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Developing a Research-Integrated PjBL Model and Descriptive Assessment for Laboratory and Science Process Skills

Khusna Arif Rakhman[1,*], Indra Cipta[1], Nurfatimah Sugrah[1], Dira Ayu Annisa[1], Ni Made Wiratini[2], & Nurbaiti Kumendong[3]

[1]Department of Chemistry Education, Universitas Khairun, Indonesia
[2]Department of Chemistry Education, Universitas Pendidikan Ganesha, Indonesia
[3]Laboratory of Chemistry, Universitas Khairun, Indonesia

*Corresponding email: khusna.arif@unkhair.ac.id

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Abstract: This study aims to describe the implementation of environmentally friendly chemistry lessons and projects and the associated levels of students' laboratory and science process skills. The Research-Integrated Project-Based Learning (RPjBL) model was proposed as a framework for developing industrially applicable processes for the synthesis of silver nanoparticles (AgNPs) using bioreduction agents derived from nature. The model was developed using the ADDIE (Analysis, Design, Development, Implementation, Evaluation) model to describe the steps involved in synthesizing AgNPs. The sample consisted of 21 students who completed assessments of their laboratory and science process skills and their project performance. Expert reviews of the RPjBL model and the accompanying instruments (learning modules, instructional syntax, and assessment instruments) were performed through focus group discussions (FGDs) and the Delphi technique. The content validity of the RPjBL model, along with the supporting assessment instruments, was evaluated via Aiken's V analysis. The overall content validity was over 0.87. Reliability for each instrument was measured using Cronbach's alpha; the results indicated very good reliability (all > 0.70). Student assessment data demonstrate that students have a high level of proficiency in laboratory techniques, including the preparation of chemicals and materials (mean = 80.95), chemical handling (mean = 82.86), and performing laboratory procedures (mean = 80.00). Assessment of students' ability to perform the science processes demonstrated exceptionally high proficiency, especially in observing (mean = 88.10) and interpreting data (mean = 90.48). Assessment of students' project performance (using several measures of how well students understood the research process and the quality of their project presentations) had a mean of 75.69. Inferential analysis using Pearson's correlation indicated a positive, but non-significant, relationship between students' laboratory and science process skills. Overall, these findings suggest that the RPjBL model has the potential to integrate research-based education and green chemistry into the laboratory experience.

Keywords: research-integrated project-based learning, green chemistry, laboratory skills, science process skills.

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INTRODUCTION

Project-Based Learning (PjBL) is a well-recognized teaching model in chemistry laboratory education that provides students with opportunities to learn authentic scientific practices by completing projects focused on solving real-world problems. Studies that were conducted previously show that the use of PjBL was successful in promoting the development of critical thinking, collaboration, problem-solving, and laboratory competencies among students, especially in areas of environmental, analytical, and instrumentation-focused chemistry (Adami, 2006; Davis, Pauls, & Dick, 2017; Kerr & Yan,

2016; Wellhöfer & Lühken, 2022). Commonly, the PjBL designs emphasize developing fundamental laboratory skills, analytical methods, and the ability to interpret data, as well as applying these skills in real-world environmental contexts. Despite a large body of prior work on incorporating PjBL into chemistry laboratory education, few documented studies integrate students into recent advances in chemical research, specifically in a research-integrated (RPjBL) format. The majority of existing PjBL laboratory designs do not go beyond analytical or environmental chemistry examples and do not include emerging research fields such as green nanotechnology or the biosynthesis of nanomaterials. Although green chemistry principles are being increasingly included in laboratory instruction to increase students' awareness of environmental concerns and sustainability issues (Das & Marsili, 2010; Grasso, Zane, & Dragone, 2019), the majority of the documented examples are in the form of modified instructional experiments rather than providing students with opportunities to engage in authentic research experiences that reflect current scientific practice. Finally, while biosynthesis of metallic nanoparticles has been studied at length by scientists from both a mechanistic and technological standpoint (Dahoumane et al., 2014; Das & Marsili, 2010; Mukherjee et al., 2001), there is very little documentation of the systematic incorporation of this topic into the project-based chemistry laboratory education. As such, this represents a gap in the field and creates a need for the development of an RPjBL model that provides opportunities for students to develop their laboratory and science process skills and to apply these skills in the context of contemporary research, including environmentally friendly nanomaterial biosynthesis.

The PjBL approach enables students to participate in experimental approaches to learning in laboratory settings. Using this method, students will develop practical skills, be able to think critically, work cooperatively with other students, and develop solutions to scientifically relevant and real-world problems based on their theoretical conceptualizations through hands-on experience in a project. Furthermore, the PjBL method provides students with an opportunity to develop a better understanding of complex scientific theories than non-PjBL students. As students relate theoretical conceptualizations to their hands-on experience with a project in a classroom or field setting, they will develop a deeper understanding of theoretical conceptualizations than non-PjBL students. An additional benefit of the PjBL method is that it serves as a bridge between academic learning and experiential learning. The literature has demonstrated that PjBL methods, such as mobile virtual labs, have significantly enhanced students' constructivist thinking and scientific understanding. For example, Fadli et al. (2024) recently completed a study examining the effects of mobile PjBL on improving critical thinking and practical skills in students participating in a geographic practicum. Movahedzadeh et al. (2012) also stated that when PjBL methods are used in laboratory courses, as recommended by the National Research Council, students are more likely to engage in their own learning, exhibit greater confidence, and have a deeper understanding of the scientific process. The PjBL method also encourages students' creativity and problem-solving, as well as the development and display of general scientific knowledge. Nasir (2018) noted that the PjBL method provided a structured framework for students to identify and extend their abilities. Dewi et al. (2021) further stated that the contextual learning opportunities made available through the PjBL method provide students with an opportunity to develop their creative potential and illustrate their knowledge in meaningful ways. Chu et al. (2023) further emphasized that PJBL develops scientific inquiry skills and increases student self-efficacy, which supports the relationship between

the application of scientific knowledge and conceptual understanding.

Due to the need for additional research-oriented lab experiments, educators are developing new formats for project-based curricula. Project-based labs allow students to become more familiar with the scientific method and will enable them to generate and design their own research methods rather than simply follow the demonstration-based format traditionally used in educational settings (Beach & Alvarez 2015). When larger projects are broken down into smaller projects, the results are team-based, collaborative learning experiences that reinforce teamwork skills (Budner & Simpson 2018).

The world faces numerous large-scale global developmental challenges, but there are many creative, innovative, and environmentally friendly ways to address them. Many frameworks can aid problem-solving and help find creative, innovative, and environmentally friendly solutions. The use of some of the most effective frameworks for problem-solving includes green chemistry, which consists of twelve guiding principles aimed at reducing the overall amount of hazardous substances produced or consumed throughout the life cycle of a substance (Armstrong et al., 2019), and green synthesis of silver nanoparticles (AgNPs) using biosynthesis in the synthesis of functional materials. In addition to the relative ease of implementing biosynthetic methods to produce AgNPs and their alignment with basic chemical principles, especially redox reactions, biosynthesis of AgNPs also holds significant potential in chemistry education as a component of a laboratory experience. Chemistry students in their first year of college are typically introduced to redox reactions early in their coursework because redox reactions are central to introductory chemistry. However, students often perceive the study of redox reactions as abstract due to the inherent abstraction in electron-transfer theory and the associated mathematics. Therefore, chemistry education should include AgNP biosynthesis to give students hands-on experience of redox reactions in a laboratory setting.

Using RPjBL to help students create their own biosynthetic AgNP experiments will help them understand redox reactions and develop and apply their lab skills. Students will be able to plan, execute, and analyze data from their experiments and present their results in the form of scientific posters. In doing so, the RPjBL model provides students with an opportunity for early research experiences and supports the inclusion, access, and retention of chemistry students in STEM education (Pourhejazy & Isaksen, 2024). Additionally, RPjBL fosters the development of critical 21st-century skills, including innovation, communication, and collaboration (Liu et al., 2023). With RPjBL, students can connect knowledge and practices, thus resulting in more efficient learning experiences (Provost, 2022; Watts & Rodriguez, 2023). Although it has great potential, current research seldom discusses the systematic implementation of RPjBL through a validated, structured learning module. Therefore, this paper presents the design and development of an RPjBL-based learning module on AgNP biosynthesis through the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) in order to make it valid, reliable, and effective (Nadiyah & Faaizah, 2015; Yu, Hsueh, Sun, & Liu, 2021).

The novelty of the present study lies in extending PjBL beyond these conventional applications by conceptualizing and operationalizing an RPjBL model that explicitly embeds authentic, contemporary chemical research into undergraduate laboratory instruction. The RPjBL model integrates modern chemical research practices into an undergraduate laboratory setting. While there has been much research on PjBL, very few studies have included a structured model of current research practices, especially in newer areas of study, such as green nanotechnology. Additionally,

although there has been a significant amount of literature on the biosynthesis of metallic nanoparticles (i.e., Dahoumane et al., 2014; Das & Marsili, 2010; Mukherjee et al., 2001), there is little documentation on integrating the biosynthesis of nanomaterials into project-based chemistry laboratory education.

In terms of theory, this study builds upon existing PjBL scholarship by presenting RPjBL as a learning model that connects instructional laboratory practice with authentic research activities. As a result, RPjBL extends PjBL's learning focus from skill acquisition to introducing students to early-stage research experiences. This model also supports integrating green chemistry, research inquiry, and laboratory skill development into a cohesive learning structure. This study will contribute methodologically to the field by developing and validating a structured RPjBL module based on the ADDIE model. Furthermore, this study includes validated instructional syntax and assessment instruments for evaluating laboratory skills, science process skills, and project performance. In contrast to many studies of PjBL that report classroom use without documenting formal development processes, this study presents a systematic R&D-based design for creating RPjBL modules, supported by data demonstrating content validity and reliability. Finally, the study illustrates the consistency with which RPjBL can be implemented across multiple laboratory courses utilizing a single instructional syntax. Based on the objectives of this study, the research is guided by the following research questions:

1. How can an RPjBL model be developed to support environmentally friendly chemistry learning and industrially relevant AgNP synthesis?
2. To what extent does the proposed RPjBL model demonstrate content validity and reliability as evaluated by experts and empirical testing?
3. How does the implementation of the RPjBL model influence students' laboratory skills and science process skills?
4. How well do students perform in project-based research activities when the RPjBL model is applied?

METHOD

Research Design

The R&D approach used in this study was based on the ADDIE model. In line with the objectives of this study, the research was conducted during the analysis, design, development, and implementation phases. As such, there were no large-scale trials or field tests to conduct; therefore, the evaluation phase will be completed in later studies reporting the results of the development and initial implementation of the RPjBL model.

Participants

Twenty-one students were selected using purposive sampling. The criteria used are: (1) students enrolled in the six consecutive chemistry laboratory courses for the fourth semester of the 2024-2025 academic year, and (2) who had no prior experience with laboratory instruction on the biosynthesis of AgNPs. Additionally, the five experts who conducted the validation process comprised two in chemistry pedagogy, two in chemistry content, and one in educational measurement. The experts were selected using the following criteria: at least 5 years of professional experience in their respective fields and a Master's degree or PhD.

Procedures

Analysis Stage

A needs analysis was conducted to identify gaps in the prevailing redox learning approach. It

involved student learning reflection, interviews with lecturers, and a review of the curriculum. Results showed that there were insufficient practical and collaborative elements that existed in the prevailing learning approach. The results justified the establishment of an innovative model to explore student engagement, laboratory skills, and science process skills. Subsequently, an AgNP biosynthesized by RPjBL was chosen as an intervention.

Design Stage

Based on the analysis, a structured RPjBL learning module and supporting tools were designed. The design phase involved developing a module that guides learners through industrially practicable and scalable steps for the biosynthesis of AgNPs (Table 1).

To monitor and evaluate the implementation of the RPjBL for biosynthesis of AgNPs, three assessment instruments were designed to quantify

Table 1. Description of the developed RPjBL module on AgNP biosynthesis

Component	Description
Bioreductants Used	Natural plant extracts: *Ananas comosus* (AC), *Myristica fragrans* (MF), and *Lansium domesticum* (LD)
Biosynthesis Stages	1. Preparation of bioreductants: Fruits were chopped, macerated in distilled water for 24 hours, then filtered to obtain the extract. 2. Synthesis of AgNPs: 0.2 mL extract + 0.1 M NaOH added to 5 mL 0.5 mM $AgNO_3$, stirred for 1 minute. Color change indicates AgNP formation. 3. Characterization: UV-Vis spectroscopy (280–800 nm), with peak absorbance at 400–480 nm. Morphology and size were analyzed via transmission electron microscopy (TEM).
RPjBL Syntax (Phases)	1. Problem Orientation: Introduction to redox reaction and green chemistry using local natural resources. 2. Project Planning: Students grouped and prepared mini-research proposals using AC, MF, or LD. 3. Project Implementation: Lab work including extraction, synthesis, and property observation of AgNPs. 4. Monitoring and Mentoring: Continuous supervision by lecturers to ensure research quality. 5. Project Presentation: Results communicated through scientific posters and peer discussions. 6. Reflection and Evaluation: Students reflect on their learning; lecturers evaluate using feedback, observations, and questionnaires.
Research Integration	Aligned with real research protocols for nanoparticle biosynthesis and adapted from prior studies (Dicks, 2023; Nabila et al., 2025; Sikdar & Sikdar, 2023; Thummaneni, Surya Prakash, Golli, & Vangalapati, 2022; Wirwis & Sadowski, 2023).
Educational Focus	Enhances student laboratory skills, research abilities, scientific reasoning, and understanding of green chemistry concepts

the effectiveness of the learning process. These are: (1) a laboratory skills observation sheet to assess students' technical skill in performing experimental; (2) a science process skills observation sheet to evaluate students' capacity to utilize scientific inquiry skills such as hypothesizing, observing, analyzing, and concluding; and (3) a project outcome rubric to assess the quality and scientific value of the resulting product developed during the RPjBL.

These instruments were designed and administered to align with the learning objectives and competencies covered in the RPjBL model.

Development Stage

Validation from an expert perspective was conducted throughout the development process, using both an expert panel and a Delphi-based expert-judgment method; the expert panel also participated in a focus group discussion (FGD). Five experts were intentionally selected to validate the content and construct of the new product. The five members of the expert panel included two experts in chemistry pedagogy, two experts in chemistry content, and one expert in educational measurement. Each expert was an expert in chemistry education; three held a Master's degree, two a PhD; and all five had at least 5 years of professional experience in their respective areas. Two of the experts in pedagogy had experience in creating and implementing innovative learning models. In contrast, the two content experts had deep knowledge of chemistry, and the expert in educational measurement had experience in assessing and evaluating student learning.

Before conducting the validation process, the experts were provided with copies of the RPjBL learning tools and module, and they reviewed these materials before attending any FGD. During the FGD, the experts shared their views on the RPjBL model and its tools, based on three main criteria: content validity, pedagogical feasibility, and the technical delivery of the learning tools. In addition to collecting expert judgments using a Likert-scale-based validation tool that solicited both quantitative judgments and qualitative comments or recommendations, a single-round Delphi was appropriate given the level of agreement among the experts' judgments, as evidenced by Aiken's V coefficients exceeding the predetermined thresholds. The instruments' reliability exceeded the required standards. The content validity of each item was determined by comparing Aiken's V coefficients to the predetermined thresholds. Following completion of the validations, the experts' recommendations were used to revise and refine the RPjBL model and its tools, after which the final validation of the model and tools was conducted.

Implementation Stage

The RPjBL module on the biosynthesis of AgNPs was tested as a pilot study using 21 students in a Chemistry Education program from Universitas Khairun, Indonesia. All of the students are taking the same six consecutive chemistry laboratory classes during their 4th semester of the 2024-25 academic year. Due to the small number of participants, the study's goal was to investigate the feasibility of implementing the RPjBL model in the curriculum and the extent to which students use laboratory and scientific processes in this specific learning environment, rather than to broadly assess instruction effectiveness. The RPjBL model used an identical instructional structure across the six laboratory classes; therefore, there was consistency and cohesiveness in implementation.

Students were introduced to the theoretical concepts of redox reactions and their application in the biosynthesis of AgNPs during the first course session. Students were then divided into small research groups to begin Phases 1 (problem orientation) and 2 (project planning) of the RPjBL model. Phase 3, which involved implementing AgNP biosynthesis, spanned courses 2 through 4. During these courses, students set up laboratory equipment and chemicals, isolated bioreductants from organic compounds, synthesized AgNPs, analyzed and characterized the data and results. Phase 4 (monitoring and mentoring) was incorporated into all aspects of the research. Additionally, mentoring was available in course 5 to help students analyze their

research data and prepare final reports. Phase 5 (project presentation) was completed during course 6, when student research groups presented their findings as scientific posters and participated in classroom discussions. Finally, Phase 6 (reflection and evaluation) was completed during course 6, using guided reflection techniques to help students reflect on their learning experiences, and an assessment of the RPjBL model was conducted through observation, a questionnaire, and student feedback.

Evaluation Stage

The ADDIE-based development of the RPjBL model in this research was limited to the implementation phase. The typical final evaluation phase of the ADDIE model, which includes conducting large-scale model trials and extensive field testing, was not performed. However, a limited formative evaluation was conducted during the implementation phase to enable iterative refinement of the model. This formative evaluation included observational assessments of students' laboratory and science-process skills, as well as student presentations and teacher feedback sessions during classroom instruction. Data collected from these formative evaluations provided an initial assessment of the feasibility and clarity of the developed RPjBL model, but did not assess its overall effectiveness.

Instruments

This study employed three measurement instruments developed based on constructs and indicators adopted from previous studies (Gomez-del Rio and Rodriguez, 2022; Mursali et al., 2024; Lukitasari et al., 2021; Sasipraba et al., 2020). Five experts evaluated the content validity and reliability of the instruments. The results of these assessments are presented in the Results section. The instruments used in this study were: (1) a laboratory skills observation sheet consisting of five assessed indicators, (2) a science process skills observation sheet consisting of six assessed indicators, and (3) a project performance assessment rubric consisting of six assessed indicators.

Data Analysis

During the implementation stage, students' laboratory skills were observed through four indicators, and their science process skills were evaluated using six indicators. These indicators are described in detail in the following section. Observations were made throughout the laboratory activities to assess the students' development in both laboratory skills and science processes. The data were analyzed descriptively by calculating the mean, standard deviation, and 95% Confidence Interval (CI) for each indicator to estimate central tendency and the precision of the mean scores within the sample. Students' laboratory and science process skills were analyzed descriptively, with each skill assessed based on the achievement categories outlined by Azwar (2012): very good (>97.6), good (84.8–97.5), fair (59.2–84.7), poor (43.2–59.1), and very poor (<43.2). In addition to descriptive analysis, inferential statistical analysis was conducted to examine the relationship between students' laboratory and science process skills, thereby providing empirical evidence of the association between the two skill domains and supporting an evaluation of the effectiveness of the RPjBL model within a controlled learning environment.

■ RESULT AND DISCUSSION

Background Analysis

The development needs for the RPjBL of AgNPs biosynthesis were analyzed using three elements: (1) Outcome-Based Education (OBE) curriculum needs, (2) student assessment, and (3) the lecturer's need to create an environment where they can integrate the theory and practice of chemistry learning via the most recent research topics. A summary of the three elements for developing RPjBL is depicted in Figure 1.

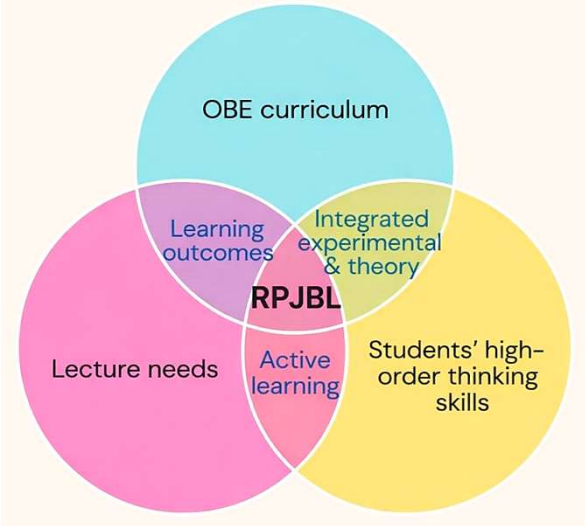

Figure 1. Analysis of foundation aspects in RPjBL development

RPjBL Model

In this study, an RPjBL model was developed, comprising its major components: module development, syntax development, and assessment instrument development. In the module development phase, a structured educational environment has been created to incorporate the biosynthesis of AgNPs into the curriculum. In the syntax development phase, the progressive nature of the RPjBL method has been established through a series of phases, including problem orientation, project planning, implementation, monitoring and mentoring, presentation, and reflection. Additionally, the assessment instruments have been developed to evaluate students' lab and science process skills and their overall learning outcomes.

A research module was also developed to enable students to conduct a project-based inquiry into the biosynthesis of AgNPs. A student centered learning and guided research format was utilized in creating the module that includes five sections: Section 1 (Introduction): background information and redox theory relating to biosynthesis of AgNP; Section 2 (Research Objectives): three principal goals for student effort and learning outcome in terms of research objectives; Section 3 (Research Methodology): experimental protocols for laboratory procedures related to the research methodology; Section 4 (Project Observation): guidelines for managing and recording the data collected during the project observation phase of the study; and Section 5 (References): list of sources and references used in developing the module.

All the modules developed for this study are designed to be systematic and concise, allowing students to quickly and easily identify how to implement research projects in the laboratory. The module's introductory section aims to provide students with a foundational understanding of the research project's conceptual underpinnings. Section 2 of the module is designed to guide students in synthesizing, analyzing, and characterizing AgNPs, and ultimately in presenting the results of their investigation as a scientific poster. Section 3 of the module provides a step-by-step illustration of the methodology for researching the biosynthesis of AgNPs, as presented in Figure 2. These illustrations include a general biosynthesis flowchart for AgNPs (Figure 2a), the steps for extracting natural materials to produce bioreductants (Figure 2b), the process of synthesizing AgNPs (Figure 2c), and the process of characterizing AgNPs (Figure 2d).

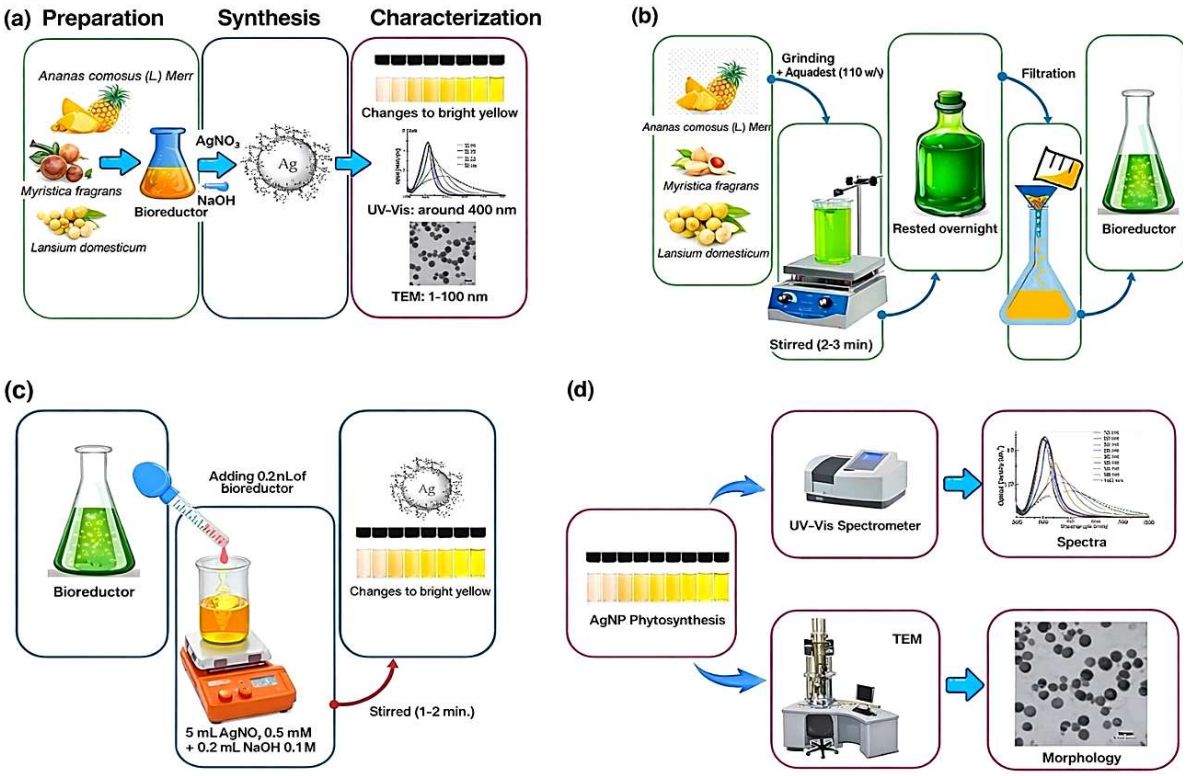

Figure 2. Flowcharts of the research methodology in the biosynthesis AgNP research module

In the project observation section, there are three student assignments. Students will first observe the physical changes in the AgNO*f* solution as it converts to AgNPs. Second, students will need to identify the highest point of the visible light spectrum corresponding to localized surface plasmon resonance (LSPR) to verify the presence of AgNPs. Finally, students will need to calculate the particle size of the AgNP from TEM images.

RPjBL uses an updated version of the PjBL syntax and is implemented in six instructional steps, with the specific details of each step illustrated in Figure 3. RPjBL is a variation of the PjBL syntax that includes student-designed research projects within the learning activity. The RPjBL syntax is structured in six phases and used throughout six courses while maintaining the structural elements of PjBL, which have been demonstrated to enhance learners' ability to think at higher levels (Martawijaya, Rahmadhanningsih, Swandi, Hasyim, & Sujiono, 2023). In the first course, the problem-oriented phase introduces students to redox reactions through a case study of the biosynthesis of AgNPs. The purpose of this stage is to integrate learning (theoretical) with an applied (practical) approach to motivate students to continue their studies and initiate the process of creating research teams, developing experimental approaches, preparing the necessary laboratory equipment, and obtaining chemicals that are required for the biosynthesis of AgNPs. This fourth-semester course covers the hands-on aspects of the research project (e.g., extraction of the natural bioreductant, synthesis of AgNPs, and analysis/characterization). During the fifth course, monitoring and mentoring occur when lecturers provide the students with the structure needed to manage their experimental data and write research reports. The final two stages of RPjBL happen in the sixth course, where presentations, discussions, evaluations take place.

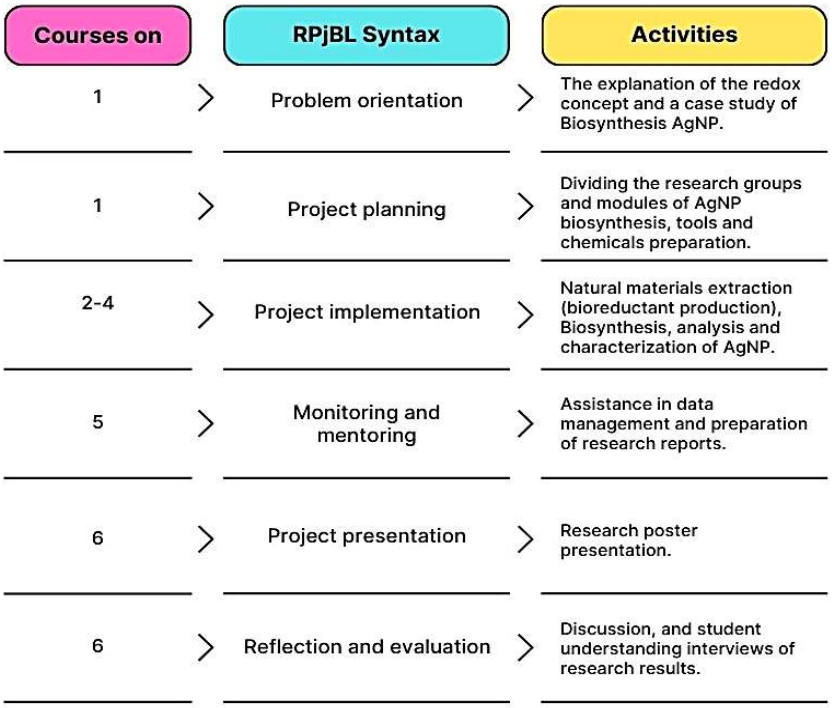

Figure 3. Syntax of the RPjBL model for the biosynthesis of AgNP

Two primary assessment tools were used to describe and examine students' laboratory and science process skills within the implementation of the RPjBL model: an observation tool and a project performance assessment tool. The assessment tools are based on learning evaluation standards for inquiry-based and project-based science education (Arafah, Amin, Sari, & Hakim, 2021; Gomez-del Rio & Rodriguez, 2022; Jalil, Herman, Sidin Ali, & Haris, 2018). The assessment tools were structured to assess both cognitive and practical outcomes, ensuring that students were evaluated on their content knowledge as well as their procedural and higher-order skills. Tables 2, 3, an 4 provide descriptions of the indicators/aspects being evaluated.

The laboratory skills indicators (Table 2) were selected to represent critical knowledge areas for undergraduate chemistry students, especially those concerning the safe use of laboratories; precision in performing procedures; proper use of apparatus, instruments, etc., and chemicals; and accountability for their correct use. These indicators are crucial foundational elements for successfully engaging in research activities, as they align with professional laboratory practices most often referenced in higher education chemistry curricula. In addition, the science process skills indicators (Table 3) were selected to demonstrate higher-order cognitive and procedural skills, such as observation, hypothesis development, experimental design, data interpretation, and logical conclusion formation. These are generally acknowledged as the major components of scientific inquiry and are important for preparing students to participate in research-based learning settings at universities. Additionally, the project performance rubric (Table 4) was developed to assess students' ability to synthesize their conceptual understanding, experimental logic, data analysis, and scientific communication into a collaborative research setting. The assessment of poster presentations and teamwork demonstrates how the development of communication and collaborative skills can be considered an important learning outcome in contemporary higher education and professional practice in STEM fields.

Table 2. Indicators of students' laboratory skills in biosynthesis of AgNP

No.	Indicator	Description
1	Preparation of chemicals and equipment	Ability to organize and prepare all materials properly
2	Handling of equipment	Proper and safe usage of laboratory equipment
3	Handling of chemicals	Proper and safe usage of chemicals
4	Compliance with procedures	Following experimental protocols accurately
5	Hygiene and laboratory safety	Maintaining cleanliness and safety standards

Note: Likert scale (1-5) was used. The indicators are adapted from Gomez-del Rio and Rodriguez (2022).

Table 3. Indicators of students' science process skills

No.	Science Process Skill	Description
1	Observation	Accurately noticing and recording experimental phenomena
2	Classifying	Sorting or categorizing data meaningfully
3	Interpreting	Concluding observed data
4	Formulating hypotheses/questions	Generating relevant questions or hypotheses
5	Designing experimental procedures	Planning steps for an investigation
6	Concluding logically	Making evidence-based conclusions

Note: Likert scale (1-4) was used. The indicators are adapted from Mursali et al. (2024).

Table 4. Project rubric assessment criteria

No.	Assessment Aspect	Description
1	Problem formulation and objectives	Clarity and relevance of research goals
2	Experimental design	Accuracy, logic, and completeness of the design
3	Data analysis and interpretation	Quality of analysis and correctness of interpretation
4	Scientific reasoning in discussion	Depth of understanding and use of scientific concepts in analysis
5	Poster presentation	Visual clarity, organization, and delivery of scientific content
6	Team collaboration	Level of cooperation, role-sharing, and collective problem-solving

Note: The rubric is modified from Lukitasari et al. (2021) and Sasipraba et al. (2020).

Validity and Reliability Results

Before the instructional implementation, components of the RPjBL model for the biosynthesis of AgNP namely the module, syntax, and assessment instruments were validated by five experts using FGD and Delphi techniques. The validity results, presented in Table 5, are based on Aiken's V index calculated on a four-point Likert scale at a significance level of $p < 0.05$. According to the V table, the threshold Aiken's V value is 0.87, which meets the recommended criteria for educational R&D studies (Sugrah, Suyanta, & Wiyarsi, 2023). The average validation scores exceeded 0.87, indicating that the RPjBL instructional tools for AgNP biosynthesis are valid. Reliability was assessed using Cronbach's alpha to ensure internal consistency of the instruments. The reliability of

the product and research instruments was analyzed using Cronbach's alpha. An instrument is considered reliable if the reliability coefficient is e" 0.70 (Azwar, 2012). As shown in Table 5, all Cronbach's alpha coefficients exceed 0.70, indicating that all instruments are reliably constructed.

RPjBL Implementation

At the beginning of the RPjBL implementation, students were given basic questions as part of the RPjBL introduction model, which consisted of two fundamental questions: (1) In some cases, reducing agents in redox reactions are amino acids found in many

Table 5. Validation and reliability results of the RPjBL model

RPjBL Instruments	Aspects			V average	α (Cronbach's Alpha)
	V Content	V Pedagogical feasibility	V Technical presentation		
Module	0.93	0.87	0.93	0.91	0.91
Syntax	0.87	0.93	0.87	0.89	0.87
Laboratory Skills Observation Sheet	0.93	0.93	0.93	0.93	0.85
Science Process Skills Observation Sheet	0.87	0.87	0.93	0.89	0.91
Project Rubric Assessment	0.93	0.95	0.87	0.92	0.78

local natural materials. If this statement is true, can local natural material extracts be used as bioreductors for AgNP synthesis? (2) If local natural material extracts can be used as reducing agents in AgNP synthesis, what are the characteristics of the AgNP? Furthermore, students were directed to conduct research project activities in the laboratory using the biosynthesis of AgNPs module. The students' projects were structured into two main activities: laboratory research to obtain data and answers to fundamental questions, and an assignment to create a research report in the form of a poster.

The RPjBL for biosynthesis AgNP was implemented according to the developed syntax, in which each learning activity was observed, and the involvement of students' laboratory and science process skills that emerged was assessed. Students' laboratory skills in RPjBL were the main indicator of chemistry experimental learning and were analyzed to demonstrate active, student-centered learning (Gomez-del Rio & Rodriguez, 2022). Meanwhile, science process skills were analyzed to measure the impact of RPjBL on students' higher-order skills (Paristiowati, Afrizal, & Ananda, 2023). The monitoring and assessment of students' laboratory skills and science processes in RPjBL are described in Table 6.

Student activity in implementing RPjBL is monitored and assessed by integrating laboratory skills and science process skills. This approach

Table 6. RPjBL assessment design

Course	Learning Activity	Integrated Skills	Output
1	Problem Orientation: In the first session, students are introduced to the concept of redox reactions and a case study on the AgNP reduction reaction.	-	Students' understanding of the RPjBL biosynthesis of AgNP

	Project Planning: Students are divided into research groups, create a research flow diagram, and select a fruit sample to use as a bioreductor.	-	Students' group research
2	Research Project Implementation 1: • Preparation of glassware and chemicals • Extraction of local natural materials to produce reducing agents.	1. LS: Prepare glassware and chemicals. 2. SPS: Observation, experiment, and communication.	Extract local fruits (bioreductors)
3	Research Project Implementation 2: Biosynthesis of silver nanoparticles (AgNP).	1. LS: Chemical management and follow the research procedure. 2. SPS: Observation, experiment, prediction, and communication.	Silver nanoparticles
4	Research Project Implementation 3: • Characterization of AgNP using UV-Vis spectrophotometry and TEM • Data analysis.	1. LS: Managing samples for analysis. 2. SPS: Observation, experiment, communication, and data interpretation.	UV-Vis spectra, TEM images, and data interpretation.
5	Monitoring and Mentoring: In the second session, monitoring of data management, report preparation, and constructing conclusions.	SPS: Interpreting data and drawing conclusions.	Students' understanding of analytical data management and creation of a research poster.
6	Project Presentation: Students present their research posters.	SPS: Communication of research results.	Research poster presentation.
	Reflection and Evaluation: Students present their research poster, followed by evaluation of the RPjBL model.	SPS: Communication of research results.	Research poster presentation and student understanding test.

Note: LS: laboratory skills, and SPS: science process skills.

was chosen because both are essential to developing a chemist's professional character. As shown in Table 6, the assessment of laboratory skills is conducted during the research implementation in the laboratory. In contrast, science process skills are observed throughout research project activities, data analysis, monitoring, and research poster presentations. Additionally, the stages of RPjBL also produce measurable outputs that serve as indicators of learning outcomes.

The poster shown in Figure 4 is an example of one of the students' final presentations after implementing the RPjBL model in their classwork. The poster provides a synopsis of the student's research on the biosynthesis of AgNPs, along with results from UV-Vis spectroscopy and TEM characterization. Overall, the RPjBL model successfully provided students with the opportunity to utilize local bioresources as bioreducing agents for the synthesis of AgNPs.

RPjBL Effectiveness

Overall student performance in laboratory and science process skills is shown in Tables 7 and 8. As shown in Table 7 and Figure 5, overall, students have performed well across nearly all assessment indicators, and the activities allowed them to engage in both laboratory practices and scientific inquiry. The better-performing indicators of laboratory skills included handling chemicals, adherence to procedural guidelines, and overall

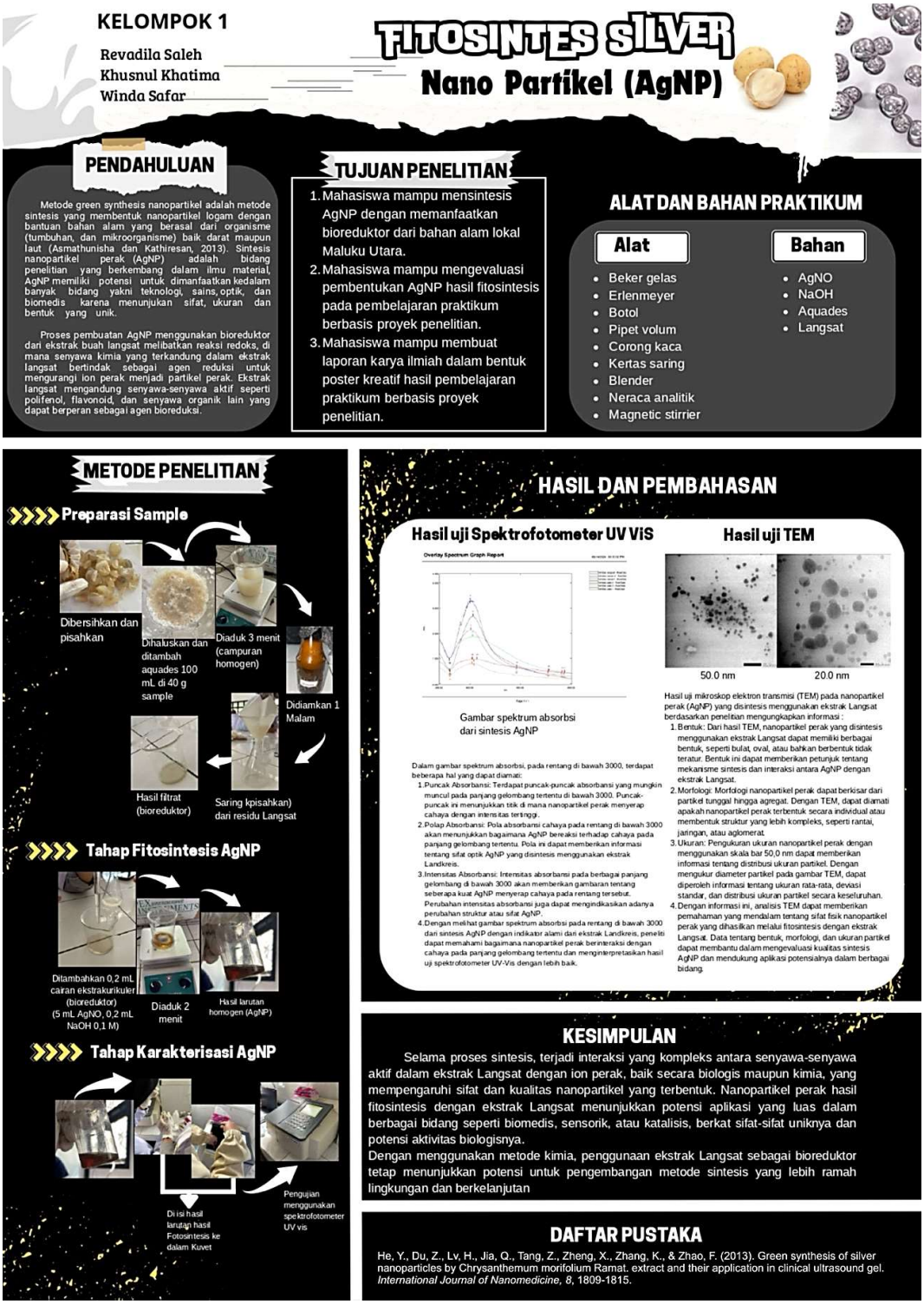

Figure 4. Students' poster from an RPjBL project about making AgNP using local materials

laboratory safety. It appears that the structure and guidance inherent in the RPjBL model helped students adhere to the established experimental protocol. The laboratory equipment skills indicators were found to be weaker, which represents an opportunity for additional instructional support in future implementations of this model.

In relation to the science process skills (Table 8 and Figure 6), there is strong evidence of student participation in higher-order inquiry-related indicators, specifically in the design of the experimental procedure and the interpretation of experimental data. These findings suggest that the RPjBL model has enabled students to participate in planning investigations and analyzing experimental results. Students also demonstrated consistent levels of foundational science process skills, including observation, classification, and hypothesis formulation; therefore, they have demonstrated a balance between basic and advanced scientific processes. Given the pilot-study nature of this research and the lack of a comparison group or pretest data, these findings should be viewed as descriptive rather than as an indicator of increased performance.

Laboratory skills have narrow 95% CIs (Table 7), indicating very low variability and stable mean estimates for the sampled population. With most of the performance measures for these skills at or above "very good," and with performance on handling equipment consistently at the "good" level, it appears that performance on this particular skill may be slightly lower than on the other two laboratory skills. However, performance was generally consistent across the three skills. In addition, the CIs for science process skills (Table 8) indicate that performance for each of the five skills measured is compact and completely contained within the "very good" category. The small amount of variability and high consistency in student performance across these skills are evident in their experimental procedure design.

Table 7. Students' laboratory skills (N=21)

Indicators	Mean	Std. Dev.	95% CI	Category
Preparation of chemicals and equipment	80.95	0.740	[80.61, 81.29]	Very Good
Handling of equipment	75.24	0.768	[74.89, 75.59]	Good
Handling of chemicals	82.86	0.727	[82.53, 83.19]	Very Good
Compliance with procedures	80.00	0.775	[79.65, 80.35]	Very Good
Hygiene and laboratory safety	80.95	0.669	[80.65, 81.25]	Very Good

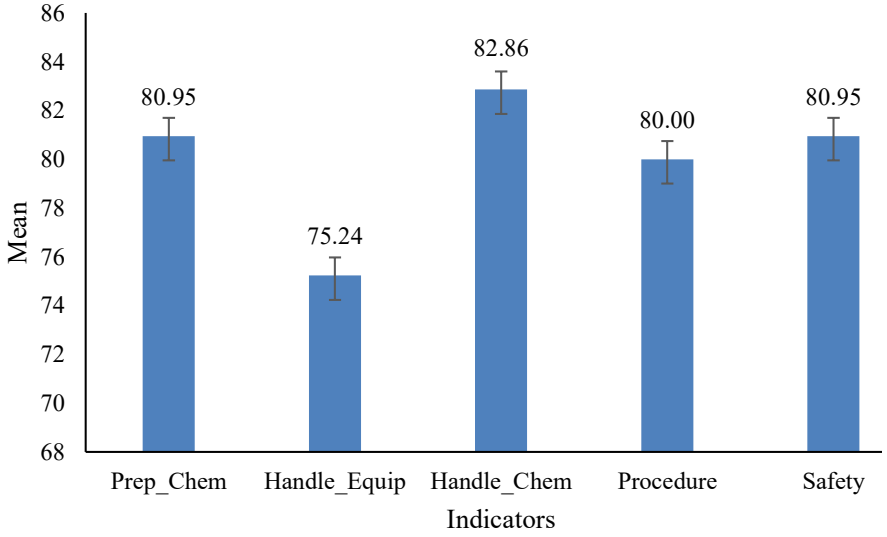

Figure 5. Mean scores of students' laboratory skills across five indicators (N = 21)

Table 8. Students' science process skills (N=21)

Indicators	Mean	Std. Dev.	95% CI	Category
Observation	88.10	0.680	[87.79, 88.41]	Very Good
Classifying	86.90	0.512	[86.67, 87.13]	Very Good
Interpreting	90.48	0.669	[85.40, 86.02]	Very Good
Formulating hypotheses/questions	85.71	0.676	[85.40, 86.02]	Very Good
Designing experimental procedures	91.67	0.483	[91.45, 91.89]	Very Good
Concluding logically	84.52	0.669	[84.22, 84.82]	Very Good

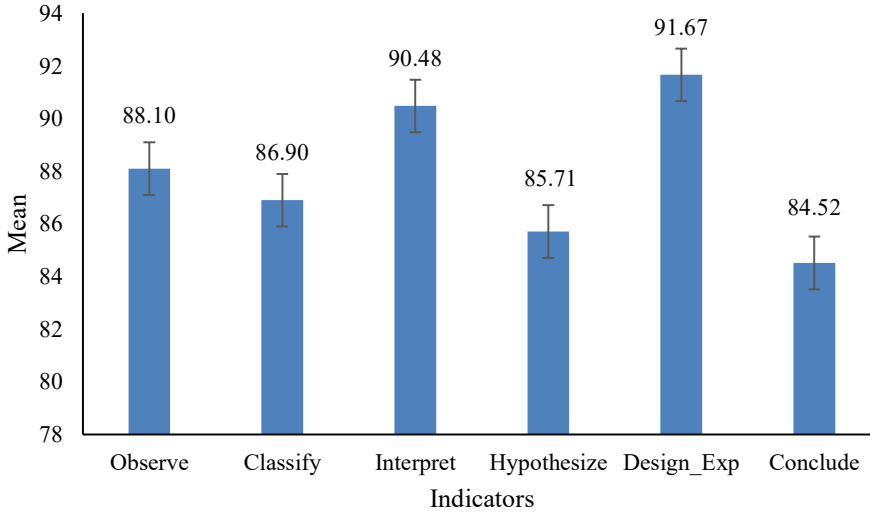

Figure 6. Mean scores of students' science process skills across six indicators (N = 21)

The overall project score results have an appropriate blend of central tendency and dispersion (Table 9). A mean score of 75.69 indicates that, overall, the students performed well on their projects; a median of 76.00 suggests that the data distribution was concentrated around this score. The standard deviation of 4.38 indicates moderate variability in the scores. This variability indicates that although many students performed similarly, there was variation in the quality of their projects. The lowest project score of 69.00 and the highest of 83.50 show the range of student performance. A skewness of 0.31 indicates that the students' project scores were approximately symmetrically distributed but slightly weighted toward higher project scores. The skewness, however, is very close to zero; therefore, there are no extreme deviations from symmetry in either direction. In general, the distribution of students' scores suggests relative consistency in student performance across the sample rather than a pronounced concentration of high-scoring projects. The 95% CI indicates that the average performance for projects completed by members of this cohort would likely lie between 73.69 and 77.69. This represents a fairly stable estimate of group-based project results for the pilot sample used here.

Table 9. Overall project scores (N=21)

Statistic	Value
Average	75.69
Median	76.00
Standard Deviation	4.38
Minimum	69.00
Maximum	83.50
Skewness	0.31
95% CI	[73.69, 77.69]

Further analysis was conducted to examine whether there was a correlation between students' laboratory skills and students' science process skills. The normality test results presented in Table 10 indicate that both variables were normally distributed, as evidenced by Shapiro–Wilk p-values exceeding the 0.05 threshold for students' laboratory skills ($p = 0.084$) and science process skills ($p = 0.073$). Therefore, a parametric correlational analysis was deemed appropriate, and Pearson's product–moment correlation was used. The results in Table 11 show a positive, but non-significant, relationship between students' laboratory and science process skills ($r = 0.333$, $p = 0.140$, $n = 21$). Additionally, Figure 7 presents a scatter plot illustrating the relationship between students' laboratory skills and science process skills. The distribution of data points suggests a positive but weak linear trend, consistent with the non-significant Pearson correlation result. In conclusion, although students with higher laboratory skills tended to demonstrate higher science process skills, the relationship was not statistically significant, suggesting that improvements in laboratory skills were not necessarily associated with proportional gains in science process skills within the sample.

Table 10. Normality testing

Variables	Shapiro-Wilk		
	Statistic	df	Sig.
LS	0.919	21	0.084
SPS	0.916	21	0.073

Table 11. Pearson correlation test results

Variables	Statistics	LS	SPS
LS	Pearson Correlation	1	0.333
	Sig. (2-tailed)	-	0.140
	N	21	21
SPS	Pearson Correlation	0.333	1
	Sig. (2-tailed)	0.140	-
	N	21	21

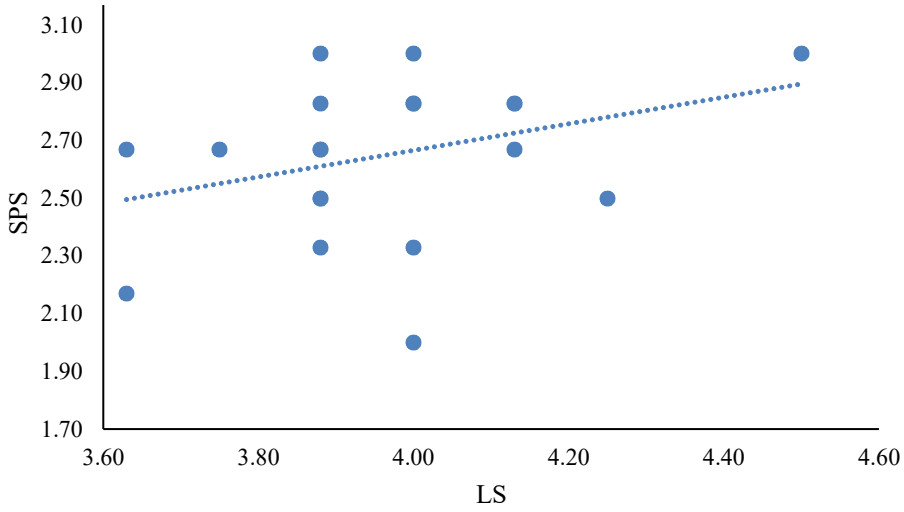

Figure 7. Scatter plot illustrating the relationship between students' laboratory skills and science process skills (N = 21)

Student interviews were conducted to further support the study's findings, and Table 12 shows that the thematic analysis found that the RPjBL model had a significant positive effect on both cognitive engagement and practical awareness of science. Consistently, students stated that the model had created a "meaningful" or "contextual" connection between theoretical chemistry concepts and their real-world applications by using local bioreductors in their research projects. These qualitative findings provide strong evidence of the model's ability to facilitate high levels of science process skills. Specifically, the students' self-assessed improvement in critical thinking and their active participation in the development of experimental design are consistent with the very high scores and low variability found in the higher-order inquiry assessment. The students' reported success in procedure design ("very good"), consistent with the findings from the student interviews, clearly demonstrates that they were able to go beyond simply memorizing the processes of synthesizing nanoparticles to an analytical understanding of those processes through direct involvement the research process.

In addition, the qualitative data provide an essential explanatory mechanism for the quantitative findings related to the laboratory skill assessments. Although the quantitative findings showed that students' skills with the laboratory equipment were slightly lower than those for the other indicators, the qualitative data indicated that the limitations of the laboratory equipment and the challenge of achieving reproducibility with natural extracts were the two main obstacles the students faced in developing these skills. Therefore, it appears that the "Good" but not "Very Good" score for equipment handling may have been due to external infrastructure constraints rather than a failure of the instructional model. Furthermore, the lack of a significant correlation ($r = 0.333$, $p = 0.140$) found between laboratory skills and science process skills in the statistical analysis also aligns with the student feedback, which indicates that the students believed they achieved a great deal of conceptual clarity and analytical clarity (science process skills) even if they struggled with the physical optimization of variables such as pH and temperature (laboratory skills). Finally, the students' unanimous consensus that the model is suited for implementation validated the high mean project scores and suggested that the RPjBL model is a robust instructional model for developing scientifically literate individuals.

Table 12. Thematic analysis results

Main Theme	Sub-Theme	Example of Interview Transcript (Evidence)
1. Cognitive & Skill Transformation	Integration of Theory & Practice	"I did not only understand nanoparticle concepts theoretically, but was also directly involved in the research process..." (Student 1)
	Science Process Skills	"Training research skills ranging from experimental design to the analysis of results..." (Student 2)
	Critical Thinking	"...how this process can improve critical and creative thinking abilities." (Student 4)
2. Local Relevance & Green Chemistry	Utilization of Local Materials	"Making it easier for students to utilize natural materials available in the surrounding environment." (Student 3)
	Environmental Awareness	"...the learning felt more relevant to the surrounding environment and fostered awareness of the potential of local resources and green chemistry principles." (Student 7)

3. Experimental Challenges	Natural Material Variability	"Consistency in the quality of natural extracts is difficult to maintain because it is influenced by the type of material, environmental conditions, and extraction methods." (Student 2)
	Reaction Condition Optimization	"I also experienced difficulties in controlling reaction conditions, such as pH, temperature, and reaction time..." (Student 4)
	Reproducibility	"Synthesis based on natural materials often faces difficulties in reproducibility... making data validation difficult." (Student 3)
4. Infrastructural Constraints	Equipment Limitations	"Limitations in laboratory tools and materials, especially nanoparticle characterization instruments." (Student 7)
5. Affective Response	Motivation & Novelty	"This is something new and is new knowledge for me... a very valuable experience." (Student 10)
6. Pedagogical Implementation	Model Feasibility	"Suitable for implementation." (Consistently stated by all informants).

The primary purpose of this study was to develop and detail an RPjBL model that integrates research-based projects focused on environmentally friendly chemistry into the undergraduate laboratory learning environment. Specifically, the model used was for the biosynthesis of AgNPs. Therefore, the data contained in this report is separated into three sections: 1) the viability of the developed RPjBL model; 2) the reliability and validity of the instructional and assessment tools created to accompany the model; and 3) a descriptive analysis of students' laboratory skills, science process skills, and project performance at the time of completion. Unlike studies that assess the impact of various models on student learning outcomes, this study provides evidence of the practical application and instructional coherence of RPjBL as a research-based learning model. The results of this study also serve as an initial empirical base for developing and implementing green chemistry-based research into the context of project-based laboratory instruction in higher education settings.

The background analysis in this study significantly influenced the design of the RPjBL model, particularly by aligning with the principles of OBE, students' learning needs, and instructional demands. OBE in higher education emphasizes the achievement of clear learning outcomes and the development of high-level cognitive abilities, such as laboratory competence and science process skills (both of which are key areas of chemistry education) (Japee & Oza, 2021; Syeed, Shihavuddin, Uddin, Hasan, & Khan, 2022). OBE also supports student-centered learning environments that support active engagement through hands-on and inquiry-based experiences (Mutiawati, Mailizar, Johar, & Ramli, 2023). As a result of these curricular requirements, the RPjBL model was developed to incorporate current research topics (in particular, green synthesis of AgNPs) into the learning process, connecting students' theoretical understanding with practical research activities. Therefore, the alignment of the instructional design ensures that it meets the curriculum outcomes and provides meaningful learning experiences that reflect contemporary scientific practice.

The RPjBL model is based on the PjBL concept, incorporating authentic research into instruction as a persistent and integral component of the PjBL experience's overall design. The inclusion of research activities in the PjBL design

is consistent with the underlying tenets of Research-Based Science Education (RBSE). RBSE promotes conceptualizing science as active participation in ongoing inquiry processes, rather than replicating predetermined laboratory exercises (Rector, Wooten, Puckett, Pilachowski, & Coble, 2018; Vidal, Raschid, & Mestre, 2004). As such, through RPjBL, students do not merely complete project work; they are required to formulate their own research questions, design experiments, collect and evaluate empirical data, and collectively present their results. Therefore, RPjBL incorporates collaborative/inquiry-oriented learning tasks that reflect evidence-based practices, including teamwork, critical thinking, and authentic problem-solving, which are essential for achieving the desired outcomes of undergraduate science education (Gómez, 2016; Zhu & Zou, 2011). Therefore, RPjBL provides a comprehensive and scalable model for integrating undergraduate research experiences into the chemistry laboratory curriculum.

A deliberate attempt has been made to merge theoretical chemistry concepts, laboratory experience, and research experience into an educational sequence for the RPjBL model. Theory-practice connection in the context of chemistry education is best supported by specific structural elements in instructional design which link fundamental concepts to meaningful laboratory experiences and gradually provide students with opportunities to engage in practices representative of real-world applications (Bester, van Wyk, & Maree, 2024; Gilmanshina, Sagitova, & Khalikova, 2018). The theoretical aspect of the RPjBL model regarding the redox reaction and its application to the biosynthesis of AgNPs aligns with the student's experimental approach and subsequent data interpretation, exemplifying the transition from theory to practice and reflection. Evidence suggests that when instructional design incorporates a structured curriculum and integrates both theoretical and laboratory components, it is possible to minimize fragmentation between theory-based instruction and experimental experiences (Lau, Teow, Low, & Tan, 2023). The inclusion of research experiences within the laboratory experience and continuous mentoring, along with linking research competency to conceptual understanding, provides a framework for connecting theory, practice, and scientific investigation in a meaningful way.

A narrow range of CI for laboratory and science process skills indicates that scores are highly consistent across students on this measure and that RPjBL delivery was relatively consistent for all students. CIs are frequently used in educational measurement to quantify the precision of test scores and the extent to which variation is attributable to measurement error (Lee, Brennan, & Kolen, 2006; Price, Lurie, Raju, Wilkins, & Zhu, 2006), particularly when assessing composite or domain-level constructs. The CIs being relatively close together and within the same performance band indicate little variability in the mean estimate of students' performance levels and suggest that few students have extreme performance levels. This supports the idea that well-constructed and internally reliable assessments will yield observed scores clustered around their mean (Kim, Park, & Lee, 2021). Therefore, although the study is a pilot and the sample size is relatively small, the consistency of the CI measures may reflect instructional coherence and the reliability of the measurement processes employed, rather than indicating improved learning outcomes or instructional practice.

Even though the students had a great deal of science process skills, the quality of the projects at the end was only rated "fair"; there was a gap between procedural proficiency and product-level performance. The above-mentioned finding is supported by previous studies, which concluded that process-oriented learning methods (such as project-based) improve students' inquiry and process skills; the translation of those skills

into higher-quality project outputs is dependent upon other types of competences and sustained instructional support (Firmansyah et al., 2022; Zouganeli et al., 2014). Students' science process skills represent their ability to participate in scientific activities such as observing, hypothesizing, and interpreting data. Project quality is determined by a greater number of abilities, including the ability to synthesize results, make decisions, and communicate scientifically. Previous studies have shown that without an organized system for assessing and providing formative evaluations, students may demonstrate strong procedural skills yet produce suboptimal project outcomes (Ou & Lin, 2023; Hu et al., 2019). Further, research has emphasized the value of providing students with feedback and collaborative learning environments to help them improve the quality of their projects. To create high-quality project products, students need opportunities to iterate and refine their ideas and receive feedback to ensure their products meet project requirements (Requena-Carrión et al., 2010). Thus, it appears that science process skills are foundational for RPjBL; however, developing high-quality project products will require iterative feedback, explicit performance criteria, and opportunities for students to integrate their skills repeatedly.

Pearson correlation results showed a statistically nonsignificant positive association between student laboratory skills and science process skills. Thus, higher levels of laboratory skills were associated with higher levels of science process skills overall, but the effect did not reach statistical significance across all participants. The conceptual implications of this result support prior research on the nature of science process skills (e.g., Darmaji et al., 2019; Darmaji et al., 2021), which views these as multifaceted cognitive abilities necessary for scientific inquiry (i.e., basic and integrated skills). Additionally, prior meta-analyses found a significant positive correlation ($r = 0.529$) between science process skills and broader cognitive learning outcomes (Agus, 2022). Moreover, numerous investigations have documented improvements in both laboratory and science-process skills resulting from inquiry-oriented laboratory instruction (Gunawan et al., 2019). Nonetheless, the lack of a significant correlation in this investigation indicates that developing laboratory skills does not necessarily lead to corresponding increases in science process skills (specifically higher-level skills such as hypothesizing and designing experiments) unless instructors provide deliberate cognitive scaffolding beyond mere laboratory procedures. This interpretation is consistent with prior research documenting how deficits in foundational science process skills may impede students' ability to perform well in terms of science overall (even in rich laboratory environments) (Markawi, 2015; Darmaji et al., 2018). Therefore, laboratory experiences remain a vital component of science education; however, the present results indicate a need for educational designs that intentionally integrate process-skill development during laboratory activities to allow for balanced, reciprocal skill development.

This study supports the feasibility of the proposed instructional model, as the evaluation results provide substantial evidence of the reliability and validity of both expert judgments and instrument assessments. The definition of feasibility in educational studies is broad. It includes both theoretical viability and empirically based indicators of how well an instructionally based model may be perceived, implemented, and assessed within a variety of real-world instructional environments (Ford, McNally, & Ford, 2017; Youhasan, Chen, Lyndon, & Henning, 2021). For example, the validity of the instructional model was supported by the results of expert evaluations, which indicated that all of the components of the instructional model (i.e., model parts, procedural aspects of the model,

and assessment tools) were appropriately conceptualized and developed to provide clear instructional coherence in a contextual environment that would support the achievement of instructional goals and objectives. Furthermore, high reliability coefficients among judges across several aspects of the model provide additional evidence of consistent scoring and indicate that the model will be implemented reliably across evaluators, regardless of their individual biases or ambiguities in its application. Consistency in evaluative practices is a significant factor in determining whether a model is practical, because if there is instability or unreliability in the use of assessment instruments or the scoring procedures used to evaluate the model, then it is unlikely that educators will adopt the model, even if it has been determined to be theoretically sound (Khairani, Djulia, & Bunawan, 2023). Finally, the systematic approach taken to develop and validate the model reflects the feasibility guidelines for instructional models recommended in the literature (e.g., ADDIE, DBR), which require iterative refinements to instructional models and include input from experts in the field before they can be considered for widespread implementation (Astuti, Sumarni, & Saraswati, 2017; Ford et al., 2017). Overall, the results of this study demonstrate that the model is not only valid and reliable but also feasible for pilots to test and implement, and provides a solid foundation for future studies on instructional models.

■ CONCLUSION

The purpose of this study was to implement the RPjBL model to investigate how it would develop laboratory and science process skills by having students synthesize AgNPs. Furthermore, this study aimed to determine whether the RPjBL model would enable students to develop their laboratory and science process skills through participation in collaborative, peer-based research projects in a laboratory setting. During these projects, students working in small groups developed hypotheses, created plans for conducting experiments, performed the experiments, collected and analyzed the data, and presented their findings via posters. All of these activities were representative of the five stages of the RPjBL model (problem orientation, project planning, research execution, data analysis, and poster preparation for project presentations). The RPjBL model includes two types of skills used throughout the model (laboratory skills and science process skills). Skills associated with a laboratory setting include preparing, using, and disposing of chemicals, as well as properly operating and caring for equipment. Skills that are associated with the scientific process include making observations about phenomena, organizing and classifying data, generating testable hypotheses to be evaluated from data, and making conclusions based on the data you have obtained through your observations. The descriptive results suggest that students demonstrated these skills during the RPjBL activities. Due to the pilot nature of the study and the limited number of participants, there was no pre-test data nor a comparison group, so results are to be viewed with caution. These results describe student performance and engagement as they participate in the RPjBL framework, not improvements in their skills; however, this study has provided some insight into the feasibility of an RPjBL model based on environmentally friendly nanomaterial biosynthesis and its potential as a laboratory learning environment for research-oriented undergraduate chemistry education.

Research on the future of the RPjBL pilot study is needed to include quasi-experimental or experimental designs, which can be based on a control or comparison group (such as traditional laboratory teaching or flipped classroom methods), as well as larger sample sizes to allow researchers to make stronger causal inferences

about the RPjBL model's effectiveness. To assess whether the RPjBL model leads to measurable increases in learning, it would be beneficial to conduct pre-test/post-test assessments of students' knowledge of laboratory and science process skills, and of cognitive learning. Additionally, future research could explore how integrating digital tools and virtual laboratory equipment could assist students in designing experiments and collecting/analyzing data, especially in situations where students have limited access to laboratories. Further, future research could investigate the importance of peer collaboration through analyzing patterns of student interactions and assessing the relationships between individual/group performance and collaborative behavior in the context of the RPjBL model. Ultimately, addressing the aforementioned areas will enhance the systematic development and validation of the RPjBL model across all possible educational environments.

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■ ETHICAL STATEMENT

Before the research project commenced, all participants provided consent by signing a form created as part of the process. There was no such institutional requirement for IRB approval from the university at the time of the study's completion. However, every element of the study complied with all ethical standards for voluntary participation, confidentiality/anonymity, and the protection of participant rights.

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