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Project-Based Learning in Chemistry: Improving Laboratory Skill through Gravimetric Alkaloid Analysis of Local Natural Materials

Nurfatimah Sugrah[1], Khusna Arif Rakhman[2*], Nur Jannah Baturante[3], Indra Cipta[4], Ni Made Wiratini[5], Agung Abadi Kiswandono[6], Dimas Saman[7]
[1,2,3,4,7] Department of Chemistry Education, Universitas Khairun, Ternate, Indonesia.
[5] Department of Chemistry Education, Universitas Pendidikan Ganesha, Bali, Indonesia
[6] Department of Chemistry, Universitas Lampung, Bandar Lampung, Indonesia

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*Corresponding Author Email:
Khusna.arif@unkhair.ac.id

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Abstract: Conventional chemistry laboratory instruction often separates theoretical understanding from practical activities, limiting students' opportunities to develop integrated knowledge and laboratory skills. Project-Based Learning (PjBL) has been widely recognized as an effective approach to promote active, collaborative, and experiential learning in chemistry education. This study implemented PjBL in an analytical chemistry laboratory course involving 21 students, with samples divided into four groups. Students conducted projects on the isolation and gravimetric determination of alkaloids from local natural materials in North Maluku. Learning outcomes were evaluated through observations of laboratory activities, data analysis, collaboration, and research poster presentations. The imple mentation of PjBL showed high student participation (91.7%) and improved laboratory skills, including chemical handling, gravimetric analysis, data management, and scientific communication. Students successfully produced research reports and posters, while most participants reported enjoyable learning experiences, increased motivation, and improved collaboration and problem-solving skills. Research-based PjBL effectively integrates theoretical knowledge and laboratory practice, while supporting the development of laboratory competence, collaborative learning, and scientific communication skills among chemistry education students.

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INTRODUCTION

The declining interest in science, technology, engineering, and mathematics (STEM) education, despite the growing demand for STEM-related careers, has encouraged educators to develop learning experiences that foster students' knowledge and professional skills (O'Rourke, 2021). In chemistry education, laboratory learning plays a crucial role in supporting this goal by providing opportunities for students to apply theoretical concepts in practical contexts. Previous studies have shown that research-based laboratory experience can enhance students' interest in STEM, promote critical thinking, and improve communication skills (Dorn et al., 2021; Heller et al., 2020; Kerr & Yan, 2016). For chemistry education students, laboratory experiences are particularly important because they contribute to the development of both conceptual understanding and practical laboratory competencies required for future professional practice. When appropriately designed, chemistry laboratory activities also support the development of collaboration, communication, and time-management skills (Scarborough et al., 2022).

The focus of teaching chemistry through laboratory experiences has become a central principle of science pedagogy and underlies systematic science learning (Barr et al., 2022). Laboratory learning experience can enhance motivation, personal engagement, and knowledge retention among chemistry students (Provost, 2022). However, the effectiveness of traditional instruction-based laboratory activities remains a subject of debate because students often follow predetermined procedures with limited opportunities for inquiry and decision-making (Bretz, 2019). The primary goal of laboratory learning is to incorporate essential aspects of chemistry learning into practical learning and to provide opportunities for managing laboratory equipment and chemicals (Liu et al., 2023). To address this challenge, research-based laboratory activities can be designed using the PjBL approach, which provides opportunities for students to engage in authentic problem-solving and independent investigation (Davis et al., 2017; Ealangov & Jamaludin, 2024; Robinson, 2013). Previous studies have shown that PjBL can enhance cognitive achievement, professional skills, scientific literacy, creative thinking (Vogler et al., 2018), and learning motivation (Chrysti Suryandari et al., 2018; Roslina et al., 2023; Saraha et al., 2022; Setyawati et al., 2023). However, most reported PjBL implementations in chemistry laboratories focus on general laboratory projects or environmental and synthetic research projects involving gravimetric alkaloid analysis of local neutral materials, and have received limited attention. This context provides students with opportunities to integrate analytical chemistry concepts, laboratory techniques, scientific communication, and collaborative research experiences within a single learning project. Therefore, this study explores the implementation of PjBL through a gravimetric alkaloid analysis project using local natural materials as a strategy to develop laboratory skills and meaningful learning experiences among chemistry education students.

At the beginning of the second year of chemistry studies in undergraduate Chemistry Education, students are introduced to analytical chemistry. Analytical chemistry is a course that teaches various analytical methods and chemical separations to manage analyte objects into data and information. One of the analytical methods studied is gravimetry. Gravimetry is an analytical method that utilizes signals resulting from changes in the mass of the analyte in its application (Harvey, 2004). As it supports the development of competencies associated with the analytical chemist profile, this method continues to be highly relevant for preparing chemistry education students for professional laboratory practice. To prepare for integrated learning between theory and practice, the delivery of gravimetric methods requires a more concrete learning design, such as utilizing local issues or natural resources. Determining the alkaloid content of natural material samples by gravimetry can be used as a concrete learning design, where this analytical method has been previously reported on *Peperomia pellucida (L.) kunth, Carica papaya* leaves, and *Rauvolfia tetraphylla* (Ahmad et al., 2017; Julianti et al., 2014; Verma, 2017). Alkaloid content analysis involves several complex stages, including preparation, extraction by maceration, and determination of the alkaloid content gravimetrically (Ahmad et al., 2017). This process can provide a broader learning space for the development of theoretical chemical knowledge and laboratory skills (Doughan & Shahmuradyan, 2022). In analytical chemistry education, laboratory instruction frequently emphasizes procedural accuracy and technical competency. While these aspects are essential, students often have limited opportunities to engage in authentic scientific inquiry, formulate research questions, interpret experimental data, and communicate findings in formats commonly used by scientists. As a result, laboratory activities may not fully support the development of higher-order scientific skills required for future chemistry professionals. Research-based PjBL offers a promising alternative by positioning students as active investigators rather than passive followers of laboratory instructions. Through authentic research experiences, students can simultaneously develop conceptual understanding, technical competencies, scientific reasoning, and communication skills.

Although numerous studies have reported the effectiveness of PjBL in a chemistry laboratory course, its implementation in analytical chemistry learning, particularly in gravimetric analysis, remains limited, particularly in authentic research projects using local natural materials. Furthermore, there is limited evidence regarding how such projects contribute to the development of laboratory skills and scientific communication among chemistry education students. The study specifically explores how PjBL can be implemented in an analytical chemistry laboratory setting and how it supports the development of laboratory skills, scientific communication, and student engagement.

METHOD

Research design

This study employed a descriptive qualitative approach to evaluate the implementation of PjBL in an analytical chemistry laboratory course focusing on gravimetric alkaloid analysis.

Participants and Research Setting

The study was conducted in the Department of Chemistry Education at Universitas Khairun, Terna, Indonesia, during the 2024/2025 academic year. Participants consisted of 21 second-year undergraduate chemistry education students enrolled in the analytical chemistry course. Students were divided into four groups to conduct a research project on different local natural materials.

Pedagogical approach

The implementation of PjBL followed six main stages adapted from previous studies: determining basic questions, designing projects, scheduling activities, monitoring projects, testing results, and evaluating experiences (Budner & Simpson, 2018; Davis et al., 2017; Scarborough et al., 2022). These stages were organized into introductory, core, and closing activities over eight weeks. Detailed learning activities are presented in Table 1.

Table 1. PjBL activity and assessments

Course	Activity	PjBL syntax number	Assessment	Output
1	Introduction, lecture course in gravimetric, selection of research groups, assignment of the alkaloid determination method reading.	1–3	Discussion of the alkaloid determination from a natural sample method.	List of research groups and the chart method.
2-5	Data collection	4	Student activity	Data summaries
6-7	Preparation of task products	4	Student activity	Research poster
8	Research task presentation	5–6	Student presentation	Learning outcomes

Data Collection

Data were collected through observations of students' laboratory activities, research logbooks, research posters, presentations, and student responses during the learning process. Observation aspects included laboratory skills, collaboration, chemical management, adherence to procedures, data analysis, and scientific communication skills.

Analysis of Alkaloid

Gravimetric analysis of the alkaloid content in local natural material samples was conducted according to the stages outlined in previous research (Ahmad et al., 2017; Wardatun et al., 2019). The samples used in this student research project consisted of different local natural materials within each group. The local natural materials used included Myristrica fragrans, Flacourtia inermis, and Syzygium cumini (L.) Skeels, and Moringa oleifera, which were labeled as S1, S2, S3, and S4, respectively.

For the analysis of alkaloid content, each sample (S1, S2, S3, and S4) was prepared by cutting it into small pieces and drying it in an oven at 60 °C. The dried samples were then macerated with 10% acetic acid at sample-to-solvent ratios of 1:2.5, 1:5, 1:10, and 1:20 (w/v), left to stand, and stored for 2, 24, 36, and 72 hours. Next, filtration was performed to separate the filtrate from the maceration residue. The obtained filtrate was then concentrated on a water bath until the remaining volume was reduced to 25%. The concentrated filtrate was then added to concentrated ammonium hydroxide to adjust the pH to 9, and left to stand until a precipitate formed. The precipitate formed was filtered, washed with distilled water, and then dried. The precipitate on the dry filter paper was then weighed, and the mass change was recorded compared to the blank filter paper before filtration. The alkaloid content was determined as a percentage (w/w) by calculating the difference in the weighing results of the precipitate formed.

Data Analysis

The collected data were analyzed descriptively to examine student participation, laboratory skill development, and learning outcomes during PjBL implementation. Student responses were summarized qualitatively based on reflective statements and learning evaluations.

RESULT AND DISCUSSION

Implementation of project-based learning

The gravimetric alkaloid analysis research process was guided by a previously developed practicum module (Rakhman et al., 2024). The implementation of PjBL in the laboratory, according to syntax 4, demonstrated high student participation, at 91.7%, indicating strong engagement throughout the research activities. Students were actively involved in laboratory procedures, group discussions, and writing research diaries. This finding supports previous studies reporting that project-based learning promotes active participation and student-centered learning environments in chemistry laboratories (Rakhman et al., 2026). The research activities required students to take responsibility for experimental planning, sample preparation, data collection, and interpretation, thereby encouraging greater ownership of the learning process.

The average laboratory activity duration was 210 minutes per day, exceeding the allocated laboratory time of 170 minutes. This finding suggests that students were highly engaged in completing their research tasks and collaborating within their groups. Similar observations were reported by Scarborough et al., (2022), who found that laboratory research projects increased student commitment and participation because students perceived the activities as authentic scientific investigations rather than routine laboratory exercises. Furthermore, the collaborative nature of PjBL has been shown to strengthen teamwork, communication, and problem-solving skills while fostering deeper conceptual understanding (Aga, 2024). Consistent with previous findings, students in this study demonstrated active collaboration in technical laboratory work and research discussions, contributing to a more comfortable learning environment and supporting knowledge construction through social interaction (Bhandari et al., 2024; Che Ahmad et al., 2017). The detailed activities of students and lecturers in implementing PjBL are presented in Table 2.

Table 2. Lecturer and Student Activities in PjBL

Week	Lecture activity	Students activity	Duration (mnt)
1	Introduce the gravimetric methods and project-based learning plans.	Listening to a lecture.	170
2	Assistance and observation.	Group discussion, chemical preparation, and maceration of samples.	210
3	Assistance and observation.	Group discussion, sample maceration, extractant filtration and treatment, and first gravimetry analysis.	210
4	Assistance and observation.	Group discussion, extractant filtration and treatment, and second gravimetric analysis.	210
5	Assistance and observation.	Group discussion, extractant filtration and treatment, and third gravimetric analysis.	210
6-7	-	Group collaboration to develop task products.	450
8	Assessment	Research result presentation	170

Students spent an average of 40 min longer collecting research data than in traditional learning. This additional time is believed to help create a more comfortable and enjoyable learning environment in the laboratory. This statement is supported by Andriani, (2025), who reported that a relaxed learning environment enhances student engagement, promotes positive attitudes, and promotes effective time management, all of which contribute to improved academic achievement.

Analysis of alkaloid

Four groups of students participated in the gravimetric analysis of alkaloids as part of a research project. Each group examined samples from various natural products, including jamblang leaves (*Syzygium cumini (L.) Skeels*, S4), nutmeg (*Myristica fragrans*, S2), tome-tome fruit (*Flacourtia inermis*, S1), and moringa leaves (*Moringa oleifera L*., S3). Using maceration, the study investigated how alkaloid yields were affected by the sample-to-solvent ratio and extraction period (Fig. 1).

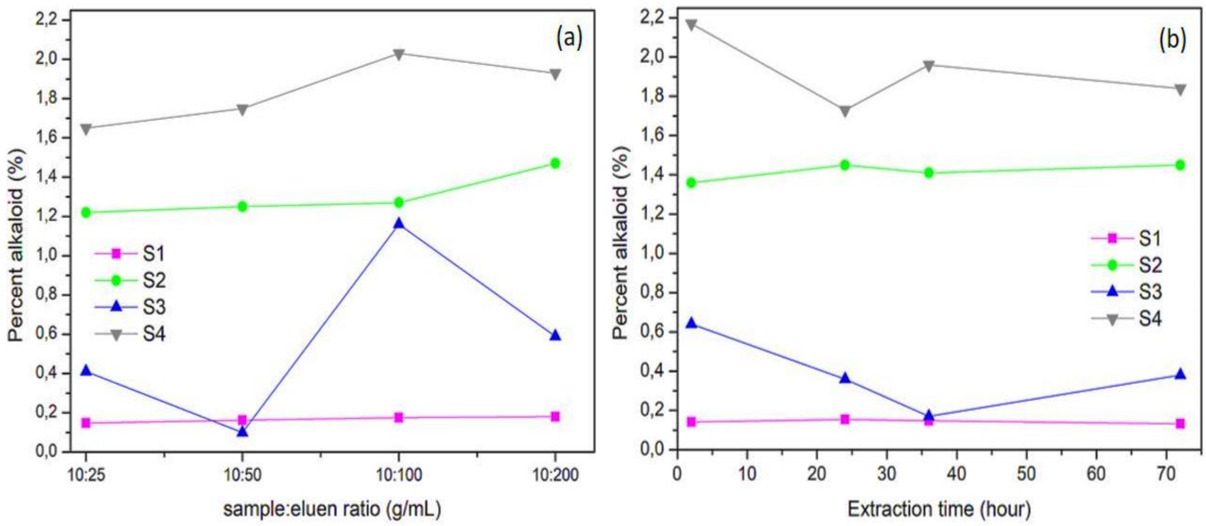

Figure 1. Percent of alkaloid (a) sample: solvent extraction ratio, (b) extraction time.

The alkaloid content was shown in descending order according to the gravimetric results: S4 > S2 > S3 > S1. Acetic acid was chosen as a solvent in the maceration process because alkaloids dissolve well in this solvent, making it easy to separate from other secondary metabolite compounds in the sample (Fadhly et al., 2015; Kapondo et al., 2020; Xiao et al., 2023). Figure 1 illustrates the alkaloid yield in each sample, which is influenced by the maceration time and the sample-to-solvent volume ratio. The yield data show that the optimal alkaloid percentage is obtained at a sample-to-solvent volume ratio of 1:10 g/mL for S1, S3, and S4, while S2 is at 1:20 g/mL. Meanwhile, the optimum maceration times for each sample are 24 hours for S1 and S2, and 2 hours for S3 and S4. Alkaloid compounds dissolved in acid during the maceration process are then neutralized by adding base to form a precipitate. Determination of alkaloid content in percentage is calculated from the difference in mass between the precipitate and the empty filter paper (Dewi, 2020; Teng et al., 2023). The highest alkaloid content is shown by S4 at 2.17%, followed by S2 at 1.47%, S3 at 1.16%, and S1 at 0.21%. The observed differences in alkaloid yields among samples and extraction conditions provided meaningful opportunities for students to engage in data interpretation and scientific reasoning. Rather than following predetermined laboratory procedures, students were required to analyze experimental outcomes, compare extraction parameters, and construct evidence-based explanations. This finding supports previous studies reporting that project-based laboratory learning promotes higher-order thinking, problem-solving, and deeper engagement with scientific concepts (Chimwayange, 2025; Eshun et al., 2026; Situmorang, 2026).

Learning outcomes and output

The learning process begins with an introductory stage covering syntax 1-3 of the PjBL, namely the lecturer provides an introduction to gravimetric analysis, determines basic questions about alkaloid analysis, creates a project design by dividing groups and sample types, and arranges a schedule for implementing the alkaloid analysis research project on local natural material samples. Figure 2 illustrates the stages of implementing the PjBL gravimetric alkaloid analysis research project in the laboratory. The introductory stage is conducted through a lecture session led by the lecturer, followed by the implementation of the gravimetric alkaloid analysis research project in the laboratory, assisted by the gravimetric practicum module, until the PjBL output is presented in the form of a research poster. Through evaluations of their poster presentations and observations of their laboratory procedures, students' learning outcomes are assessed.

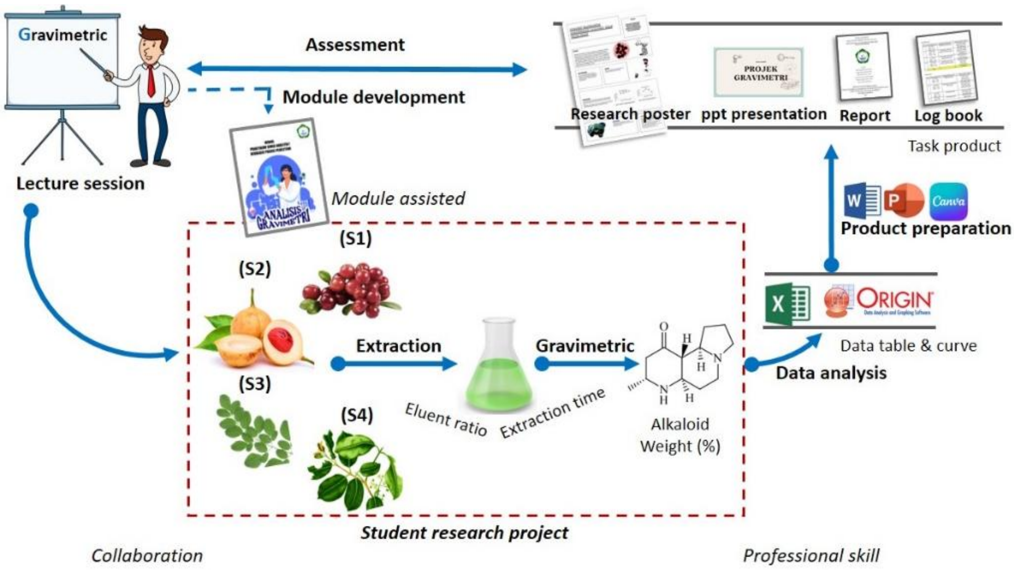

Figure 2. Illustration of Project-based Learning Stages

Improved chemical knowledge and skills, particularly in gravimetric analysis, as well as the production of research posters based on students' laboratory work, are among the key learning outcomes and outputs of this project-based learning (PjBL) approach. A thorough analysis of the PjBL activities is presented in Table 3, which highlights the knowledge- and skill-based learning objectives, as well as the corresponding outputs. While knowledge-oriented outcomes are often associated with assignment preparation, skill-oriented outcomes are directly related to laboratory research activities. The development of students' professional competencies is greatly aided by these factors taken together.

In PjBL, learning objectives are visible throughout the entire research process. Students create chemical materials, obtain a thorough understanding of gravimetric and maceration processes, and compute alkaloid percentages while gathering data. During the data analysis phase, they determine the ideal extraction parameters, including the maceration duration and sample-to-solvent ratio for natural product samples. Students show that they can write reports, handle references, effectively present research material, make arguments, explain findings, and draw meaningful conclusions as they create the final project output. One of the most critical aspects of developing scientific skills is the presentation of research data in reports (Yusof et al., 2022).

Table 3. Learning outcomes and output

Activity	Learning outcomes		Output learning
	Skill	Knowledge	
Lecture session		Students understanding of analysis gravimetric	
Research collect data	• Tools and chemical preparation • Maceration technique • Filtration technique • Balancing technique • Data management • Organizing research collaboration	• Calculate the chemical concentration. • Maceration procedure • Gravimetric procedure • Calculate alkaloid percent	Data and research logbook

Activity	Learning outcomes		Output learning
	Skill	Knowledge	
Data analysis	• Operating the software for data analysis • Converting data to curve presentation	Determine the optimum condition	Data table and curve
Task product preparation	Operating the software of graphic design	• Report writing • Reference management • Data presentation • Argument writing • Write the problem-solving • Write the conclusion	Research poster, PPT, and report
Presentation and assessment	Research presentation	Alkaloid isolation method	

Student learning outcomes in laboratory skills are observed at each stage of the learning process. Laboratory skills are more dominant during research data collection than at other learning stages. Some key skills at the research data collection stage include preparing tools and chemicals independently, conducting maceration, gravimetry, filtration, weighing, managing data, and collaborating on research. At the data analysis stage, students must be able to operate data analysis software such as Excel or Origin and convert data into curves. At the research output product preparation stage, students must be able to operate graphic design software such as Canva to create research posters.

Laboratory skills in learning outcomes are analyzed in this research-based learning through observations of the learning process, which include seven observations of skill aspects. The seven observed aspects represent several skill aspects in Table 3, and indicate the achievement of learning objectives and outcomes, including student activeness in observing the student collaboration process, demonstrated laboratory skills, chemical management, adherence to procedures, data management and analysis, preparation of research products, and presentation skills in research dissemination. The results of observations of the seven learning outcomes are presented in Fig. 3.

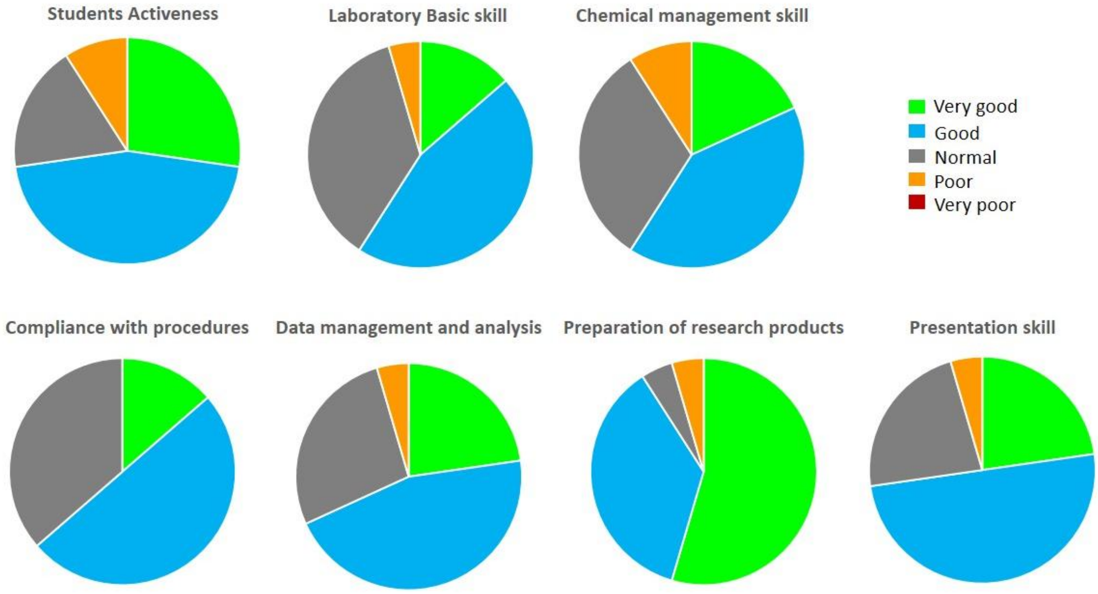

Figure 3. Diagrams of PjBL Learning Outcomes

In the process of research project-based learning in the Laboratory, 64% of 21 students were actively involved in collaboration and work, 23% were in the moderate category, and 13% were still less active. Student activeness in learning indicates a student-centered learning process. High student engagement can also be considered a success in facilitating a collaborative space and an enjoyable learning experience. Enjoyable learning has been reported to increase student activeness in the learning process in PjBL (Eshun et al., 2026). This claim is supported by survey results that show 85.7% of students enjoyed this learning experience, 76.2% of students admitted to having many discussions during the learning process, and 91.6% of students showed that this project was able to motivate their learning. The high level of student participation observed in this study may be attributed to the authentic nature of the project. Unlike conventional laboratory experience that relies on pre-experimental procedures and expected outcomes, students were required to make decisions regarding experimental implementation, monitor research progress, and interpret the results obtained from different natural materials samples. Such autonomy is considered an important characteristic of PjBL because it encourages students to assume greater responsibility for their learning process. Previous studies have shown that authentic research experiences enhance students' sense of ownership, intrinsic motivation, and persistence in completing scientific tasks (Hansen et al., 2024; Hohrath et al., 2024). Therefore, the high engagement observed in this study may reflect the effectiveness of research-oriented PjBL in fostering active participation in chemistry laboratory learning.

Project-Based Learning (PjBL) also builds students' confidence in using laboratory equipment, preparing samples, and managing chemicals. The development of laboratory skills observed in this study extends beyond the acquisition of technical procedures. Students were required to independently prepare laboratory equipment, manage chemicals, perform gravimetric analysis, and maintain a research record throughout the project. The activities resemble authentic laboratory practices commonly encountered in research and industrial settings. Consequently, students were exposed not only to analytical techniques but also to laboratory management and quality-control practices. This finding supports previous reports indicating that research-based laboratory projects contribute to the development of professional competencies and workplace readiness among chemistry students (Agustian, 2025; Madybekova et al., 2026). The ability to integrate technical and organizational skills is particularly important in analytical chemistry, where data quality depends on careful planning, documentation, and procedural consistency. During data collection in the laboratory, students' adherence to research procedures was high, allowing the research to proceed smoothly and avoiding any dangerous incidents. Students were also able to accurately and orderly record and categorize research data in a logbook. The student research logbook was used as an instrument to assess data management and analysis skills. The results of the data analysis were then presented in a report and a research poster as the final outputs of the project-based learning. The research poster presented in Fig. 4, produced from PjBL, demonstrates the achievement of outputs and outcomes. In the resulting research poster, it was observed that students were able to present research data systematically and attractively, which is a claimed scientific skill. Although this was the first time students had created a research poster, they completed it and presented the research results well. In the final assessment, students were able to present their research posters well. They demonstrated an understanding of the PjBL that had been implemented to achieve the targeted learning outcomes.

The preparation and presentation of research posters also represent an important component of scientific communication training. In chemistry education, students are often assessed through written laboratory reports, whereas opportunities to communicate findings through professional scientific formats remain limited. The poster development process required students to summarize experimental results, organize visual information, justify interpretations, and communicate findings to an audience. These activities support the development of scientific literacy and communication skills that are increasingly recognized as essential graduate competencies. Similar findings were reported by Cao et al, (2025), who found that project-based laboratory activities significantly improved students' scientific writing and presentation abilities. Therefore, the inclusion of poster-based dissemination activities may strengthen the broader educational value of laboratory learning.

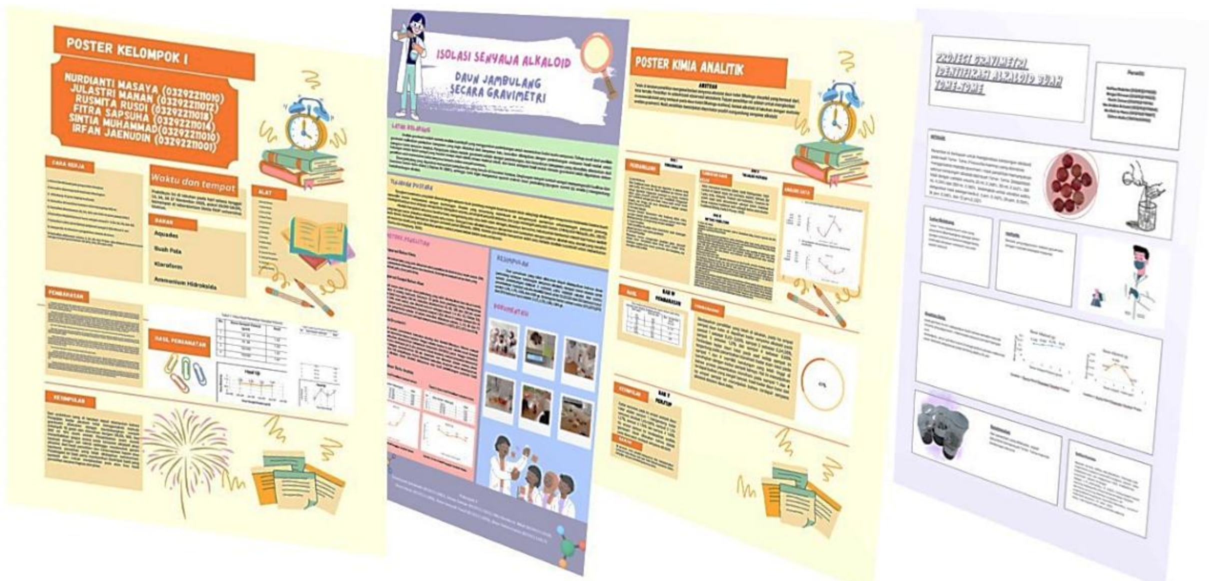

Figure 4. Poster Output of PjBL

A research project-based learning program on the isolation and determination of alkaloids in local natural materials from North Maluku provided valuable experience for second-year chemistry students. Most students provided positive feedback when asked to write about their learning experiences in the gravimetric determination of alkaloids from natural materials, including:

- *"This learning experience was delightful, and it was my first time working on a research project using natural products."*
- *"I learned to collaborate and solve problems during the practicum. I discovered independently the challenges involved in alkaloid isolation and gravimetric analysis."*
- *"I gained skills in analytical techniques for alkaloid analysis from natural products. We isolated natural product samples to analyze the alkaloid content gravimetrically."*

These positive responses suggest that PjBL provided a meaningful learning experience beyond the acquisition of laboratory techniques. Students reported increased opportunities for collaboration, problem-solving, and independent inquiry while conducting gravimetric alkaloid analysis. Similar findings have been reported in chemistry education research, where project-based laboratory activities were found to increase student motivation, engagement, and ownership of learning (Chang et al., 2024). Moreover, the use of authentic research projects has been shown to facilitate deeper conceptual understanding and the development of scientific practices, including data interpretation and scientific communication (Megawati, 2024). The present findings therefore reinforce the value of PjBL as an effective approach for integrating theoretical knowledge with laboratory experiences in analytical chemistry education.

Educational Implication

The findings of this study have several important implications for chemistry education, particularly in the design and implementation of laboratory-based learning. First, the integration of authentic research projects into analytical chemistry laboratories provides a practical framework for implementing outcome-based learning. Through the project, students were required not only to master analytical techniques for gravimetric alkaloid determination but also to demonstrate communication, collaboration, data management, and problem-solving skills. This finding supports the view that laboratory learning should facilitate the development of both disciplinary knowledge and transferable professional competencies (Memmen & Markic, 2025). Second, the use of local natural materials as research objects offers contextualized learning experiences that connect chemistry concepts with regional resources and real-world applications. Such an approach may increase the relevance of learning and encourage students to recognize the potential of local biodiversity as a scientific resource and strengthen students' engagement with chemistry (Poya, 2026).

Third, the implementation of research-based PjBL may serve as a model for redesigning laboratory courses that traditionally emphasize verification-based experiments. By engaging students in authentic scientific investigations, laboratory instruction can shift toward an inquiry-oriented, student-centered approach that promotes active participation, scientific reasoning, and independent learning. Furthermore, the integration of research activities, laboratory practice, data interpretation, and scientific communication within a single project demonstrates how chemistry curricula can be designed to support the simultaneous development of technical competencies and professional skills (Sugrah et al., 2025). Such an approach may better prepare chemistry education students for future careers as educators, researchers, or laboratory professionals.

Limitations and Recommendations

This study has several limitations that should be considered when interpreting the findings. First, the study involved a relatively small number of participants (21 students), which may limit the generalizability of the findings to other educational contexts. Second, the project was implemented within a single analytical chemistry topic, namely the gravimetric determination of alkaloids from local natural materials. Consequently, the effectiveness of the approach across different chemistry disciplines and laboratory contexts remains to be explored. Despite these limitations, the findings suggest that research-based PjBL provides meaningful opportunities for integrating theoretical knowledge, laboratory practice, scientific communication, and collaborative learning in analytical chemistry education. For educational practice, chemistry instructors may consider incorporating an authentic research project using locally relevant materials to enhance student engagement and laboratory competence. Such a project can also support outcome-based learning by simultaneously developing technical and professional skills.

Future research should involve larger and more diverse student populations from multiple institutions to improve the generalizability of the findings. Further studies may also employ quantitative or mixed-methods designs to examine the effects of PjBL on laboratory skills, scientific communications, problem-solving abilities, critical thinking, and academic performance. In addition, future investigation could explore the implementation of research-based PjBL in other chemistry disciplines, such as organic chemistry, environmental chemistry, instrumental analysis, or biochemistry, to evaluate its broader applicability in chemistry.

CONCLUSION

This study demonstrated that PjBL can be effectively implemented in an analytical chemistry laboratory through an authentic research project involving the isolation and gravimetric determination of alkaloids from local natural materials. The implementation of PjBL provided students with opportunities to engage in experimental planning, laboratory investigation, data analysis, scientific communication, and collaborative problem-solving throughout the research process.

The findings indicated that PjBL supported the development of laboratory competencies, including sample preparation, chemical handling, gravimetric analysis, data management, and research dissemination through reports, posters, and presentations. Students also demonstrated a high level of participation and positive perceptions of the learning experience, suggesting that PjBL can promote engagement, collaboration, and meaningful learning in analytical chemistry education.

These findings highlight the potential of research-based PjBL as an instructional strategy for integrating theoretical knowledge with authentic laboratory practice while fostering both technical and professional skills among chemistry education students. Future research should investigate the effectiveness of this approach using larger participant groups and different analytical chemistry topics. Further studies may also examine its long-term impact on scientific reasoning, laboratory competence, communication skills, and academic achievement through quantitative or mixed-methods research designs.

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