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Developing 21st Century Skills Through STEM-Based Lesson Study and Project-Based Approaches in Chemistry Learning

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Abstract

Background/purpose. Learning chemistry is often considered challenging due to its abstract nature. To address this, the application of Project-Based Learning (PjBL) emphasizes learning through real-world projects to enhance conceptual understanding. The Science, Technology, Engineering, and Mathematics (STEM) approach enriches this process by promoting cross-disciplinary integration and contextual problem-solving, particularly through Lesson Study, with a focus on developing the 4C skills (Critical Thinking, Creativity, Communication, Collaboration).

Materials/methods. This research employs a qualitative descriptive approach, involving 5 chemistry teachers, 3 lecturers, 10 prospective teachers, and 30 grade XII students from a high school in Indonesia. The learning process is implemented across three stages of Lesson Study (Plan-Do-See), with data collected through observations, interviews, documentation, and student reflections. Specifically, 30 students were observed during the planning stage, 28 during the implementation stage (due to 2 absences), and 30 during the reflection stage.

Results. The findings demonstrate that STEM-PjBL integrated with Lesson Study significantly enhances 4C skills, with an overall development rate of 85% across the cohort. Critical Thinking improved by 87%, evident in students' ability to analyze problems and evaluate the effectiveness of their voltaic cell designs, with 25 out of 30 students demonstrating advanced analytical skills. Creativity increased by 83%, showcased through the innovative use of local materials such as dragon fruit, papaya, and chayote as alternative electrolytes, with 24 students proposing unique designs. Communication advanced by 80%, as observed in students' systematic idea presentations during discussions, poster sessions, and Q&A sessions, involving 27 students. Collaboration rose by 88%, reflected in effective task division, conflict resolution, and collective project responsibility, with 26 students actively participating in team dynamics.

Conclusion. The integration of STEM-PjBL based on Lesson Study proves effective in developing students' 4C skills in chemistry learning, contributing to a student-centered, 21st-century learning design that fosters global competence. However, limitations include a small sample size and the study's context-specific nature, suggesting caution in generalizing findings to broader populations.

1. Introduction

Chemistry, as a branch of natural science, focuses on the composition of matter, changes in matter, properties of substances, and the principles and laws governing these transformations (Nurfatonah et al., 2024). Its significance in everyday life is undeniable, yet many students perceive it as a challenging subject due to its reliance on abstract concepts (Cooper & Stowe, 2018; Rahmawati et al., 2022). This difficulty is compounded by factors such as the abstract nature of chemical concepts, which are often hard to visualize directly (Stroumpouli & Tsaparlis, 2022; Defista & Aznam, 2024; Sausan et al., 2020; Akbar et al., 2024), and the integration of complex materials, mathematical applications, and advanced technologies that demand creative and innovative teaching approaches beyond traditional classroom methods (Qian et al., 2023; Rahmawati et al., 2023). The lack of direct engagement in experiments or practical applications further disconnects chemistry from real-life contexts, while rigid teaching methods and limited innovation often diminish students' interest (Podschuweit & Bernholt, 2018; Minata et al., 2022; Elvi Nurhayati Selian et al., 2024). Researchers have underscored the need to integrate everyday phenomena into chemical education to make abstract concepts more concrete (Winarni et al., 2022; Landa et al., 2020; Adauyah & Aznam, 2024), yet current learning often prioritizes conceptual understanding over practical application.

In the context of 21st-century demands, Indonesian society must adapt to rapid technological and scientific advancements, necessitating an education system that fosters literacy skills, knowledge, technology mastery, and attitudes aligned with modern challenges (Aldi et al., 2025; Jannah et al., 2025; Thornhill-Miller et al., 2023). The Indonesian government promotes the "4C" skills—critical thinking, creativity, communication, and collaboration—as essential for navigating this era. This requires an active learning approach where teachers act as facilitators, encouraging student participation (Nuraeni et al., 2019; Novia et al., 2024; Budiyanto et al., 2024). However, traditional chemistry education often falls short in cultivating these skills, highlighting a critical need for innovative pedagogical strategies.

To address these challenges, educators have explored models like Project-Based Learning (PjBL), which engages students in solving real-world problems, fostering critical and creative thinking (Hikmah et al., 2023; Anggito et al., 2021; Fitri et al., 2024), and promoting collaboration through team-based projects (Siyamuningsih et al., 2025; Deria et al., 2023; Halimatusyadiyah et al., 2022). Research, such as that by Wahyudi and Lazulva (2021), confirms the effectiveness of PjBL in enhancing students' critical thinking and idea generation. Similarly, the STEM (Science, Technology, Engineering, and Mathematics) approach, which aligns with 4C skills, offers a meaningful, engineering-driven learning process that prepares students for global challenges and boosts interest in chemistry (Winaryati et al., 2023; Suriti, 2021; Ariyatun & Octavianelis, 2020). Despite these advancements, the integration of PjBL and STEM remains limited by inconsistent implementation and a lack of collaborative teacher development.

A notable research gap exists in the simultaneous application of Lesson Study, STEM, and PjBL to enhance 21st-century skills in chemistry education. While Lesson Study supports teacher collaboration and professional growth through planning, implementation, and reflection (T. de Jong et al., 2023; Sulistia et al., 2019; Rati et al., 2023), and has been shown to improve learning communities (Winaryati et al., 2023; Rozimela, 2020; Rabbani et al., 2023), its integration with STEM and PjBL is underexplored. Previous studies have applied these models individually or in pairs, but not as a cohesive framework, particularly for abstract topics like voltaic cells, which require concrete contextualization.

This study aims to address this gap by describing students' 4C abilities (creativity, critical thinking, collaboration, and communication) through the application of a Lesson Study-based PjBL model with a STEM approach in teaching voltaic cell concepts. Its unique contributions include: (1) the innovative integration of Lesson Study, STEM, and PjBL, a rare combination for developing 21st-century skills; (2) a focused enhancement of 4C skills; (3) contextualization of abstract voltaic cell concepts through real-life projects; (4) teacher professional development via collaborative Plan-Do-See cycles; and (5) a replicable model for other science subjects. The research question guiding this study is: How can the integration of Lesson Study, STEM, and Project-Based Learning (PjBL) be effectively implemented in teaching voltaic cell concepts?

2. Literature Review

Project Based Learning (PjBL) is a constructivism-based pedagogical approach that emphasizes active, collaborative, and real product-oriented learning. PjBL has consistently been shown to increase interest, motivation, achievement, and mastery of 21st-century skills. According to Al-Kamzari & Alias (2025), PjBL is able to improve critical thinking, creativity, collaboration, and communication skills. Their research underlines that the design and implementation of PjBL in secondary schools significantly strengthens student engagement and conceptual understanding through contextual and problem-based learning experiences. (Long et al., 2025) explained that PjBL, especially in science and mathematics, supports more equitable and contextual learning outcomes and improves students' problem-solving skills, metacognition, and academic achievement. They emphasized that the success of PjBL implementation is highly dependent on teacher beliefs, authentic project-based curriculum design, and student involvement in decision-making. In the context of higher education in Indonesia, Vinco et al. (2025) showed that the implementation of PjBL in the History Learning Community program had a positive impact on the development of students' academic and social competencies. PjBL bridges classroom learning with real involvement in the community.

STEM education is a response to the global need for human resources who are able to compete in the era of technology and innovation. The STEM approach integrates science, technology, engineering, and mathematics in real contexts. (Amalina et al., 2025) emphasized that students' interest in STEM careers is influenced by cognitive factors (mathematics and science knowledge), motivational (self-efficacy and outcome expectations), and socioeconomic status. They suggested the need for interventions based on authentic learning experiences to increase STEM career interest among Indonesian students. PjBL also plays a role as an implementative approach in STEM education. Research by Fitriani et al. (2025) demonstrates that PjBL in the STEM context fosters cross-disciplinary learning, enhances 21st-century competencies, and promotes future career readiness.

The 21st-century skills were initially formulated as 4Cs, namely critical thinking, creativity, collaboration, and communication. However, in the context of Indonesia and global demands, this approach was expanded to 6Cs, with the addition of character, compassion, and citizenship or culture. In the research by Vinco et al. (2025), the development of the 6Cs was integrated through PjBL in response to the challenges of the VUCA world, demographic shifts, and the development of the new Indonesian Capital City (IKN). The results showed a significant increase in all 6Cs indicators through student involvement in community-based history projects. (Pardede, 2020); (Qurbonova, 2024)classified 4Cs as key competencies in facing global challenges, (Vinco et al., 2025); (Azmi et al., 2024) proposed the addition of culture and connectivity to adapt learning to multicultural and digital contexts.

Literature gap identification is 1) STEM and PjBL are often studied separately, previous studies have highlighted the effectiveness of PjBL or STEM in improving conceptual understanding or motivation in science learning, but very few have integrated both approaches within the lesson study framework as a means of teacher professional development; 2) Limited focus on 4Cs skills in chemistry education, much of the literature emphasizes cognitive outcomes (e.g. conceptual mastery, academic achievement), but there is a lack of research that explicitly explores how 4Cs skills emerge in chemistry learning processes; 3) Abstract chemistry concepts remain disconnected from real life contexts, studies have shown that students struggle to understand chemistry because of its abstract nature. However, few attempts have been made to contextualize abstract concepts through authentic STEM PjBL projects; 4) the lesson study research focusing narrowly on teacher reflection, while lesson study has been widely examined as a tool for reflective teaching practice, its contribution to supporting innovative instructional models such as STEM PjBL has not been fully documented. This research fills the gap is 1) integrates lesson study, STEM, and PjBL simultaneously, creating an innovative instructional model rarely explored in the literature; 2) provides empirical evidence of students' 4Cs skills emerging concretely in a chemistry project (voltaic cell); 3) contextualizes abstract chemistry concepts by using local materials as electrolytes, there by bridging theory with everyday practice; and 4) promotes teacher professional development by enabling collaboration among teachers, pre service teachers, and lecturers through the Plan-Do-See cycle.

3. Methodology

This study evaluates the perceptions and experiences of model teachers, observer teachers, and students regarding the implementation of chemistry learning designed and executed using a qualitative descriptive method. This approach aims to develop theoretical insights by emphasizing naturalistic observation and in-depth understanding (Khan et al., 2023). Key characteristics include the researcher's direct involvement in the field as an observer, categorization of actors, documentation of phenomena in observation logs, non-manipulation of variables, and a focus on natural settings. The method seeks to explore how the 4C skills (Critical Thinking, Creativity, Communication, Collaboration) are cultivated through the integration of Project-Based Learning (PjBL) with STEM, facilitated by the Lesson Study framework. Data are gathered through active collaboration among teachers and students, utilizing observation, reflection, and documentation of learning activities (Amroh et al., 2025; Kandel & Kandel, 2023).

3.1. Research Design

The study adopts a qualitative descriptive design structured around the Lesson Study implementation framework, which consists of three iterative stages to ensure a cyclical and reflective process: (1) Plan (Planning): Teachers, including 5 model teachers, 3 lecturers, and 10 prospective teachers, collaboratively design a PjBL-STEM learning plan targeting the development of 4C skills. This phase involves a detailed project plan for Volta Cell material, integrating science (chemical reactions), technology (electrode design tools), engineering (circuit construction), and mathematics (voltage calculations), with a structured timeline and role assignments documented in a lesson plan template. (2) Do (Implementation): The designed plan is executed in the classroom with 30 grade XII students, while researchers and observer teachers (totaling 18 observers) conduct real-time observations using a predefined observation protocol to assess implementation fidelity and its impact on students' 4C skills. Each session lasts 90 minutes and is conducted over three weeks. (3) See (Reflection): Teachers and researchers jointly analyze observation data, student reflections, and project outcomes during a 60-minute post-lesson debrief, evaluating the learning process and students' 4C skill development using a reflective feedback form. The Lesson Study cycle is visually represented in Figure 1, with each stage documented to support replicability.

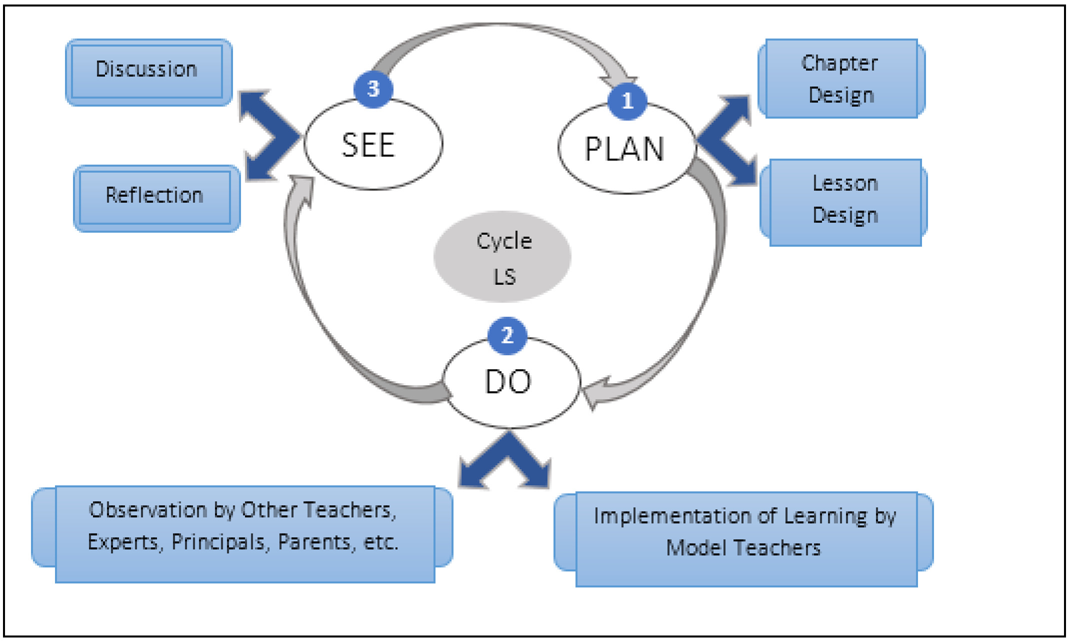

Figure 1. Lesson Study Cycle Flow

3.2. Research Subjects

Participants include 5 chemistry teachers from SMA Negeri 9 Semarang as model teachers facilitating PjBL-STEM learning and collaborating in Lesson Study. Additionally, 3 lecturers and 10 prospective teachers from Semarang City serve as observers, monitoring and reflecting on the learning process. The primary participants are 30 grade XII students studying Voltaic Cell material, selected based on heterogeneous academic abilities (assessed via prior semester grades ranging from 60 to 90) to ensure representative data.

3.3. Research Location and Time

The study was conducted at SMA Negeri 9 Semarang, chosen purposively due to the school's established chemistry curriculum and the readiness of teachers and students to implement the PjBL-STEM model within the Lesson Study framework. The research spanned one semester, from January 15 to June 15, 2025, encompassing planning (4 weeks), implementation (6 weeks), and reflection (2 weeks) phases, with sessions scheduled on Thursdays from 10:00 AM to 11:30 AM.

3.4. Data Collection Procedures and Instruments

Data were collected through multiple techniques to ensure validity and depth:

(a) Participatory Observation: Conducted during implementation by 18 observers using a structured 4C Observation Checklist, a 20-item instrument with Likert-scale ratings (1-5) and open-ended notes, focusing on Critical Thinking (e.g., problem analysis), Creativity (e.g., innovative material use), Communication (e.g., clarity in presentations), and Collaboration (e.g., task division). Observations targeted all 30 students, with 10 observed per session across three groups.

(b) Interviews: Semi-structured interviews were conducted with 5 model teachers and a purposive sample of 10 students post-implementation, using an Interview Guide with 15 open-ended questions (e.g., "What challenges did you face in designing the voltaic cell?") to explore experiences and perceptions, lasting 20-30 minutes each.

(c) Documentation: Included photos, videos (recorded with a handheld camera), and field notes captured during all stages, using a Documentation Log to categorize materials (e.g., student projects, lesson plans).

(d) Student Reflection: Students completed a Reflection Questionnaire, a 10-item tool with open-ended and 5-point Likert-scale responses, administered after each stage to assess skill development and challenges, with a 100% response rate (30/30 students).

3.5. Data Analysis Techniques

Data from transcripts, interviews, field notes, videos, photos, and learning documents were analyzed as qualitative data to build an understanding of individual experiences and the meaning of Lesson Study activities (Amroh et al., 2025; Kandel & Kandel, 2023). The analysis followed a thematic approach: (1) Data Coding: Initial codes were assigned to 4C skill indicators using NVivo software, with inter-coder reliability checked by two researchers (kappa = 0.85). (2) Thematic Development: Codes were grouped into themes (e.g., “Creative Problem-Solving,” “Collaborative Dynamics”) based on Lesson Study stage outputs. (3) Interpretation: Themes were interpreted in the context of 4C skill development, validated through triangulation of observation, interview, and reflection data (Winaryati et al., 2024). This process produced a comprehensive representation of complex experiential data, ensuring rigor and replicability.

4. Results

This study aims to analyze the emergence of 4C skills (Critical Thinking, Creativity, Communication, and Collaboration) in project-based learning (PJBL) with STEM integration on Volta Cell material, using the Lesson Study approach. Data were obtained through observation, student reflection, activity documentation, and interviews with teachers and students. The following are the results of the study, summarized based on the stages of Lesson Study and the indicators of 4C skills.

4.1. Planning Stage (Plan)

At this stage, chemistry teachers and lecturers involved in Lesson Study work collaboratively to design PJBL STEM-based learning. The planning process includes the Identification of Learning Objectives, where the Model Teacher designs project learning that will focus on students to explore information from various learning sources, simple investigations and process information, it is expected that students can analyze the processes that occur in voltaic cells and explain their uses, and can design voltaic cells using materials around them. This project is designed to encourage students to understand the working principles of voltaic cells while integrating STEM aspects.

The model teacher arranges the learning steps, including group discussions, experiments, and presentations of results. These activities are designed to facilitate student collaboration and communication. The following is a flow of stages of student activities in working on STEM integrated projects that have been arranged in the form of the following Learning Implementation Plan (RPP=Indonesian):

RENCANA PELAKSANAAN PEMBELAJARAN (RPP)

Sekolah : SMA Negeri 9 Semarang
Mata Pelajaran : KIMIA
Kelas/Semester : XII/Ganjil
Materi Pokok : Sel Volta
Alokasi Waktu : 6 JP

A. Kompetensi Inti (KI)

KI 1 : Menghayati dan mengamalkan ajaran agama yang dianutnya.

KI 2 : Menghayati dan mengamalkan perilaku a. jujur, b. disiplin, c. santun, d. peduli (gotong royong, kerjasama, toleran, damai), e. bertanggung jawab, f. responsif, dan g. pro-aktif, dalam berinteraksi secara efektif sesuai dengan perkembangan anak di lingkungan, keluarga, sekolah, masyarakat dan lingkungan alam sekitar, bangsa, negara, kawasan regional, dan kawasan internasional.

KI 3 : Memahami, menerapkan, menganalisis dan mengevaluasi pengetahuan faktual, konseptual, prosedural, dan metakognitif pada tingkat teknis, spesifik, detil, dan kompleks berdasarkan rasa ingin tahunya tentang a. ilmu pengetahuan, b. teknologi, c. seni, d. budaya, dan e. humaniora dengan wawasan kemanusiaan, kebangsaan, kenegaraan, dan peradaban terkait penyebab fenomena dan kejadian, serta menerapkan pengetahuan pada bidang kajian yang spesifik sesuai dengan bakat dan minatnya untuk memecahkan masalah.

KI 4 : Menunjukkan keterampilan menalar, mengolah, dan menyaji secara: a. efektif, b. kreatif, c. produktif, d.kritis, e. mandiri, f. kolaboratif,g.komunikatif, dan h. solutif, dalam ranah konkret dan abstrak terkait dengan pengembangan dari yang

D. Materi Pembelajaran

1. Materi Reguler
- Sel Volta
- Potensial Standar Sel (E^o sel)

2. Materi Pengayaan
Membuat sel volta dengan menggunakan bahan dari sayur dan buah-buahan.

3. Materi Remedial
- Potensial Sel

E. Metode Pembelajaran

1. Pendekatan : ***STEM***
   Siklus EDP : *Ask – Imagine – plan* – creat - *improve*
2. Model : ***PjBL STEM***
3. Metode : Diskusi, tanya jawab, *windows shopping*, **eksperimen**

F. Media Pembelajaran

1. Alat : Voltmeter
2. Bahan: Bahan praktikum
3. Media: PPT, LCD, spidol dan papan tulis

G. Sumber Belajar

Brady. 2008. *Kimia Universitas Asas dan Struktur*. Tangerang: Binarupa Aksara
Chang. 2005. *Konsep-Konsep Inti Kimia Dasar Jilid 1*. Jakarta: Erlangga
Johari. 2006 *Kimia Untuk SMA Kelas 1*. Jakarta: Erlangga
Purba Michael. 2006. *Kimia Untuk SMA Kelas X*. Jakarta: Erlangga
Watoni,dkk. 2017. *Kimia SMA dan MA untuk Kelas X Kurikulum 2013 Edisi Revisi*. Bandung: Yrama Widya
LKPD

Translate:

LESSON PLAN (RPP=Indonesian)
School : SMA Negeri 9 Semarang
Subject : Chemistry
Grade/Semester : XII/Odd
Main Topic : Voltaic Cell
Time Allocation : 6 class periods (JP)

A. Core Competencies (KI = Indonesian)

KI 1: Appreciate and practice the teachings of the religion they adhere to

KI 2: Appreciate and practice honest behavior, discipline, politeness, care (mutual cooperation, teamwork, tolerance, peace), responsibility, responsiveness, and proactiveness in interacting effectively according to the development of the child in their environment family, school, society, and the surrounding natural environment, nation, state, regional areas, and international community.

KI 3: Understand, apply, analyze, and evaluate factual, conceptual, procedural, and metacognitive knowledge at technical, specific, detailed, and complex levels based on a desire to know about: a) science, b) technology, c) arts, d) culture, and e) humanities with insights into humanity, nationality, statehood, and civilization related to the causes of phenomena and events, as well as applying procedural knowledge to specific fields of study according to their talents and interests to solve problems.

D. Learning Material

1. Regular Material
- Volta Cell
- Standar Cell Potential (E^o cell)

2. Enrichment Material
- Making a voltaic cell using materials from vegetables and fruits

3. Remedial Material
- Cell Potential

E. Learning Methods

1. Approach: STEM
   EDP Cycle: Ask-Imagine-Plan-Create-Improve
2. Model: PjBL STEM (Project-Based Learning with STEM approach)
3. Methods: Discussion, Q&A, window shopping, experiment

F. Learning Media

1. Tool: Voltmeter
2. Materials: Practical materials
3. Media: PPT, LCD, markers, and whiteboard

G. Learning Resources

Brady. (2008. *Chemistry: The Study of Matter and Its Changes*. Tangerang: Binarupa Aksara
Chang. (2005). *Essential Concepts of General Chemistry Vol. 1*. Jakarta: Erlangga
Johari. (2006). *Chemistry for Senior High School Grade X*. Jakarta: Erlangga

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KI 4: Demonstrate the skillsof reasoning, processing, and presenting creatively, productively, critically, independently, collaboratively, communicatively, and with integrity in abstract and concrete realms related to the development of learned materials in school independently and effectively.	Purba Michael. (2006). *Chemistry for Senior High School Grade X*. Jakarta: Erlangga Watoni, et al. (2017). *Chemistry for Senior and Islamic High Schools Grade X, 2013 Curriculum Revised Edition*. Bandung: Yrama Widya LKPD (Student Worksheet)

Figure 2. Lesson Plan

The RPP(Indonesian) is a guide for model teachers to implement learning in the classroom. The plan activity is carried out collaboratively through the presentation of the model teacher about the learning activities to be implemented, followed by discussion and input from the lesson study team. The results of the discussion activities produced STEM-integrated PjBL learning activities in Table 1:

Table 1. STEM Integrated PjBL Learning Activities

Stages of the PjBL Learning Model	
Reflection Stage	Students learn the voltaic cell process by observing existing examples by empowering available materials (voltaic cells from natural materials) through video viewing.
Research Stage	Students discuss in groups to solve problems
Discovery Stage	The results of the discussion were presented in the form of posters through window shopping activities.
Application Stage	Students work in groups to test and design voltaic cells
Communication Stage	Students present project results and receive feedback.

Table 2. STEM Integrated PjBL Learning Activities

Stages of the STEM Approach	
Ask	Students work in groups to formulate the problems given in the project assignment
Imagine	Students seek information in the problem solving process
Plan	Students create a draft project completion plan using poster media.
Creat	Students create a schedule of project completion activities
Improve	Students discuss the results of the design trials, especially the problems identified in making voltaic cells.

The results of the learning implementation plan have been discussed collaboratively with the hope that the learning plan can be structured with a focus on developing 4C skills. The 4C skill indicators are explicitly integrated into each stage of the learning process. PjBL learning implemented using the STEM (Science, Technology, Engineering, Mathematics) approach can be analyzed for its application in PjBL STEM learning on the Volta Cell material as follows: a) Science, students will learn about the application of the voltaic cell concept in everyday life; b) Technology, the use of simple tool technology that has been made from student project results using natural materials available in the environment that can produce electricity; c) Engineering, students design voltaic cells to create a series of voltaic cells that can produce electricity; and d) Mathematics, students calculate the electric current and potential difference produced by the voltaic cell series.

4.2. Implementation Stage (Do)

At the do stage in lesson study, the model teacher will carry out learning in the classroom by implementing STEM Integrated PjBL learning with reference to the RPP that has been created.

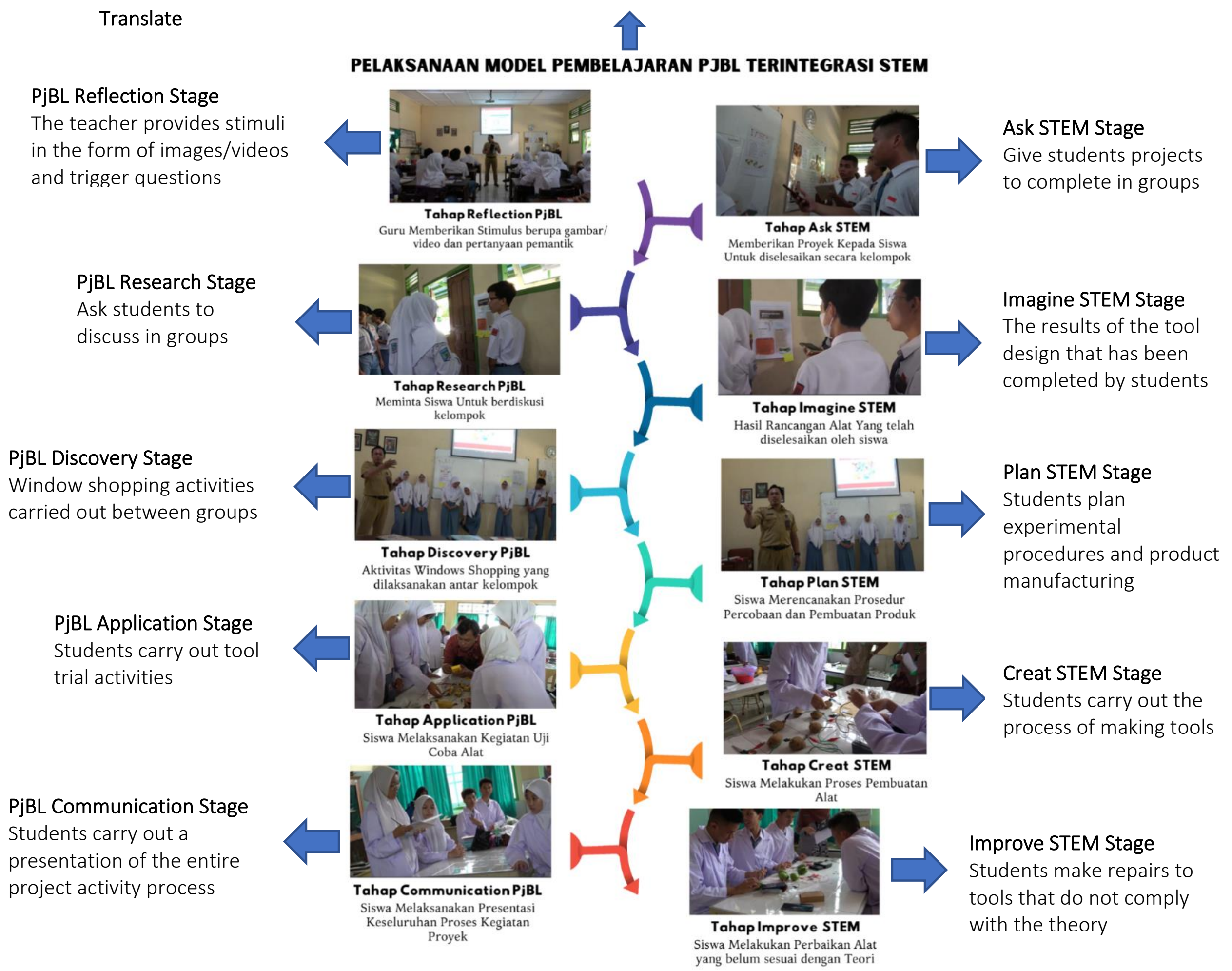

Figure 3. Implementation of the STEM Integrated PjBL Learning Model

The implementation of learning involves 2 activities, including the Project-Based Learning Model with the STEM Approach. In this case, learning will be carried out in accordance with the STEM integrated PjBL learning activities, each of which has 5 implementation flows which will be described through the following learning documentation results:

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Figure 4. PjBL Reflection Stage

In this meeting, the model teacher conducted the reflection phase of project-based learning (PjBL). The teacher presented a picture of a series of voltaic cells and asked several questions for students to answer. This stage aims to help students understand the context of the problem and provide inspiration so that they can immediately begin the investigation process. In addition, this phase functions to connect students' prior knowledge with the material that needs to be learned. Based on the results of the observations, students were found to be able to accurately identify information through the presentation of videos and images.

Figure 5. PjBL Research Stage and STEM Approach Ask Stage

The next stage in project-based learning (PjBL) is the research stage, where students conduct research that encourages them to be more active in contributing to the learning process. At this stage, the model teacher divides the students into discussion groups and assigns them the task of solving the problem: "How to design a set of tools using natural materials around that can produce electricity." This phase marks the beginning of the STEM activity flow, especially at the "Ask" stage, where students begin to ask various questions that will be used to formulate problems in completing the project. During the research stage, the teacher plays an active role in guiding the discussion to ensure that students develop a conceptual understanding that is relevant to the project being worked on.

Based on the results of observations and documentation, students were seen as quite active in discussing in groups and putting forward very creative ideas. Some groups even used materials that were rarely used in simple experiments. The activity of searching for information sources, designing, and producing designs is included in the "imagine" stage of STEM learning. The designs they have created are then printed on posters, as shown in the picture below.

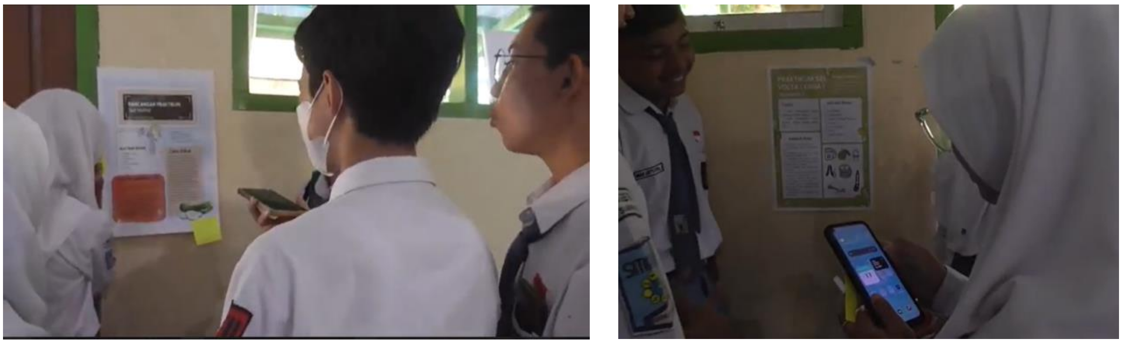

Figure 6. Imagine Stage of STEM Approach

The design plans made by students were presented through window shopping activities. In this activity, each group's design was displayed on the wall, with one group member serving as a presenter, while the other members walked around to observe and provide feedback on the designs of the other groups. The feedback was written on paper containing the design of each group's tools. This activity aims to train students to enhance their critical thinking skills, while encouraging them to be open and receptive to input from other groups. In addition, students are also trained to think rationally in assessing the designs they observe from other groups.

Figure 7. PjBL Discovery Stage and STEM Approach Plan Stage

The learning process ends with students conveying the conclusions they have obtained. The model teacher then gives students the opportunity to agree on the design that will be tested at the next meeting. In addition, an agreement is also made to determine the schedule for completing the tool and implementing the trial. This agreement marks the end of the "plan" stage in the discovery phase of the PJBL STEM learning flow. Furthermore, the activity will continue to the "create" stage, where students will begin to make tools according to the design that has been designed, with guidance from teachers at school.

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Figure 8. PjBL Application Stage and STEM Approach Create Stage

The image above illustrates the implementation of the tool trial as part of the application stage in the PJBL learning model's rollout. This trial was carried out by students systematically, following the procedures they had prepared. Each group showed high enthusiasm when observing how their tools functioned. If there was a failure or inconsistency with the initial design, they attempted to identify the cause and correct the errors that occurred. This experience encouraged students to connect the events they experienced with the theories they had learned in previous sessions, thereby increasing their enthusiasm for the learning process.

Figure 9. PjBL Communication Stage

Each group presented the results of their tool trials to their friends and teachers, which is part of the communication stage in PJBL learning. At this stage, students are able to explain the relationship between the practicum they did and the concept of voltaic cells. They also revealed the obstacles and failures they had experienced, along with the steps they took to overcome them. The results of observations obtained from the implementation of this learning as a whole have demonstrated the ability of Critical Thinking, as shown by the students' capacity to analyze problems and evaluate the results of experiments. For example, several students were able to identify weaknesses in their voltaic cell designs and provide solutions to improve efficiency.

Creativity skills also emerge from various innovations by students, such as the use of different alternative electrolyte materials for each group (including tomatoes, potatoes, limes, chayote, dragon fruit, bananas, guavas, and papaya). Meanwhile, students' communication skills are demonstrated through improvements in conveying ideas and project results systematically. Some students who were initially passive began to be actively involved in discussions. In addition to collaboration skills, students are able to work together effectively, although some groups may require the assistance of a facilitator to resolve internal conflicts.

4.3. Reflection Stage (See)

Reflection was conducted through a joint discussion between the model teacher, chemistry teacher and lecturer involved in the lesson study. The following are the main findings obtained from the results of the reflection by the lesson study team: From the Model Teacher's Perspective,

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Teachers stated that the Lesson Study approach helped them design more focused and collaborative learning, Teachers also observed an increase in student involvement, especially in the aspects of communication and collaboration. According to some members of the lesson study team, the most important aspect of learning is fun learning, which can be observed in the implementation of learning, as evidenced by the students' joy during the learning process.

From Students' Perspective, Most students felt that project-based learning helped them understand the Voltaic Cell material more deeply, Students stated that the project activities gave them space to think creatively and collaborate with classmates, Some students admitted that the reflection session helped them realize their strengths and weaknesses in the learning process, Many students mentioned that this activity was a new experience that was challenging but also fun, especially in communicating and sharing ideas. The reflection process in lesson study helps teachers and students understand the impact of learning on the development of 4C skills and provides valuable input for improving future learning designs.

Figure 10. Reflection Stage

5. Discussion

This study aims to analyze the emergence of 4C skills (Critical Thinking, Creativity, Communication, and Collaboration) in project-based learning (PBL) with a STEM approach, through reflection on Lesson Study results using the Volta Cell material. Based on the study's results, 4C skills were identified at various stages of learning, indicating that the PJBL STEM learning model can be an effective means of developing 21st-century competencies. This section will discuss the research findings in the context of previous research, their implications for education, and the challenges faced.

5.1. The Critical Thinking Skills

Critical thinking skills were evident in students' ability to analyze problems, identify weaknesses in project designs, and evaluate experimental results. For example, some students were able to propose modifications to the voltaic cell design to increase the efficiency of electric current. This finding is consistent with previous research by Nurmaliah et al. (2021), Papers Busnawir et al. (2025), and Irma Waty Simanjuntak & Purwaningsih (2024), which show that STEM-based learning improves students' ability to solve complex problems because it requires them to integrate concepts from various disciplines. Another study by Guo et al. (2020), Cahyadi et al. (2024), Novalia et al. (2025), and Issa & Khataibeh (2021) also confirmed that PJBL encourages students to think critically through survey activities and project evaluation. However, it is worth noting that the level of critical thinking among students in this study varied, depending on their academic background and previous learning experiences. This aligns with the findings of Shongwe (2024) and Milaturrahmah et al. (2017), which state that critical thinking is a skill that needs to be trained gradually through structured learning.

5.2. The Creativity

Students' creativity was evident in their project designs, such as the use of alternative electrolytes (e.g., lemon water) and innovations in the structure of voltaic cells. This activity provided space for students to think outside traditional boundaries and come up with unique solutions. This finding is supported by research (Lou et al., 2017; Hanif et al., 2019; Vistara et al., 2022), which states that the STEM approach in project-based learning allows students to develop creativity through exploration of ideas and experiments. PJBL learning provides a real-world context that is relevant to students, making them more motivated to innovate. However, some groups of students need more guidance to generate creative ideas. This shows that the success of developing creativity in PJBL STEM learning is highly dependent on the role of the teacher as a facilitator, as stated by (Kuhn et al., 2024; Mastul, 2024; Tonna et al., 2017), which highlights the importance of teacher mentoring in motivating students to think creatively.

5.3. The Communication Skills

Students' communication skills developed during the group discussion process and presentation of project results. Most students showed the ability to convey ideas systematically, although some students took longer to feel confident speaking in public. This finding supports the results of research by Kurniawati et al. (2019) and Purnami & Widiadnya (2024), who found that project-based learning facilitated the improvement of students' communication skills, especially through interactions between group members and feedback from teachers. In addition, students' involvement in project presentations provided them with valuable experience in conveying ideas professionally, as expressed by Asmayani et al. (2025), Kurniawan (2025), and McKinney (2023) in their study on the effectiveness of PJBL. However, this study also found that students who are less accustomed to public speaking need additional learning strategies, such as presentation simulations, to increase their confidence. This aligns with the recommendations (Adamson et al., 2023; Blackmore et al., 2018; Kozyar et al., 2022), which suggest using simulation-based learning techniques to enhance students' communication skills.

5.4. The Collaboration Skills

Collaboration is evident in the division of tasks and cooperation between group members. Students are able to discuss, resolve conflicts, and work together to achieve common goals. However, some groups require teacher intervention to resolve internal conflicts. This finding supports research by Andriyani & Anam (2022), Desyarti Safarini (2019), Mustamin et al. (2024), and Rehman et al. (2024), which shows that project-based learning encourages students to work together effectively because they share responsibility in completing the project. In addition, according to Sagala et al. (2020), Sappaile et al. (2025), and Sudarso et al. (2024), Collaboration in PJBL helps students develop interpersonal skills that are important for their professional lives. However, this study also shows that effective collaboration requires a good group structure and clear role allocation, as expressed by L. de Jong et al. (2022) and van Leeuwen & Janssen (2019). This suggests that teachers should provide explicit guidance on how to collaborate.

5.5. Effectiveness of Lesson Study

The implementation of Lesson Study in this study provides a significant contribution to improving the quality of learning. Teachers can design and reflect on learning collaboratively, resulting in more effective strategies for developing students' 4C skills. This aligns with research (Lundbäck & Egerhag, 2020; Yun et al., 2024), which suggests that Lesson Study enables teachers to understand learning practices from the students' perspective, thereby facilitating data-driven improvements. In addition, Lesson Study enables teachers to share experiences and gain new insights from their colleagues, as noted by Lundbäck & Egerhag (2020) and Yun et al. (2024).

5.6. STEM and PjBL Context

STEM integration in project-based learning on Voltaic Cell material offers significant benefits, including increased student relevance and motivation. This project combines science (voltaic cell chemistry), technology (use of measuring instruments), engineering (voltaic cell design and construction), and mathematics (efficiency calculations). This finding is supported by research from Baptista & Martins (2019), English (2016), and İbrahim (2021), which highlights the importance of the STEM approach in helping students understand the relationships between scientific fields. In addition, PJBL with a STEM approach provides students with opportunities to apply theoretical concepts to real-world contexts, as noted by Lee & Lee (2025), Rahmania (2021), and Yusri et al. (2024).

6. Conclusion

Based on the research conducted, it has been shown that learning with the Project-Based Learning model integrated with the STEM approach through the Lesson Study framework is effective in developing 4Cs skills (Critical Thinking, Creativity, Communication, Collaboration) in students. This learning is designed to encourage students to face real challenges through the integration of science, technology, engineering, and mathematics concepts that are relevant to everyday life. The implementation of PJBL STEM encourages students to analyze and evaluate information related to the concept of voltaic cells. Exploration and discussion activities have been shown to stimulate students' critical thinking in understanding the relationship between theory and practice. Students' creativity is monitored through the voltaic cell model-making project and the way students present their experimental results. Students demonstrate innovative abilities in designing solutions and conveying new ideas.

Group discussions and presentations of project results offer students opportunities to enhance their communication skills, both in explaining concepts and collaborating with other team members. Lesson Study, as a reflective method, facilitates collaboration among students, teachers, and observers. Students learn to share responsibilities, listen to others' opinions, and work towards common goals. Overall, Lesson Study-based PJBL STEM learning offers a holistic approach to eliciting 4Cs skills in the classroom. The results of this study make significant contributions to educational practices, particularly in learning design that focuses on developing students' skills to address global challenges.

7. Suggestion

The suggestions in this study are: 1) the Lesson Study-based STEM-PjBL model can be implemented more widely in learning at various levels and subjects, especially in topics that require conceptual understanding and practical application; 2) teachers need to continue to be supported through training and mentoring to improve their ability to design and implement innovative learning that focuses on developing 21st century skills; 3) Lesson Study as a collaborative approach between teachers should be developed sustainably as part of improving the quality of learning in schools; 4) schools and educational institutions are expected to provide support in the form of time, resources, and policies so that this learning model can be implemented optimally; 5) This study can be the basis for further research, both qualitatively and quantitatively, to explore the impact of the STEM-PjBL model in a broader and more varied context.

Declarations

Author Contributions. Eny Winaryati: literature review, conceptualization, and methodology. Zanaton H. Ikhsan: Validation and data analysis. Rose A. Rauf: Review, editing, and critical revisions. Agung Setiawan: Writing, original manuscript preparation, and data visualization. Wiwik I. Kusumaningrum:

Validation and data visualization. Lizza Nurdiana: Observer and literature review. Yousef Wardat: Corresponding author, literature review, conceptualization, methodology, validation, data analysis, review, editing, critical revisions, writing, original manuscript preparation, data visualization, and observer. All authors have read and approved the published final version of the article.

Conflicts of Interest. The authors no conflict of interest.

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Ethical Approval. This research was conducted in accordance with ethical standards for research involving secondary school students. Research authorization was obtained from the school. All participants provided informed consent prior to participation. Participants were assured that their responses would be kept confidential and anonymous, and that their participation was voluntary with no academic consequences.

Data Availability Statement. The data supporting these research findings are available upon reasonable request from the corresponding author.

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