Science Education International
36(4)_2025,458-469
https://doi.org/10.33828/sei.v36.i4.9

International Council of Association for Science Education

ORIGINAL ARTICLE

Enhancing Research Skills in Chemistry Education via Integrated Project and Inquiry-Based Learning in a STEM Context

Saulet Adal[1]*, Salih Çepni[2], Turar Akylbekova[1], Aibat Ibraimov[1], Xiaoli Dong[3], Dinara Tlesbaeva[1], Zhanar Korganbaeva[1]

[1]Department of Chemistry, Abai Kazakh National Pedagogical University, Almaty, Kazakhstan, [2]Department of Science Education, Faculty of Education, Uludag University, Bursa, Türkiye, [3]Department of Chemistry, Fudan University, Shanghai, China

***Corresponding Author:** saulet.adal.99@mail.ru

ABSTRACT

This study examines the effectiveness of an integrated project-based learning (PjBL) and inquiry-based learning (IBL) framework in enhancing research competencies and laboratory literacy among undergraduate chemistry students in Kazakhstan. Traditional laboratory instruction in the region remains predominantly procedural, offering limited opportunities for authentic scientific inquiry. To bridge this gap, a research-oriented instructional module was implemented with 18 2nd-year chemistry students using a mixed-methods design grounded in constructivist learning theory. Over a 6 weeks analytical chemistry laboratory program, participants engaged in hypothesis formulation, experimental planning, ultraviolet spectrophotometric analysis of caffeine content in coffee, data interpretation, and presentation of findings. Research skill development was evaluated using pre- and post-intervention surveys, structured questionnaires, and a five-point analytical rubric assessing six dimensions: literature review, hypothesis formulation, experimental execution, statistical data processing, scientific report writing, and oral presentation. Statistical analyses showed significant improvements across all dimensions (paired t-test, $p < 0.05$), with normalized gain (N-Gain) values ranging from 0.48 to 0.61, indicating moderate to high learning gains. The largest improvement was recorded in scientific report writing (mean increase of 1.76 points; 85.6% relative gain). Qualitative feedback further revealed strengthened inquiry skills, increased independence, improved collaborative problem-solving, and greater confidence in scientific communication. Overall, the findings demonstrate that integrating PjBL and IBL substantially enhances students' research competence and analytical capabilities. The proposed instructional model provides a scalable and replicable framework for fostering active learning and preparing research-oriented graduates in higher STEM education.

Keywords: Higher education; inquiry-based learning; meta-competence; project-based learning; research competency; STEM content knowledge

INTRODUCTION

In the current education system, a new approach is emerging that moves away from traditional teaching and is based on the active participation of students in the learning process (Borte et al., 2020; Bates et al., 2022). This trend is grounded not only in improving learners' knowledge but also in the need to develop meta-competencies such as critical thinking and research skills (Ribeiro-Silva et al., 2022; Karagöl and Bekmezci, 2015; Barrow, 2006). Within this shift, Science, Technology, Engineering, and Mathematics (STEM) education plays a pivotal role, as it not only develops disciplinary knowledge but also integrates science, technology, engineering, and mathematics to prepare students for complex, real-world challenges (Cepni et al., 2024). In this context, the importance of innovative pedagogical models such as inquiry-based learning (IBL) and project-based learning (PjBL) is particularly significant. The IBL concept, based on the philosophical and pedagogical principles of John Dewey, envisions teaching through inquiry, practical activity, and independent knowledge construction, which considerably increases students' cognitive engagement (Barrow, 2006; Antonio and Prudente, 2024).

Meanwhile, the PjBL methodology, which originated in the 1960s at McMaster Medical School in Canada, initially developed as a tool for fostering practical skills aimed at solving real-world problems and facilitating interdisciplinary integration within small groups (Barrows and Tamblyn, 1980; Dewey, 1916). Later, PjBL was adapted to a wide range of educational programs covering natural sciences, engineering, and technical specialties, proving its effectiveness (Hasanah et al., 2024; Žerovnik and Nančovska Šerbec, 2021). In STEM contexts, PjBL projects often simulate authentic industry or laboratory challenges, such as developing environmentally sustainable materials or applying engineering design to chemical processes, which makes learning more relevant and applicable (Couso and Simarro, 2020). Both of these methods, based on the principle of active interaction between students and learning materials as well as among peers, accelerate the learning process, ensure conscious understanding of concepts, foster independent thinking, and cultivate complex competencies demanded in modern education.

Traditional lecture formats do not always provide opportunities for deep understanding of theoretical material and development of practical skills. The IBL and PjBL methods enable students to pose research questions, propose hypotheses, plan experiments, and analyze obtained data – that is, to participate in all stages of the scientific process (Biswal and Behera, 2023; Panasan and Nuangchalerm, 2010). In addition, these methods increase cognitive activity and motivation to learn, improving academic performance and student engagement (Viana et al., 2019). For example, the application of the PjBL method may involve solving an environmental problem of removing heavy metals from water or developing the synthesis of a new compound with specified properties (Tuan et al., 2020). In turn, IBL develops independence skills: students define the research objectives themselves, plan the methodology, and interpret the obtained results. When applied in STEM-oriented curricula, IBL enables students to connect theoretical inquiry with experimental design, computational modeling, and technological tools, thereby enhancing both scientific reasoning and digital literacy (Crippen and Archambault, 2012).

Thus, integrating IBL and PjBL within STEM education ensures that students not only master subject matter but also gain employability skills such as teamwork, data literacy, and problem-solving that are essential for the future workforce (Dasgupta et al., 2019)**.** Overall, the combined application of IBL and PjBL within a STEM framework transforms chemistry education into an interdisciplinary, practice-oriented, and research-driven process, aligning it with global educational priorities (Halawa et al., 2024).

The Role of the PjBL Method in Developing Scientific Competence

According to recent meta-analyses and empirical studies published in international peer-reviewed journals, the PjBL method has a significant positive impact on the development of students' scientific competence, especially in applied and engineering fields. Studies (Tamim and Grant, 2013; Pratiwi and Ikhsan, 2024; Bell, 2010; Ningsih et al., 2020) have shown that students engaged in project activities consistently demonstrate increased research activity, motivation, and ability to work independently in scientific contexts. As (Tamim and Grant, 2013) noted, an effective project should be problem-based, long-term, require interaction among students, and culminate in a formal presentation – such a structure fosters the development of scientific thinking, including formulating research questions and selecting relevant methods for solving scientific problems. When embedded within STEM-oriented programs, such projects acquire additional value, as they allow learners to integrate disciplinary knowledge from science, technology, engineering, and mathematics to solve complex real-world challenges (Alsmadi, 2020).

The main effectiveness of these methods lies in the structural features and problem-based nature of PjBL. These features systematically enable the development of students' scientific competence. One of the key components of scientific competence developed within PjBL is problem-oriented thinking. Students learn to formulate goals based on real or authentic problems, justify their solutions, consider alternative approaches, and analyze constraints, demonstrating a high level of cognitive engagement (Tamim and Grant, 2013). Moreover, active work with data during project activities – collecting, processing, visualizing, and using data to justify hypotheses and project decisions – plays an important role (Pratiwi and Ikhsan, 2024; Bell, 2010). This, in turn, promotes scientific data analysis skills as a fundamental component of modern scientific competence. Within a STEM context, data-driven decision-making becomes even more critical, as projects often require integrating laboratory experimentation with technological tools such as coding, simulation, or digital visualization platforms (Chivapruk, 2021).

In addition, project work contributes to the development of skills in scientific communication. Project defense, public presentations, preparation of reports, and visual materials all contribute to forming stable skills necessary for structuring scientific information, defending one's viewpoint, speaking before an audience, and participating in scientific discussions (Bell, 2010; Ningsih et al., 2020; Syahril et al., 2021). STEM-based project tasks often require interdisciplinary teamwork and communication across domains, which mirrors the real practices of research and industry communities (Mundhe, 2023).

Furthermore, teamwork – role distribution, decision-making through consensus, and acting with shared responsibility – develops interpersonal and interdisciplinary skills (Linnenluecke et al., 2020). Such team and communication experience also plays a crucial role in fostering students' intrinsic motivation. Studies (Ningsih et al., 2020; Rofik, 2023) indicate that students involved in solving meaningful problems show greater interest in scientific work, take responsibility for outcomes, and develop scientific autonomy. This strengthens the value-semantic component of scientific competence, including the motivation for self-development and sustained interest in scientific activities. Motivational growth is particularly evident in STEM education, where students see the direct relevance of their projects to technological innovations, environmental solutions, and future professional opportunities (Kaleci and Korkmaz, 2018).

The role of modern digital technologies in supporting and developing motivation is also significant. Using digital tools such as programming modeling, data visualization, and online platforms enhances students' digital competencies essential for preparing for their future professions in line with contemporary requirements (Rahmania, 2021). In projects integrating STEM components, students acquire skills to work with specialized software, process data, and use visual analytics tools, which lead to the growth of a digital scientific culture. However, project activities are not limited to digital skill – critical thinking is also decisive. Reflective stages of project work, error analysis, consideration of alternative approaches, internal team critique, and public defense encourage students to reconsider their actions, evaluate the reliability of evidence, the correctness of conclusions, and scientific rigor (Tamim and Grant, 2013; Syahril et al., 2021). These skills directly develop the core of scientific critical thinking – the ability to assess data reliability, logical consistency of reasoning, and methodological quality.

Nevertheless, the formation of such comprehensive competencies directly depends on the structural organization of the project. Studies (Wulandari et al., 2022) have shown that without methodological support, a project may be limited to performing a technical task and lose its scientific content. Therefore, for PjBL to be successful, its structure must be carefully planned, the quality of the scientific component monitored, and focus placed not only on results but also on the scientific thinking process and justification.

In summary, PjBL contributes to the comprehensive development of students' scientific competence. This method fosters problem-based and critical thinking, applied research skills, data handling, scientific communication, motivation, digital competence, and interdisciplinary interaction. Such competencies are especially important in the training of master's and doctoral students since their scientific work goes beyond theoretical knowledge to include the practical implementation of research objectives, presentation of results, and interaction with the scientific community. When integrated into STEM education, PjBL becomes a powerful driver of innovation, as it not only equips students with core scientific competencies but also prepares them for interdisciplinary collaboration and the challenges of the Fourth Industrial Revolution (Kelley and Knowles, 2016). In this regard, PjBL is considered an essential tool for forming the professional-scientific identity of a future researcher.

Opportunities of the IBL Method and its Integration with PjBL

Various studies have shown that the IBL method is an effective approach for developing students' scientific competence. This method is implemented by actively involving students in the research process and the act of questioning. The study conducted by Justice and colleagues demonstrated that the IBL method enhances critical thinking, the ability to formulate learning and main research objectives, and increases students' motivation and confidence towards scientific activity (Bahri et al., 2020). The basis of this effectiveness lies in students' direct participation in the scientific research process. A key component of IBL is students' active involvement in the scientific method: all stages from questioning to data collection and analysis, and drawing conclusions are included. Such engagement in the scientific method strengthens students' scientific thinking skills and their ability to work with empirical materials (Wale and Bishaw, 2020). As noted by Hmelo-Silver and colleagues, students' investigation of authentic scientific problems and their ability to develop hypotheses and explanatory models contribute to deeper subject understanding and the development of scientific analytical skills (Simbolon and Koeswanti, 2020). When integrated into STEM education, IBL acquires an additional dimension by connecting the scientific method with technological tools, engineering design, and mathematical modeling, thereby strengthening interdisciplinary competencies and preparing students for real-world challenges (Kelley and Knowles, 2016).

Critical thinking skills also play an important role during scientific research. These abilities actively develop when using the IBL method because students compare hypotheses, analyze evidence, and make reasoned decisions. This enables them to evaluate the logic of reasoning and the validity of experimental data (Situmorang et al., 2021). Along with improving critical thinking, students also develop skills for managing their own learning. The core of IBL is not searching for ready answers to questions but the research process itself. This process requires constant reconsideration and analysis of data sources, methods, and alternative solutions. Such an approach fosters students' metacognitive abilities—the skills of conscious monitoring and regulation of their learning process (Voet and De Wever, 2018). Mastering research results is not enough; presenting them effectively is also an essential element of IBL. This method also develops scientific communication skills. Students must organize their research, present evidence, participate in discussions, and defend their hypotheses. This ensures their training in structurally presenting scientific positions and exchanging academic views (Wale and Bishaw, 2020; Simbolon and Koeswanti, 2020). In STEM-related projects, these communication activities often extend beyond traditional academic settings, simulating real research conferences, laboratory meetings, or interdisciplinary collaborations, which better prepare students for professional scientific environments (Mateos-Núñez et al., 2020).

Communication activity also positively affects students' intrinsic motivation. The motivational potential of the IBL method is high: According to data from Prince and Felder, tasks based on self-directed research increase students' interest in the learning process, strengthen their responsibility for outcomes, and stimulate future scientific pursuits (Warr and West, 2020). However, pedagogical support plays a decisive role in achieving such results. The effectiveness of the IBL method largely depends on methodological support from the instructor. The teacher must help students formulate appropriate questions according to their level, provide necessary resources, and assess not only the results but also the research process itself (Bahri et al., 2020; Voet and De Wever, 2018). Without such support, IBL risks becoming an aimless activity lacking scientific depth. This is especially critical in STEM education, where tasks often involve complex problem-solving, computational analysis, or laboratory experimentation that require structured guidance to maintain scientific rigor (Monera and Salic-Hairulla, 2021).

Thus, IBL is regarded as a powerful tool for developing students' scientific potential. It fosters problem-based research, critical thinking, data handling, scientific communication, motivation, and metacognitive skills. These elements make IBL an important tool for preparing students for independent research work and future scientific careers. Within the STEM framework, IBL also plays a strategic role in cultivating innovation, as it allows students to explore cross-disciplinary questions, apply digital technologies, and connect abstract theory with applied practice, aligning education with the competencies required for the Fourth Industrial Revolution (Aguilera and Ortiz-Revilla, 2021).

PjBL and IBL methods are widely recognized as modern pedagogical approaches aimed at comprehensive development of professional and interdisciplinary competencies within higher education, especially in chemical education. The PjBL methodology is based on performing specific and meaningful project tasks, which contribute to deeper mastery of study materials, increased intrinsic motivation, and active student engagement in the learning process (Markula and Aksela, 2022; Mihić and Završki, 2017; Juntunen and Aksela, 2014). Furthermore, systematic implementation of project work develops students' critical and systematic thinking, teamwork, time management, responsibility, and self-organization skills (Tamim and Grant, 2013; Pratiwi and Ikhsan, 2024; Bell, 2010). However, some studies point out certain limitations of the PjBL method, namely: it requires considerable time to implement, demands professional facilitation skills from instructors, and fair assessment of each student's contribution within teamwork can be challenging (Domenici, 2022; Adauyah and Aznam, 2024; Vilela et al., 2025). In contrast, IBL involves active student participation in the learning process: They pose scientific questions, formulate hypotheses, conduct experiments, collect data, and analyze results. This method develops research activity, metacognitive abilities, scientific thinking systems, and deep understanding of subject matter, especially in laboratory and practice-based disciplines (Martín-Garcia et al., 2024; Levy and Petrulis, 2012; Pedaste et al., 2015).

Nevertheless, the effectiveness of IBL directly depends on its structure and the quality of pedagogical support: If tasks are too open-ended or unstructured, students may lose motivation, face cognitive overload, or struggle to assess their own progress (Warr and West, 2020; Prince and Felder, 2006). Integrating PjBL and IBL within a STEM framework addresses these challenges by providing both structure and authenticity: project tasks supply practical relevance, while inquiry ensures analytical depth and scientific grounding (Al-Mutawah et al., 2021). The scientific literature frequently emphasizes the effectiveness of integrating PjBL and IBL methods. The practical orientation of project activities and the analytical content of inquiry-based approaches complement each other, enabling a balance between theory and practice. Such integration produces a mutually reinforcing effect: Projects become scientifically grounded and content-rich, while research objectives acquire real-life relevance and motivational appeal (Warr and West, 2020; Mihić and Završki, 2017; Liu et al., 2023). In addition, this approach develops important skills such as self-directed learning, interdisciplinary thinking, reflection, and professional adaptation, fully meeting modern chemical-technological and academic demands. In particular, when embedded in STEM education, the combination of PjBL and IBL creates a transformative learning environment where students experience the full cycle of scientific research and innovation, preparing them for leadership in both academia and industry (Bozkurt et al., 2019).

The Purpose, Research Gap, and Research Questions

In recent years, research on innovative pedagogical methods has shown that both PjBL and IBL independently contribute to improving student learning outcomes. PjBL is widely recognized for fostering collaboration, project management, and the application of knowledge to real-world problems, while IBL has been proven effective in developing critical thinking, problem-solving, and scientific inquiry skills (Markula and Aksela, 2022; Bahri et al., 2020). However, in chemistry education, studies have mostly focused on either laboratory practice or theoretical training in isolation. The integration of PjBL and IBL in chemical education remains insufficiently explored, particularly in the context of higher education.

This gap is even more evident in Kazakhstan's higher education system, where chemistry teaching often relies on traditional lecture-based methods and fragmented laboratory tasks. While these approaches provide students with theoretical foundations, they do not always foster advanced research skills, laboratory literacy, or scientific communication competence. Given national priorities for modernizing higher education and preparing competitive specialists for scientific and industrial sectors, implementing integrated pedagogical strategies such as PjBL and IBL is urgently needed. Their combination offers opportunities to connect theoretical chemistry with authentic laboratory research, while simultaneously enhancing students' motivation, independence, and readiness for future scientific careers.

Although several initiatives aim to modernize STEM education in Kazakhstan, empirical evidence supporting the implementation of integrated instructional models remains limited. Conducting this research in the Kazakhstan context is therefore essential, as it allows for evaluating how PjBL-IBL integration functions within a system transitioning from traditional lecture-based instruction toward competency-based and research-oriented education. This contextual need provides a strong justification for situating the study in Kazakhstan.

The purpose of this study is to investigate the effectiveness of integrating PjBL and IBL methods in higher chemical education to improve students' research competence, laboratory literacy, independent cognitive activity, and scientific communication skills. By combining theoretical perspectives with empirical evaluation, this study aims to determine how integrating these approaches can support students in independent research work and prepare them for professional careers in science.

This study seeks to answer the following key research questions:

1. How effective is the integration of PjBL and IBL methods in developing students' scientific research competence?
2. How does the integrated learning module affect students' laboratory literacy, scientific data handling, and presentation skills?
3. Does combining PjBL and IBL methods influence students' learning motivation and self-assessment achievements?

METHODS

This study was designed as an experimental work aimed at developing research competence and laboratory literacy among Chemistry major students at a higher education institution. Grounded in constructivist educational theory, the study implemented a combined approach of PjBL and IBL. This approach aimed to expand students' scientific cognition, enhance their ability to connect theory with practice, and foster independent research capabilities (Bell et al., 2010; Thomas, 2000). A mixed-methods approach was employed, collecting and analyzing both quantitative and qualitative data simultaneously.

The participants were second-year students enrolled in the Chemistry program at a pedagogical university in Kazakhstan. A total of 18 students (n = 18), aged 18–20 years, voluntarily participated in the study. The sample consisted of pre-service chemistry teachers, selected intentionally due to the central role research competence plays in their professional preparation. As future educators, their ability to implement inquiry-based and research-oriented practices in schools makes them an appropriate population for evaluating the impact of the integrated PjBL–IBL model. The study was conducted at this university because its curriculum includes laboratory work, project-based tasks, and research-focused components, providing an authentic context for assessing the effectiveness of the instructional intervention. All participants voluntarily provided written informed consent and received an information sheet prepared according to ethical standards. Ethical approval for this study was obtained from the Institutional Research Ethics Committee of Abai Kazakh national pedagogical university (Approval No.2, dated 21/11/2025). All participants voluntarily provided written informed consent before data collection.

At the initial stage, a pre-survey assessed students' baseline research competence and laboratory literacy. This included their ability to work with scientific literature, formulate hypotheses, conduct experiments, perform statistical analysis, write scientific reports, and present findings.

Materials and instruments were selected to support STEM learning while integrating PjBL and IBL principles.

- Quantitative data: Structured questionnaire via Google Forms
- PjBL indicators: project planning, teamwork, task execution (Thomas, 2000)
- IBL indicators: scientific questioning, hypothesis testing, inquiry, and reflection (Bell et al., 2010).

Laboratory sessions promoted active, student-centered learning**.** Tasks followed a methodological guide. Students were encouraged to independently plan, design, and execute experiments. Each stage – from literature review and hypothesis formulation to experimental work, data analysis, report writing, and oral presentation – was aligned with PjBL and IBL approaches. Students worked in small groups (PjBL) while engaging in independent inquiry and reflection (IBL).

The module focused on determining caffeine content in coffee using ultraviolet spectrophotometry. Students conducted a literature review, formulated hypotheses, performed experiments, analyzed data statistically, and presented findings. Reflection activities included guided questions, group discussions, and self-assessment exercises to enhance critical thinking and scientific reasoning.

An educational module was developed to deepen students' research competence and subject-specific chemical knowledge (Table 1).

Students selected coffee samples, ground and weighed beans, and performed extraction using distilled water and dichloromethane. Caffeine content was measured using a PG Instruments T80+ spectrophotometer at λ = 272 nm. Data were processed using Origin software. Method reliability was evaluated through standard deviation, relative standard deviation, limit of detection, and limit of quantification Smith et al., 2018). The experimental procedure is illustrated in Figure 1.

The instructor acted as a facilitator, guiding autonomous decision-making, ensuring adherence to safety protocols, and providing scientific-methodological support. The learning process followed Kolb's experiential learning cycle (concrete experience → reflection → conceptualization → active experimentation) (Kolb, 1984) and Vygotsky's Zone of Proximal Development (ZPD) (Vygotsky, 1978). This framework allowed students to gradually master complex tasks.

Table 1: Learning module structure

S. No.	Intervention stages	Activities performed
1.	Initial survey	Baseline research competence assessed
2.	Research stages	• Literature review on caffeine determination methods • Hypothesis formulation and research question definition • Laboratory experiment using ultraviolet spectrophotometry • Statistical processing of data • Report writing • Oral presentation of results
3.	Final survey	Post-intervention assessment
4.	Final evaluation	Interviews on course content and effectiveness

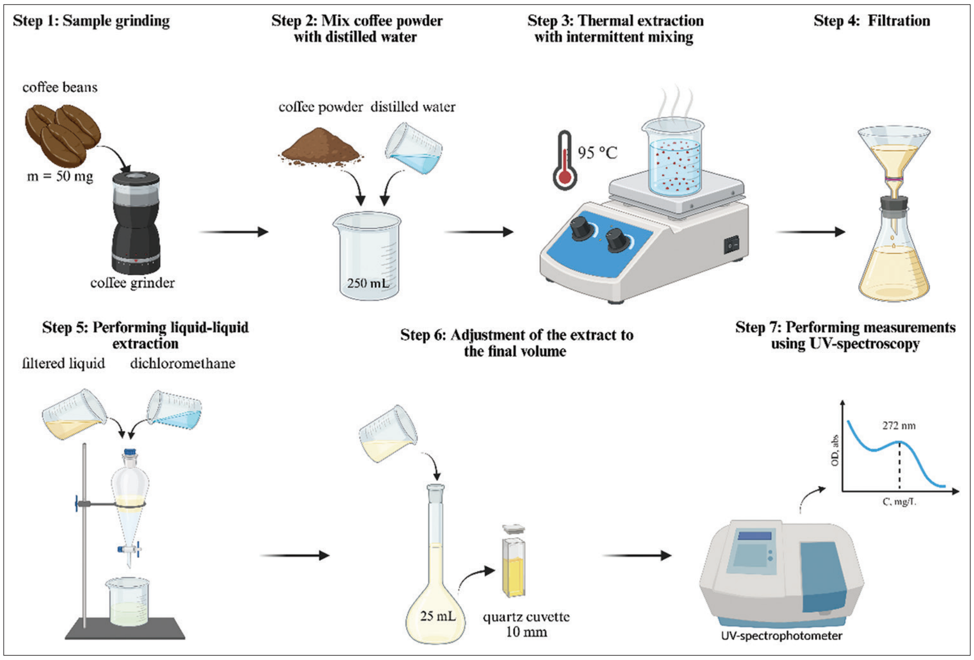


Figure 1: Sequence of stages of the experimental study

Students documented their research in structured reports and presentations, including method descriptions, experimental conditions, calculations, graphs, data interpretation, and conclusions. Evaluation was based on six criteria: literature review, hypothesis formulation, experiment execution, data processing, report writing, and oral presentation. Each criterion was rated on a five-point scale. An assessment rubric was developed to comprehensively evaluate students' research competence and project outcomes (Table 2).

The integration of PjBL and IBL within the STEM-focused laboratory module provided students with opportunities to develop scientific knowledge, research competence, critical thinking, and collaborative problem-solving skills**.** The learning experience fostered independent inquiry, reflective practice, and effective scientific communication**,** making it a highly effective tool for professional and research competence development.

The data were collected over one academic semester, from March to June 2024, during the implementation of the "Physical and Chemical Analysis Methods" course. The study was conducted in accordance with institutional ethical standards and research guidelines. Participation was voluntary, and all respondents were informed about the study's purpose and provided verbal consent before participation.

FINDINGS AND DISCUSSION

During the study, the STEM-focused learning module aimed at developing students' research competencies was implemented and evaluated. The module integrated PjBL and IBL approaches, providing students with opportunities for project work, independent inquiry, and reflective practice. This integration allowed for both qualitative and quantitative assessment of changes in students' learning activities and competency levels. The data were collected during the spring semester of the 2023–2024 academic year, between March and May 2024.

To determine the pedagogical effectiveness of combining PjBL and IBL methods, students' outcomes were systematically analyzed based on pre-established assessment criteria (Supplementary Table 1). A heatmap (Figure 2) was used to visualize changes across six key indicators: literature review, hypothesis formulation, experiment conduction, statistical data processing, research report preparation, and scientific presentation of results. The color gradient illustrated variations in individual student progress and overall group development.

The results demonstrated the effectiveness of combining PjBL and IBL approaches. Students showed substantial improvement in experimental conduction and statistical data processing, confirming that hands-on laboratory work and inquiry-driven tasks promote analytical thinking and evidence-based decision-making. Meta-analytic evidence indicates that project-based learning has a strong positive effect on students' learning outcomes, engagement, and higher-order thinking skills across educational contexts (Zhang and Ma, 2023). In addition, earlier empirical studies have demonstrated that project-based learning plays a significant role in developing students' statistical literacy and data analysis abilities (Koparan and Güven, 2014). In this context, PjBL enhanced students' abilities in collaborative problem-solving, project management, and teamwork, while IBL promoted independent inquiry and reflective thinking. Recent case studies in science education indicate that project-based learning contributes to higher levels of student engagement, deeper conceptual understanding, and

Table 2: Evaluation criteria for assessing student research projects (five-point scale)

Evaluation criteria	1	2	3	4	5
Literature review	No scientific literature was reviewed or misused.	Limited literature was used, not entirely relevant to the research question.	The literature reviewed lacks depth and a weak analytical approach.	Relevant and reliable literature was reviewed with structured analysis.	A comprehensive and in-depth literature review covering all aspects of the research topic.
Hypothesis formulation	No hypothesis was presented or scientifically unsupported.	The hypothesis is proposed but lacks scientific justification.	The hypothesis presented but insufficiently supported by evidence.	A logical and scientifically justified hypothesis was presented.	The hypothesis is well-founded with scientific data and tested through experiment or research.
Conducting experiments	Experiment not conducted or methodology incorrect.	The experiment was conducted, but was poorly organized or unreliable.	An experiment was conducted, but lacked sufficient structure.	Experiment well-organized with a clear purpose.	Highly organized and reliable experiment with repeatable and valid results.
Statistical data processing	Data analysis is absent or incorrectly performed.	Basic statistical methods were used, but not comprehensive.	Primary statistical methods were applied, but the analysis lacks completeness.	Accurate and relevant statistical analysis applied to the data.	Complex and precise statistical analysis with valid and reliable results.
Report writing	The report is incomplete, unstructured, and does not meet scientific standards.	The report lacks a complete scientific structure or weak analysis.	Report has general structure but lacks full scientific evidence and conclusions.	The report meets scientific standards with clear data and analysis.	Complete, high-quality report that meets scientific standards, with clear results and conclusions.
Oral defense and presentation	The presentation lacks structure and no scientific justification.	Short and precise presentation, but low credibility of scientific conclusions.	It has a clear presentation but lacks scientific connections.	Scientific conclusions supported by evidence and interaction with the audience.	Highly confident and convincing presentation, effective communication with the audience.

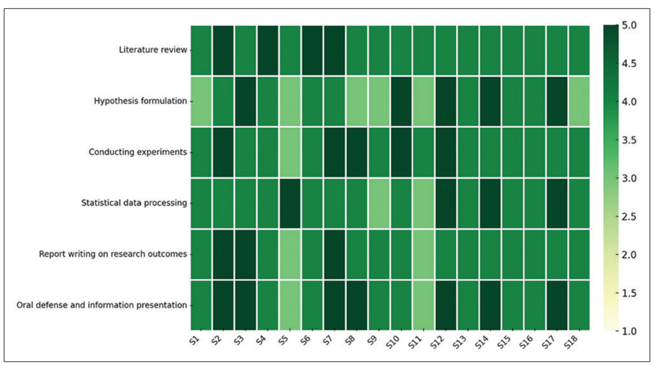


Figure 2: Visualization of student summative assessment results

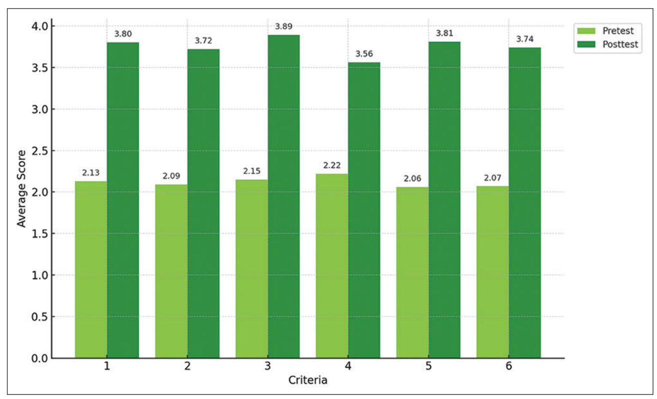


Figure 3: Growth of average scores in the context of six key criteria

the development of research-related skills (Santos et al., 2023). These findings align with previous research showing that PjBL enhances collaborative skills and practical application of knowledge (Thomas, 2000; Bell, 2010), and IBL fosters critical thinking and independent inquiry (Hmelo-Silver, Duncan, and Chinn, 2007; Pedaste et al., 2015).

Progress in the literature review criterion was comparatively lower, which may be attributed to limited coverage of theoretical content or insufficient prior experience in critically analyzing scientific literature. Nevertheless, the overall average improvement across all criteria ranged from 0.7 to 1.1 points, with the highest gains observed in students S3 (+1.3), S5 (+1.4), and S8 (+1.5), reflecting high engagement and motivation throughout all stages of the module.

The heatmap (Figure 2) served as an effective tool for monitoring student progress, identifying strengths and weaknesses, and informing pedagogical adjustments. Quantitative analysis using pre- and post-intervention surveys (Supplementary Table 2) revealed statistically significant improvements across all six assessment criteria (paired t-test, $p < 0.05$). Normalized Gain (N-Gain) values ranged from 0.48 to 0.61, indicating moderate instructional effectiveness. Results are also presented in a diagram showing average score increases (Figure 3).

Analysis of survey results demonstrated positive progress in all areas, with average growth ranging from 1.33 to 1.74 points and relative gains between 60.0% and 85.6% (Table 3). The most substantial improvement occurred in "Writing a scientific report based on research results" (1.76 points; 85.6% relative gain), emphasizing the importance of scientific communication skills. The comparatively lower progress in "Statistical

Table 3: Analysis of changes in students' evaluations before and after the questionnaire on various criteria

Criteria	Literature review	Hypothesis formulation	Conducting experiments	Statistical data processing	Report writing on research outcomes	Oral defense and information presentation
Average score before the questionnaire	2.13	2.09	2.15	2.22	2.06	2.07
Average score after the questionnaire	3.80	3.72	3.89	3.56	3.81	3.74
Average growth by score	1.67	1.63	1.74	1.33	1.76	1.67
Increase in %	78.3	77.9	81.0	60.0	85.6	80.4
Calculation of N-Gain	0.58	0.56	0.61	0.48	0.60	0.57

Data Processing" suggests the need for additional practical exercises, real-life examples, and strengthened methodological support, consistent with prior studies highlighting challenges in developing statistical competencies in STEM learning (Cooper, Underwood, and Hilley, 2010).

Students' laboratory work, including the determination of caffeine content using spectrophotometry, is provided in Supplementary Figure 1. The absorbance spectrum of the caffeine standard solution (Supplementary Figure 1a) and the calibration curve recorded at 272 nm (Supplementary Figure 1b) illustrate the experimental procedure and corroborate the observed improvements in laboratory and analytical skills.

Overall, participants demonstrated systematic understanding of the research process, analytical thinking, competence in data handling, and confidence in documenting and orally defending their findings. The average individual score increase was 1.63 points (5-point scale), confirming the effectiveness of the integrated STEM + PjBL + IBL approach. Collectively, these results indicate that participation in project-based and inquiry-driven tasks fosters sustainable development of research competencies, critical thinking, and collaborative problem-solving skills, in line with the broader literature on active learning approaches (Bell, 2010; Pedaste et al., 2015).

CONCLUSION

The study results confirmed the high effectiveness of an integrated STEM-focused model combining PjBL and IBL methods in developing students' research competencies and laboratory literacy within higher chemical education. Survey outcomes collected before and after the intervention showed statistically significant improvements across all assessed indicators ($p < 0.05$). Average growth in self-assessed competencies ranged from 1.33 to 1.74 points, with a N-Gain of 0.57, evidencing consistent positive changes in students' core STEM skills.

Individual analyses revealed positive dynamics in all participants, with an average personal growth of 1.63 points. These findings demonstrate that the STEM-integrated PjBL and IBL methods not only foster practical laboratory and research skills but also enhance students' self-evaluation levels, motivation toward learning, and active engagement in scientific inquiry.

Throughout the module, students mastered research competencies essential for STEM education, including working with scientific literature, collecting, comparing, and analyzing experimental data, and formulating scientific questions and hypotheses. Practical laboratory research using ultraviolet spectrophotometric analysis enhanced their laboratory competencies and skills in correct and safe equipment usage. From an informational competency perspective, students strengthened their abilities to analyze data from diverse sources, process statistical data, and interpret results scientifically. Communicative competencies also improved, with students demonstrating proficiency in preparing scientific reports, presenting results both orally and in writing, creating presentations, and defending scientific arguments. In addition, reflective competencies developed, enabling students to critically assess their own work and group activities, identifying strengths and areas for improvement.

Overall, integrating STEM principles with PjBL and IBL methodologies represents an effective pedagogical strategy for the comprehensive development of scientific thinking, research skills, and professional competencies in higher chemical education. These findings underscore the importance of broadly implementing this approach within Kazakhstan's higher education system to foster independent scientific inquiry, collaborative problem-solving, and lifelong learning in STEM disciplines.

AUTHORS' CONTRIBUTIONS

Saulet Adal: Conceptualization, Methodology, Data collection and analysis, Writing – original draft, Review and Editing. *Salih Cepni:* Supervision, Validation, Methodological guidance within STEM and inquiry-based learning frameworks. *Turar Akylbekova:* Data interpretation, Review and Editing, Ensuring scientific accuracy in chemical content. *Aibat Ibraimov:* Laboratory experiment design, Data validation using spectrophotometric analysis.

Xiaoli Dong: Refinement of research instruments, Expertise in analytical chemistry, and Data interpretation. *Dinara Tlesbaeva:* Literature review organization, Questionnaire administration, Preliminary data processing. *Zhanar Korganbaeva:* Student coordination during laboratory sessions, Final manuscript editing and formatting.

DISCLOSURE STATEMENT

No potential conflicts of interest were reported by the authors.

FUNDING

This research was funded by Abai Kazakh National Pedagogical University (Contract No. 53, dated April 5, 2025).

ACKNOWLEDGMENTS

The authors would like to thank the Ministry of Education and Science of the Republic of Kazakhstan for supporting PhD student Saulet Adal.

DATA AVAILABILITY STATEMENT

The data and materials supporting the results of this study are available from the corresponding author upon reasonable request.

REFERENCES

Adauyah, R., & Aznam, N. (2024). Guided inquiry learning model in chemistry education: A systematic review. *Jurnal Penelitian Pendidikan*, 10(3), 77-87.

Aguilera, D., & Ortiz-Revilla, J. (2021). STEM vs. STEAM education and student creativity: A systematic literature review. *Education Sciences*, 11, 331.

Al-Mutawah, M.A., Alghazo, Y.M., Mahmoud, E.Y., Preji, N., & Thomas, R. (2021). Designing a need-based integrated “STEAM” framework for primary schools in Bahrain. *International Journal of Educational Practices*, 9, 602-612.

Antonio, R.P., & Prudente, M.S. (2024). Effects of inquiry-based approaches on students’ higher-order thinking skills in science: A meta-analysis. *International Journal of Education in Mathematics, Science and Technology*, 12(1), 251-281.

Alsmadi, M.A. (2020). Requirements for application of the STEM approach as perceived by science, math, and computer teachers and their attitudes towards it. *EURASIA Journal of Mathematics, Science and Technology Education*, 16(9), em1879.

Bahri, A., Idris, I.S., Muis, H., Arifuddin, M., & Fikri, M.J.N. (2020). Blended learning integrated with innovative learning strategy to improve self-regulated learning. *International Journal of Instruction*, 14(1), 779-794.

Barrow, L.H. (2006). A brief history of inquiry: From Dewey to standards. *Journal of Science Teacher Education*, 17(3), 265-278.

Barrows, H.S., & Tamblyn, R.M. (1980). *Problem-Based Learning: An Approach to Medical Education*. Berlin: Springer.

Bates, R., Brenner, B., Schmid, E., Steiner, G., & Vogel, S. (2022). Towards metacompetences in higher education for tackling complex realworld problems - a crossdisciplinary review. *International Journal of Sustainability in Higher Education,* 23(8), 290-308.

Bell, S. (2010). PjBLfor the 21st Century: Skills for the future. *The Clearing House,* 83(2), 39-43.

Bell, S., Urhahne, D., Schanze, S., & Ploetzner, R. (2010). Collaborative inquiry learning: Models, tools, and challenges. *International Journal of Science Education*, 32(3), 349-377.

Biswal, S., & Behera, B. (2023). Enhancing science process skills through inquirybased learning: A comprehensive literature review and analysis. *International Journal of Science and Research*, 12(8), 1583-1589.

Borte, K., Nesje, K., & Lillejord, S. (2020). Barriers to student active learning in higher education. *Teaching in Higher Education*, 28(3), 597-615.

Bozkurt, A., Ucar, H., Durak, G., & Idin, S. (2019). The current state of the art in STEM research: A systematic review study. *Cypriot Journal of Educational Sciences*, 14, 374-383.

Cepni, S., Aydin, M., Ada Yildiz, K., Birisci, S., Ozkan, C., & Yalabuk C. (2024). Examining the impact of modified P3 task taxonomy-enriched educational robotics PD program on teachers’ STEM content knowledge. *International Journal of Science and Mathematics Education*, 22(Suppl 1), 81-110.

Chivapruk, S. (2021). Thailand: Science, technology, engineering, and mathematics education in Roong Aroon School. In: *Different approaches to learning science, technology, engineering, and mathematics: Case studies from Thailand, the Republic of Korea, Singapore, and Finland*. Philippines: Asian Development Bank.

Couso, D., & Simarro, C. (2020). STEM education through the epistemological lens: Unveiling the challenge of STEM transdisciplinarity. In: Johnson, C.C., Mohr-Schroeder, M.J., & Moore, T.J., (Eds.), *Handbook of Research on STEM Education*. London: Routledge, pp. 17-28.

Crippen, K.J., & Archambault, L. (2012). Scaffolded inquiry-based instruction with technology: A signature pedagogy for STEM education. *Computers in Schools*, 29, 157-173.

Dasgupta, C., Magana, A.J., & Vieira, C. (2019). Investigating the affordances of a CAD-enabled learning environment for promoting integrated STEM learning. *Computers and Education*, 129, 122-142.

Dewey, J. (1916). *Democracy and Education: An Introduction to the Philosophy of Education*. United States: Macmillan.

Domenici, V. (2022). STEAM project-based learning activities at the science museum as an effective training for future chemistry teachers. *Education Science*, 12, 30.

Halawa, S., Lin, T.C., & Hsu, Y.S. (2024). Exploring instructional design in K-12 STEM education: A systematic literature review. *International Journal of STEM Education*, 11, 43.

Hasanah, I., Anwar, S., & Musthapa, I. (2024). A trend analysis of project-based learning in chemistry experiment: A bibliometric analysis. *Jurnal Penelitian Pendidikan IPA*, 10(9), 655-666.

Juntunen, M.K., & Aksela, M.K. (2014). Education for sustainable development in chemistry – Challenges, possibilities and pedagogical models in Finland and elsewhere. *Chemistry Education Research and Practice*, 4, 1-15.

Kaleci, D., & Korkmaz, O. (2018). STEM education research: Content analysis. *Universal Journal of Educational Research*, 6(11), 2404-2412.

Karagöl, İ., & Bekmezci, S. (2015). Investigating academic achievements and critical thinking dispositions of teacher candidates. *Journal of Education and Training Studies*, 3(4), 148-157.

Kelley, T.R., & Knowles, J.G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education*, 3, 11.

Kolb, D.A. (1984). *Experiential Learning: Experience as the Source of Learning and Development.* Englewood Cliffs, NJ: Prentice Hall.

Koparan, T., & Güven, B. (2014). The effect of project-based learning on the statistical literacy levels of student 8th grade. *European Journal of Educational Research*, 3(3), 145-157.

Levy, P., & Petrulis, R. (2012). How do first-year university students experience inquiry and research, and what are the implications for the practice of inquiry-based learning? *Studies in Higher Education*, 37(1), 85-101.

Linnenluecke, M.K., Marrone, M., & Singh, A.K. (2020). Conducting systematic literature reviews and bibliometric analyses. *Australian Journal of Management*, 45(2), 175-194.

Liu, R.X., Xiong, F., Chen, C., Ding, T.M., & Zhang, S.Y. (2023). Project-Based Learning in green electrochemistry for undergraduates: An efficient synthesis route of a natural product. *Journal of Chemical Education*, 100(2), 689-696.

Markula, A., & Aksela, M. (2022). The key characteristics of project-based learning: How teachers implement projects in K-12 science education. *Disciplinary and Interdisciplinary Science Education Research*, 4, 2.

Martín-Garcia, J., Dies Álvarez, M.E., & Afonso, A.S. (2024). Understanding science teachers’ integration of active methodologies in club settings: An exploratory study. *Education Sciences*, 14(1), 106.

Mateos-Núñez, M., Martínez-Borreguero, G., & Naranjo-Correa, F.L. (2020). Learning science in primary education with STEM workshops: Analysis of teaching effectiveness from a cognitive and emotional perspective. *Sustainability*, 12(8), 3095.

Mihić, M., & Zavrski, I. (2017). Professors' and students' perception of the advantages and disadvantages of project based learning. *International Journal of Engineering Education*, 33, 1737-1750.

Monera, A., & Salic-Hairulla, S. (2021). Utilization of ICT-integrated STEM lessons on biodiversity for grade 8 learners. *Journal of Physics: Conference Series*, 1835, 012074.

Mundhe, E. & Chavan, P. (Eds.). (2023). Interdisciplinary research pathway of National Education Policy (NEP)-2020. (1st ed.). S. M. Joshi College / Dr. Eknath Mundhe. ISBN 978-93-5777-343-0.

Ningsih, S.R., Disman, D., Ahman, E., Suwatno, S. & Riswanto, A. (2020). Effectiveness of using the project-based learning model in improving creative-thinking ability. *Universal Journal of Educational Research*, 8(4), 456-464.

Panasan, M., & Nuangchalerm, P. (2010). Learning outcomes of project-based and inquiry-based learning activities. *Journal of Social Sciences*, 6(2), 252-255.

Pedaste, M., Mäeots, M., Siiman, L.A., de Jong, T., van Riesen, S.A.N., Kamp, E.T., Manoli, C.C., Zacharia, Z.C., & Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational Research Review*, 14, 47-61.

Pratiwi, E.A., & Ikhsan, J. (2024). Project-based learning (PjBL) in chemistry learning: Systematic literature and bibliometric review 2015-2022. *Jurnal Penelitian Pendidikan*, 10(6), 343-354.

Prince, M.J., & Felder, R.M. (2006). Inductive teaching and learning methods: Definitions, comparisons, and research bases. *Journal of Engineering Education*, 95(2), 123-138.

Rahmania, I. (2021). Project-based learning (PjBL) learning model with STEM approach in natural science learning for the 21st century. *Budapest International Research and Critics Institute (BIRCI) Journal: Humanities and Social Sciences*, 4(1), 1161-1167.

Ribeiro-Silva, E., Amorim, C., Aparicio-Herguedas, J.L., & Batista, P. (2022). Trends of active learning in higher education and students' well-being: A literature review. *Frontiers in Psychology*, 13, 844236.

Rofik, A. (2023). The effect of collaborative problem solving & collaborative project-based learning models to improve the project competences of pre-service teachers. *Pegem Journal of Education and Instruction*, 12(3), 15.

Santos, C., Rybska, E., Klichowski, M., Jankowiak, B., Jaskulska, S., Domingues, N., Carvalho, D., Rocha, T., Paredes, H., Martins, P., & Rocha, J. (2023). Science education through project-based learning: A case study. *Procedia Computer Science*, 219, 1713-1720.

Simbolon, R., & Koeswanti, H.D. (2020). Comparison of PBL (project-based learning) models with PBL (problem-based learning) models to determine student learning outcomes and motivation. *International Journal of Elementary Education,* 4(4), 519-529.

Situmorang, M., Sitorus, M., & Sudrajat, A. (2021). Implementation of project-based learning innovation to develop students' critical thinking skills as a strategy to achieve analytical chemistry competencies. *Indian Journal of Pharmaceutical Education and Research*, 56(1), 41-51.

Smith, S.A., Lee, J.M., & Brown, J.W. (2018). So many genes, so little time: A practical approach to divergence-time estimation in the genomic era. *PLoS One*, 13(5), e0197433.

Syahril, S., Nabawi, R.A., & Safitri, D. (2021). Students' perceptions of the project based on the potential of their region: A project-based learning implementation. *Journal of Technology and Science Education*, 11(2), 295-314.

Tamim, S.R., & Grant, M.M. (2013). Definitions and uses: Case study of teachers implementing project-based learning. *Interdisciplinary Journal of Problem-Based Learning*, 7(2), 5-16.

Tuan, N.N., Hanh, B.T., & Ninh, T.T. (2020). Project-based learning in general chemistry to develop problem-solving and creativity. *American Journal of Educational Research*, 8(7), 475-479.

Viana, R.V., Jumadi, Wilujeng, I., & Kuswanto, H. (2019). The influence of project-based learning based on process skills approach to student's creative thinking skill. *Journal of Physics: Conference Series*, 1233(1), 012033.

Vilela, M., Morais, C., & Paiva, J.C. (2025). Inquiry-based science education in high chemistry: Enhancing communication skills. *Education Sciences*, 15(3), 334.

Voet, M., & De Wever, B. (2018). Teachers' adoption of inquiry-based learning activities: The importance of beliefs about education, the self, and the context. *Educational Researcher*, 70*(*5), 294-306.

Vygotsky, L.S. (1978). *Mind in Society: The Development of Higher Psychological Processes.* Cambridge, MA: Harvard University Press.

Wale, B.D., & Bishaw, K.S. (2020). Effects of using inquiry-based learning on EFL students' critical thinking skills. *Asian-Pacific Journal of Second and Foreign Language Education*, 5(1), 9.

Warr, M., & West, R.E. (2020). Bridging academic disciplines with interdisciplinary project-based learning. *Interdisciplinary Journal of Problem-Based Learning*, 14(1), 28590.

Wulandari, D.S., Prayitno, B.A., & Maridi, M. (2022). Developing the guided inquiry-based module on the circulatory system to improve student's critical thinking skills. *Jurnal Pendidikan Biologi Indonesia*, 8(1), 77-85.

Žerovnik, A., & Nančovska Šerbec, I. (2021). Project-based learning in higher education. In: *Technology Supported Active Learning: Student-Centered Approaches*. Berlin: Springer, pp. 31-57.

Zhang, L., & Ma, Y. (2023). A study of the impact of project-based learning on student learning effects: A meta-analysis study. *Frontiers in Psychology*, 14, 1202728.

SUPPLEMENTARY MATERIAL

Supplementary Assessment: Enhancing Research Skills in Chemistry Education via Integrated Project- and Inquiry-Based Learning in a STEM Context

Supplementary Table 1: Assessment criteria for students' learning outcomes based on the integration of PjBL and IBL methods

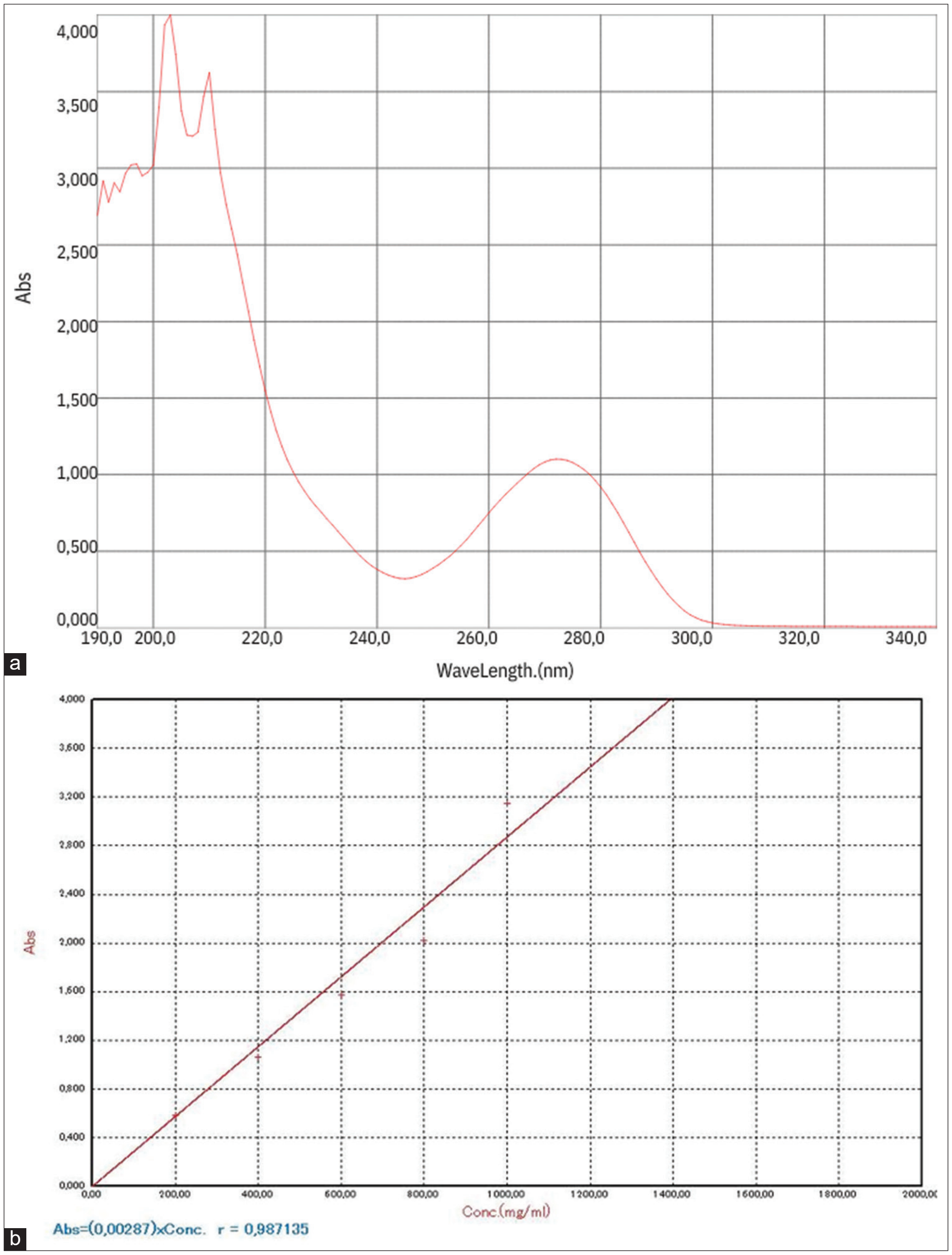
No	Assessment criteria	Description	Assessment scale
1	Literature review	Level of searching for, analyzing, and aligning scientific sources with the research topic	1–5 points
2	Hypothesis formulation	Ability to develop a scientifically grounded hypothesis aligned with the research objective	1–5 points
3	Conducting the experiment	Accuracy in planning the experiment, following the methodology, and performing laboratory work	1–5 points
4	Data processing	Calculation of results, construction of graphs, and performance of statistical analysis	1–5 points
5	Research report writing	Adherence to the structure of a scientific report, logical coherence of content, and correctness of scientific language	1–5 points
6	Presentation of results	Scientific oral and visual (presentation) communication of research findings	1–5 points

Each criterion was assessed using a 5-point Likert scale, where 1 indicates a low level and 5 indicates a high level

Supplementary Table 2: Pre- and post-test questions administered via Google Forms for assessing research skills development

Section	No	Question
1. Literature Review	1.1	I understand the components of a literature review and its purpose.
	1.2	I am able to search for and work with scientific articles in specialized academic databases.
	1.3	I can find, analyze, and critically evaluate scientific information.
2. Formulating Hypotheses	2.1	My skills in formulating scientific hypotheses are developed.
	2.2	I have mastered and apply methods for testing and validating scientific hypotheses.
	2.3	My ability to analyze data and draw conclusions based on the obtained results is at a high level.
3. Experimental Design	3.1	I understand the stages of conducting a scientific experiment.
	3.2	My skills in organizing and planning experiments are developed.
	3.3	My ability to analyze experimental results and draw conclusions is developed.
4. Statistical Analysis	4.1	I have an understanding of the basics of statistical data analysis.
	4.2	My skills in using statistical methods for data processing are developed.
	4.3	My ability to interpret statistical analysis results is developed.
5. Scientific Reporting	5.1	I understand the structure and requirements of a scientific research report.
	5.2	My skills in writing a scientific research report are developed.
	5.3	My ability to format a research report in accordance with scientific standards is developed.
6. Oral Presentation	6.1	My skills in preparing a presentation for a scientific report are developed.
	6.2	My ability to present scientific results clearly and logically in oral form is developed.
	6.3	My ability to answer questions and argue my position when presenting scientific results is developed.

Scale (1–5): 1=Very low/Completely undeveloped; 2=Poorly developed/Below average; 3=Partially developed/Average; 4=Well developed/Above average; 5=Fully developed and confidently applied



Supplementary Figure 1: (a) Absorbance spectrum of caffeine standard solution in the UV range (190–340 nm). The UV scan of caffeine standard solution shows the absorbance spectrum recorded in the range of 190–340 nm, with maximum absorbance observed at 272 nm. (b) Calibration curve of caffeine standard solution was recorded at 272 nm. The calibration curve was recorded using standard caffeine solutions (200–1000 mg/mL). A linear regression equation (y = ax + b) with the corresponding R^2 value is shown on the plot. X-axis → Concentration (mg/mL), Y-axis → Absorbance (abs), Regression line + equation + R^2