actions were taken, and what conclusions were made. In addition, students planned research stages, recorded tasks, deadlines, and assessed progress. Applying Google Forms, Padlet, and Jamboard, students answered questions like "what did I learn?", "what remained unclear?", "what needs to be changed in my research strategy?". Self-assessment methods were also used, such as the "reflective map" exercise and an interactive questionnaire to assess student's own research activity. Thus, the combination of metacognitive strategies and digital tools gave students tools for a deeper awareness of their own activities, contributed to the development of responsibility for research results, and increased the effectiveness of the formation of research competence.

Environment 3: "motivational support for student research activity through personally meaningful and practice-oriented tasks" is aimed at forming students' internal interest in research cognition, which is a key factor in the development of research competence. The personal significance and practical orientation of the tasks offered to students create conditions when students perceive research activities not as a formal requirement, but as useful, interesting and valuable things for their own professional growth. In our chemistry classes, we used contextualized professional cases. For example, the "green cosmetics" project required students to research the shelf-life of natural preservatives, making the task personally meaningful by connecting chemistry to consumer health. "Research on the effectiveness of ecological detergents", "analysis of nitrate content in products" projects allowed students to work on real, practice-oriented topics and aroused interest, since they are related to their everyday life. The problem-based learning method – another one, which was also often used, provided motivation through the formulation of practical dilemma tasks such as: "what chemical reagent is best used for water purification in a region with hard water?". Students independently searched for solutions, analyzed sources, and planned experiments. This activated their cognitive and research activities. Role-playing games (for example, "I am a chemical safety consultant"), chemical-practical cases from real production situations, and contextual tasks related to the future professional activities of students were also widely used. To maintain sustainable motivation, individual research development trajectories were introduced, students were given the opportunity to choose the topic or form of task completion. Moreover, interactive platforms (Mentimeter, Kahoot) were also used to gamify the educational process. Thus, the use of personally significant, life-related and professionally relevant tasks activated students' interest, increased the significance of research activities, and contributed to the formation of their research competence.

c. Control stage (weeks 29-30): post-test assessments were conducted using the same instruments as the statement stage to measure progress and perform statistical validation.

2.6. Schematic of the pedagogical system

To clarify the interaction between the pedagogical interventions and the expected outcomes, Figure 2 presents a conceptual schematic of the research framework. This model illustrates how the three pedagogical environments serve as inputs that directly stimulate and refine the four structural components of research competence. As illustrated in the schematic, the environments are designed to be mutually reinforcing. The motivational environment establishes the personal significance of the work, which sustains the student through the rigorous cognitive and operational demands of the research-focused environment. Simultaneously, the metacognitive-digital environment provides the reflective tools necessary for students to monitor their progress across all stages. This synergy ensures a holistic transition from passive knowledge acquisition to active research competence.

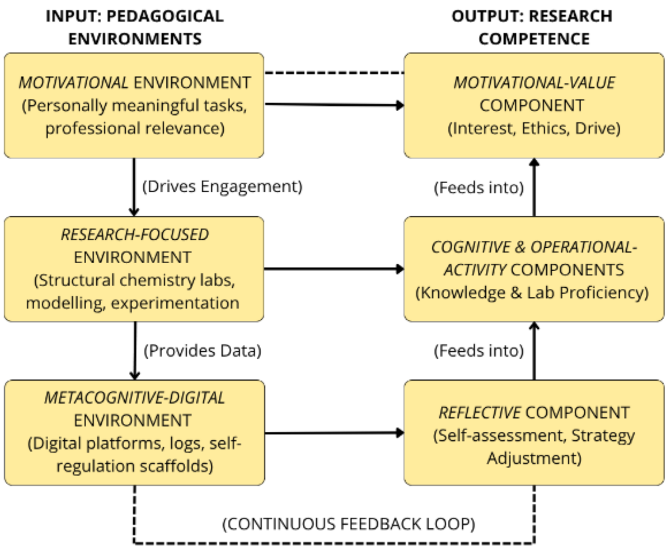

Figure 2. The structural-functional model of pedagogical environments for the development of students' research competence

3. RESULTS AND DISCUSSION
3.1. Results

The reliability of the experimental data obtained regarding the influence of the implemented pedagogical environments that ensure the formation of research competence in students in the process of practice-oriented study of chemistry in higher education institutions was checked using mathematical statistics methods. The primary empirical result is that the EG achieved a statistically superior level of research competence compared to the CG following the intervention. To carry out calculations, first of all, the results of the experiment at the statement and control stages were summarized, calculating the average value of the indicators at each level of the formation of research competence in students. The calculation was performed according to [22]:

$$S_{total} = \frac{(n_1+n_2+\cdots+n_8}{N} \cdot 100\%$$

where: S_{tot} is the total number of chemistry students who are at the appropriate level of the formation of research competence; *n1, n2, ... n8* is the number of chemistry students who meet a certain level of the studied quality within the corresponding indicator; *N* is the total number of indicators according to all criteria. The generalized results of the experimental work are presented in Table 2.

Table 2. Distribution by levels of research competence formation in chemistry students from experimental and CGs at the statement and control stages of the experiment (%)

Levels of research competence formation	Low		Mid		High	
Groups	Before	After	Before	After	Before	After
Experimental	41.81	16.35	47.27	44.85	10.91	38.79
Control	42.50	27.48	47.49	55.63	10.00	16.88

The key finding that directly answers our scientific question, namely, what pedagogical environments are effective, is the significant shift in the EG's high-level competence category, which rose from 10.91% to 38.79% after implementation of specifically designed pedagogical environments. To determine the magnitude of this effect, we calculated the effect size (Cramer's V). For the control stage, the calculated Cramer's V was 0.25, indicating a medium-to-large educational effect [22] resulting from the implemented pedagogical environments.

The static significance of this difference was confirmed using the χ^2 test. The application of this criterion required compliance with the following requirements: both samples are random and independent of each other; measurement is carried out on an ordinal scale with several selected categories (*C*). According to the conditions of use of the χ^2 test, the null hypothesis H_0 was formulated as $p\ p_{1j}=p_{2j}$, and the alternative hypothesis H_1 was as $p_{1j} \neq p_{2j}$, where p_{1j} is the probability that an object randomly selected from the first group of participants will fall into category j ($j=1, 2, 3 \ldots C$), and p_{2j} is the probability of a similar event for the participants of the second group. The number of objects in two samples from two populations was denoted as n_1 and n_2. To test the null hypothesis H_0, the value of the T statistic for the χ^2 criterion was calculated by the formula [23]:

$$T = \frac{1}{n_1 . n_2} \sum_{j=1}^{3} \frac{(n_1 Q_{2j} - n_2 Q_{1j})^2}{Q_{1j} + Q_{2j}}$$

where: n_1 is the size of the first sample (EG); n_2 is the size of the second sample (CG); Q_{1j} is the number of objects from the first sample belonging to category j; Q_{2j} is the number of objects from the second sample assigned to category j; j is the designation of the category representing a certain level of the studied characteristic.

In order to substantiate the statistical decision to test the null hypothesis H_0, a comparison was made of the empirical value of the statistic T, calculated according to the formula, with the tabular critical value $T_{krit}=5.991$. The critical value was determined based on the χ^2 distribution table, taking into account the adopted significance level $\alpha=0.05$ and the corresponding number of degrees of freedom, which was calculated according to the formula $v=C-1=3-1=2$, where C is the number of compared categories. The fact that the calculated empirical value of the T statistic exceeded the critical value of T_{krit} was considered as a statistically justified basis for rejecting the null hypothesis H_0 at the selected significance level α and confirming the alternative hypothesis H_1. This result indicated the presence of a statistically significant difference in the structure of the distribution of objects by C categories, which reflected the levels of manifestation of the studied quality within two independent samples. If the value of the T statistic was less than or equal to the critical threshold value of T_{krit}, then there was no sufficient reason to assert the presence of significant differences in the state of the studied quality in the two populations.

To guarantee the objectivity of the conclusions, it was first necessary to check whether there were statistically significant differences in the levels of formation of research competence in students in the process of practice-oriented study of chemistry in the experimental and CGs at the statement stage of the experiment. According to the requirements of the χ^2 criterion, it is necessary to formulate undirected statistical hypotheses. The null hypothesis H_0 consisted in the assumption of equality of the frequency characteristics of category j in two independent samples ($p_{1j}=p_{2j}$) means that no statistically significant differences were found in the levels of formation of research competence in chemistry students in the experimental and CGs. The alternative hypothesis H_1 had the form $p_{1j} \neq p_{2j}$ that means there are significant (statistically significant) differences in the levels of formation of research competence in chemistry students in the experimental and CGs.

Based on our data, the empirical value of the statistic T was calculated, which is 0.0740147962. Since the empirical value of T does not exceed the critical value ($0.0740147962<5.991$), there is no reason to confirm the alternative hypothesis H_1. The null hypothesis H_0 is accepted. Thus, our conclusion is that there are no significant (statistically significant) differences in the levels of formation of research competence in chemistry students in the experimental and CGs.

3.2. Statistical significance at the control stage

To conduct statistical processing of empirical data at the control stage of the experiment, a procedure similar to the statistical processing of empirical data at the statement stage of the experiment was applied. The calculated value of the T statistic is 20.4226574. Given that the calculated empirical value of the χ^2 Pearson criterion (T=20.4226574) exceeds the critical value ($T_{krit}=5.991$) at $\alpha=0.05$, based on the decision rule, the null hypothesis H_0 is rejected. The p-value was found to be $p<0.001$, confirming that the observed improvements in the EG are highly significant and unlikely to have occurred by chance.

Thus, at the statement stage, the calculated T value was 0.074(<5.991), indicating no initial difference. At the control stage, the T statistic reached 20.422 (T>5.991), allowing us to reject the null hypothesis and confirm the effectiveness of the implemented pedagogical environments for forming research competence in students in the process of practice-oriented study of chemistry in higher education institutions. While both groups demonstrated an enhancement in research competence, the observed disparities are evident in Figure 3.

As illustrated in Figure 2, the proportion of students in the EG achieving a "high" level of competence (38.79%) is more than double that of the CG (16.88%) by the end of the study. Furthermore, the EG saw a dramatic 25.46% reduction in "low" level competence, whereas the CG only saw a 15.02% reduction. This visual evidence supports the conclusion that the integrated pedagogical environments are significantly more effective than traditional instruction.

To deepen the analysis of pedagogical environments, we examined which aspects of the environments were most effective and why. So, considering the first environment– "organization of a learning setting focused on student research activity", we can conclude that the practice-oriented research setting was highly effective because it shifted the student's role from a passive observer to an active investigator. By modifying standard experiments (e.g., water hardness testing), students developed operational-activity skills that traditional instruction fails to foster. The "academic freedom" provided allowed for the internalization of the scientific method rather than mere rote memorization.

Analyzing the second environment– "using metacognitive and digital tools for reflection and self-regulation of student research activity", we revealed that the utilization of digital reflective diaries (Notion/Padlet) was the most effective tool for developing the reflective component. Unlike traditional paper logs, the digital format facilitated real-time self-regulation and peer interaction. Students reported that the "failure analysis" exercise helped reduce the "fear of error," which is a common barrier in chemical research.

Examination of the third environment– "motivational support for student research activity through personally meaningful and practice-oriented tasks" allowed us to establish that the integration of personally meaningful tasks (e.g., analyzing household detergents) proved essential for sustaining engagement. The reason for its success lies in the connection between abstract chemical theory and the students' future professional identity. When students perceived the research as "useful for their career" rather than a "formal requirement," their motivational-value scores saw the highest relative growth. Thus, the results indicate that the "synthesis" of these three environments, rather than any single one in isolation, is what led to the high-level competence growth. While the CG saw a natural increase in "middle-level" proficiency due to standard instruction, only the EG demonstrated the qualitative leap to independent scientific inquiry.

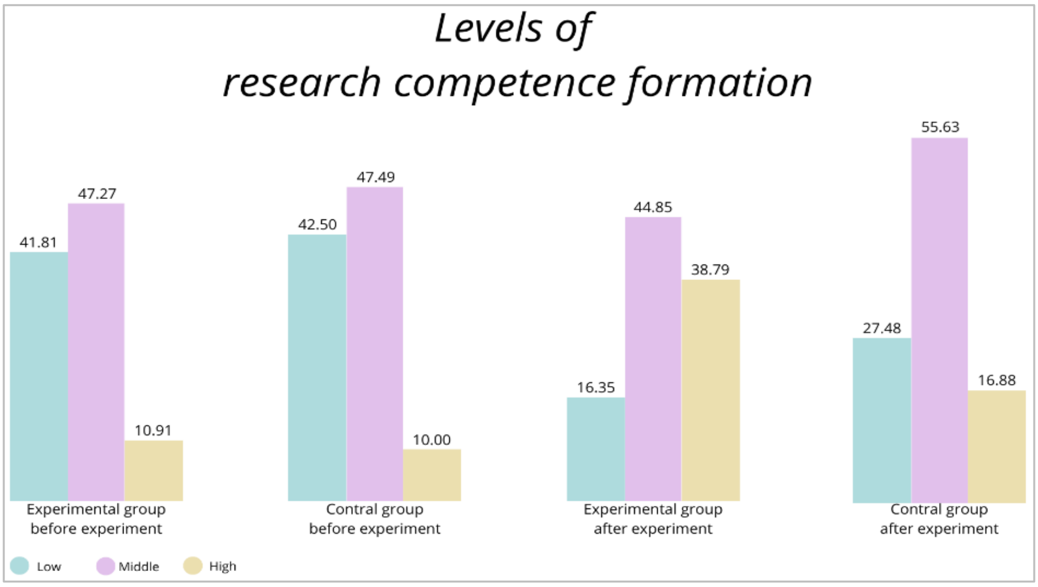

Figure 3. Comparative progress in research competence levels for experimental and CGs, pre- and post-experiment

3.3. Theoretical interpretation of pedagogical efficacy

The significant improvement in research competence within the EG can be attributed to the targeted theoretical mechanisms underlying the three pedagogical environments. Firstly, metacognitive framework of experimental design: the metacognitive-digital environment acted as a cognitive scaffold that transformed how students approached experimental design. By utilizing digital reflection logs and self-regulation prompts, students were required to convey their internal thought processes. This shift from intuitive "trial-and-error" to deliberate planning enabled students to systematically monitor their variables and adjust their hypotheses before and during lab work, effectively bridging the gap between theoretical knowledge and operational execution. Secondly, motivational persistence in research: the motivational environment served as a psychological engine for sustaining engagement during high-difficulty tasks. By framing research problems within personally meaningful contexts (such as the analysis of local environmental samples) the pedagogical design tapped into the students' intrinsic motivation. According to self-determination theory, this sense of autonomy and relevance provides the persistence necessary for students to navigate the frustrations of experimental failure and the complexities of chemical synthesis without disengaging. Thirdly, authenticity via organized inquiry: the research-focused settings created authentic learning contexts by replicating the structural and technical rigor of professional laboratories. These settings facilitated "situated cognition," where students moved beyond passive memorization to active participation in a scientific community of practice. This authenticity ensured that the cognitive and operational components of research competence were not learned in isolation but were developed as integrated professional behaviors.

3.4. Discussion

The findings confirm that the implementation of specially designed pedagogical environments significantly contributes to the effective formation of students' research competence in the context of practice-oriented chemistry education. This aligns with global trends emphasizing the shift from traditional transmissive models to active, student-centered pedagogies. However, a critical interpretation of these results suggests that the mere presence of digital tools or laboratories is insufficient; rather, it is the purposeful intersection of motivational support and metacognitive reflection that drives high-level competence.

The success of the learning setting focused on research activity reflects similar results found by Barr *et al.* [24], who demonstrated the positive effects of inquiry-based laboratories on student engagement, cognitive growth, and operational skill development. While our study mirrors these findings, we go further by identifying that "academic freedom" must be balanced with structured mentoring to prevent student cognitive overload that is a nuance often overlooked in general inquiry-based models. This supports the assertion by Toom and Husu [25] regarding the necessity of coherent, research-oriented pedagogical curricula. Our findings demonstrate that when the curriculum is intentionally structured as a systemic environment rather than a series of isolated tasks, it leads to the qualitative leap in competence observed in our EG.

Likewise, previous studies [26], [27] show that learning rooted in real-world problems enhances motivation and scientific thinking that correspond to the motivational-value and cognitive criteria in our framework. A key ramification of our findings is that research competence is not a static skill set but a dynamic process that requires "digital-metacognitive" scaffolding. Our use of digital and metacognitive tools aligns with several studies [28], [29], who emphasize the need for integrating digital reflection platforms to support students' self-regulation and reflective practice. Critically, we observed that students who engaged in digital reflection were more resilient when experiments failed, suggesting that digital tools humanize the research process by documenting the journey, not just the result. Furthermore, this systematic documentation directly addresses the concerns of Abduldayan *et al.* [30] regarding research data management. By integrating data management and project documentation as core parts of the operational-activity competence, our model ensures that students develop the professional discipline required for modern scientific inquiry.

3.5. Practical applications

The practical application of this model is highly scalable. It should be integrated into broader curricula, embedded into the core chemistry syllabus and teacher training programs. For successful institutional adoption, teacher training must shift from content delivery to research facilitation. The "water quality" and "green cosmetics" projects serve as templates for how chemistry departments can partner with local industries or environmental agencies to provide students with authentic research problems. Furthermore, the "digital-metacognitive" scaffolding, using accessible tools like Trello and Notion, can be integrated into existing curricula without requiring expensive specialized software.

What will come in handy for future researchers and educators is our validated model of "reflective mapping." Chemistry education that connects to societal and ecological issues fosters deeper professional identity and scientific literacy. Our findings provide a scalable roadmap for other natural science faculties to move beyond rote learning. Altogether, the ramifications of this study extend beyond chemistry. They suggest a fundamental need to restructure how scientific inquiry is mentored in the 21st-century university setting to bridge the gap between academic theory and real-world professional complexity.

3.6. Scope, limitations, and future research directions

The scope of this study is specifically defined by its focus on the training of third and fourth-year future chemistry teachers within the higher education system of Kazakhstan. This specific demographic was selected because students at this level have acquired the foundational chemical knowledge necessary to engage in high-level inquiry-based pedagogical practice. However, several limitations must be discussed candidly to provide a clear context for the findings. First, the research was conducted within a single institutional setting, which means the results may be influenced by specific regional pedagogical traditions and national curriculum structures. Second, while the results demonstrate significant statistical growth, the assessment of "soft skills," specifically the reflective and motivational-value components, relies on subjective rubrics and student self-reporting, which can be inclined to social desirability bias.

To address these limitations and build upon the current framework, we propose the following concrete directions for future research: i) cross-cultural and multi-institution validation: future studies should replicate these pedagogical environments across diverse international contexts and multiple universities. Such cross-cultural validation is essential to determine if the proposed framework maintains its efficiency across different educational cultures and institutional chemistries; ii) cross-disciplinary testing: while the current study focused on chemistry education, future work should explore the adaptability of this three-environment model (motivational, research-focused, and metacognitive-digital) to other STEM disciplines, such as physics, biology, or mathematics teacher training. Cross-disciplinary tests would reveal whether the proposed system can serve as a universal blueprint for fostering research competence in all science educators; iii) longitudinal tracking into teaching careers: a critical avenue for future research is the longitudinal tracking of these future teachers as they transition into professional employment. Monitoring their performance during their first five years in the classroom would provide data on whether the research competence developed during university persists and how it evolves into "action research" within a school setting; and iv) economic and scale-up assessments: as educational institutions consider the widespread adoption of this model, future studies should include rigorous economic assessments. This involves analyzing the cost-effectiveness of deploying metacognitive-digital scaffolds and specialized research settings at scale. Evaluating the resource requirements and potential "scale-up" challenges will provide institutional leaders and policymakers with the data-driven evidence needed to integrate these environments into national teacher-training policies.

4. EDUCATIONAL IMPLICATIONS

4.1. Implementation guides

The results of this study offer several concrete implications for the modernization of higher chemical education and assistance to educational stakeholders. To bridge the gap between academic theory and professional practice, we provide the following actionable guidance and a high-level implementation checklist. Actionable guidance for stakeholders:

a. For curriculum designers, i) systemic integration: research competence should not be treated as an "add-on" or a final-year requirement. Curriculum designers must embed research-focused settings across all undergraduate years, aligning laboratory tasks with global standards like the United Nations SDG 4 and national strategic goals for research-intensive education; and ii) assessment reform: moving beyond traditional exams, designers should incorporate standardized rubrics and "researcher portfolios" into the official syllabus to evaluate the "soft skills" (metacognition and reflection) that are essential for professional chemists.
b. For instructors, i) from lecturer to facilitator: instructors must shift their role from content providers to research mentors. This involves providing students with "academic freedom" while utilizing digital tools to provide real-time feedback and metacognitive coaching; and ii) focus on process over product: instructors should explicitly encourage "failure analysis" exercises. By rewarding students for their ability to troubleshoot and analyze unsuccessful experiments, instructors foster the resilience and critical thinking necessary for independent scientific inquiry.
c. For internship (pedagogical practice) supervisors, i) transition to action research residencies: supervisors should move away from treating internships as mere "observational tours" and instead structure them as "action research residencies." Future teachers should be assigned a specific pedagogical-chemical inquiry (e.g., designing and testing an inquiry-based laboratory experiment for high school students using local environmental samples). This ensures that the students will not just deliver content, but actively research the effectiveness of their own practice, thereby strengthening the operational-activity component within a real classroom context; and ii) evidence-based mentorship: evaluation rubrics used by supervisors should explicitly address the future teacher's ability to diagnose student misconceptions in chemistry, troubleshoot experimental failures in a school lab setting, and produce a reflective report based on classroom data. By requiring students to document and analyze their "teaching-as-research," supervisors help anchor the motivational-value component in the professional identity of a "teacher-researcher."

Pedagogical implementation checklist: i) diagnostic phase: assess baseline research competence using the mapped instruments (e.g., interest questionnaire and concept inventory); ii) environmental design: establish a "research-focused" setting where laboratory equipment is accessible for independent experimentation; iii) motivation check: ensure that laboratory problems are framed within personally meaningful contexts (e.g., ecological monitoring of local water or chemical analysis of regional soil); iv) digital scaffolding: deploy a digital platform for real-time reflection and peer-to-peer discussion to foster the metacognitive component; and v) evaluation loop: perform a post-intervention assessment using the Pearson χ^2 test to monitor student progress and refine the pedagogical approach.

4.2. Linking empirical findings to practical recommendations

To maximize the utility of this study, the observed improvements in research competence are translated into specific institutional recommendations across four key pillars of higher education:

a. Course design (linked to cognitive and operational findings). The significant increase in students' laboratory proficiency suggests that course design must shift from "pre-determined" results to open-ended inquiry. We recommend that chemistry curricula replace 30% of standard laboratory hours with "integrated research blocks." In these blocks, students do not follow a manual but must model their own experimental variables, directly mirroring the operational-activity growth seen in EG.
b. Internship structure (linked to motivational and operational findings). The significant growth in motivational-value and operational-activity scores within the EG suggests that pedagogical practice (teaching internships) must evolve from passive classroom observation to active scientific inquiry. We recommend that universities restructure internships as "clinical action research residencies," where future teachers are not merely "teaching a lesson," but are investigating the efficiency of specific chemical experiments or instructional strategies within a live classroom. By framing the school laboratory as a site for ongoing research, the internship reinforces the professional identity of the "teacher-researcher," ensuring that the high levels of motivation observed in our study are sustained during the transition to professional employment.
c. Faculty development (linked to the integrated framework). The efficiency of the three-environment system requires a shift in the instructor's role from "lecturer" to "research facilitator." Faculty development programs should focus on training professors in "scaffolded mentorship," i.e., teaching them how to use digital platforms for metacognitive monitoring and how to design tasks that bridge the gap between abstract chemical theory and practical application.
d. Assessment rubrics (linked to reflective findings). Because the EG showed superior growth in the reflective component, university assessment rubrics must be modernized. We recommend implementing "process-oriented rubrics" that allocate 40% of the grade to the research journal, error analysis, and the student's ability to justify their experimental adjustments, rather than grading solely on the purity of the final chemical product.

5. CONCLUSION

Thus, the conducted research has confirmed the effectiveness of pedagogical environments specifically designed to foster the formation of research competence in chemistry students within the framework of practice-oriented learning. We conclude that a systematic approach, integrating research-focused settings, digital-metacognitive tools, and motivational support, is significantly more effective than traditional instruction in preparing students for independent scientific inquiry. The nature of the evidence provided in support of this conclusion is both quantitative and qualitative, grounded in a longitudinal pedagogical experiment involving 325 participants. Statistical validation via the Pearson χ^2 test ($T=20.422>T_{krit}=5.991$) provides rigorous empirical proof of the EGs superior performance, while portfolio assessments and reflective logs offer qualitative insight into the research skills acquisition. Through this evidence, we identified the structural components of research competence, including motivational-value, cognitive, operational-activity, and reflective elements.

The significance of these results for the field of chemical education and the broader academic community lies in the provision of a replicable, data-driven framework for systemic curriculum reform and modernizing professional training. By facilitating a shift from static content delivery to dynamic, IBL, this study demonstrates that the proposed model enhances not only technical mastery but also the critical 'soft skills', such as: digital literacy and metacognitive reflection, essential for 21st-century scientific careers. By bridging the gap between theoretical knowledge and laboratory practice, this study offers a solution to the global challenge of student disengagement in STEM fields and directly aligns with global educational goals, such as the United Nations SDG 4 regarding quality education and skill development. Furthermore, this research supports national strategic goals for the modernization of higher education by providing a framework for developing a research-intensive academic environment. The broader community benefits from a model that not only produces technically proficient chemists but also develops the critical thinking and self-regulatory skills necessary for solving complex, real-world scientific problems.

Regarding future research directions, we suggest conducting longitudinal studies to track how the research competence formed during these undergraduate years translates into professional performance in industrial or academic careers. Additionally, scaling this model in different cultural and institutional contexts, or across other natural science disciplines, would further validate its universal applicability and identify any discipline-specific nuances in research mentoring.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author [AB] on request.

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