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Teachers' Voices from the Global South: Navigating Chemical Literacy through STEAM-PjBL in Resource-Limited Indonesian Classrooms

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ABSTRACT

This study examines how six chemistry teachers in Yogyakarta, Indonesia, implemented project-based STEAM learning to enhance chemical literacy and creativity within systemic constraints. Using a qualitative case study with semi-structured interviews analyzed thematically, teachers reported challenges such as limited time, inadequate laboratory facilities, uneven student readiness, and partial expertise in STEAM integration. They addressed these issues through virtual titrations, microscale buffer experiments, chemistry comics, natural indicators, and professional collaboration. Students demonstrated increased engagement, creativity, and critical reasoning, although macro–micro–symbolic translation remained difficult. The study introduces the R^3 mechanism (Representations, Resources, and Rubrics) as vital for maintaining rigorous chemistry instruction in resource-limited environments, emphasizing both teacher agency and structural support.

Keywords: Chemical literacy, Global South, Project-based learning, STEAM education, Teacher strategies

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INTRODUCTION

Chemistry education differs from other sciences because it requires students to work with three interconnected levels of representation: macroscopic phenomena, microscopic particle models, and symbolic systems like formulas and equations. This "triplet of representations" forms the basis of chemical literacy but is challenging for students to master, often leading to fragmented understanding and misconceptions (Gilbert & Treagust, 2009; Stojanovska et al., 2017; Talanquer, 2011). In this study, chemical literacy is understood and expressed through macroscopic observations, microscopic reasoning, and symbolic systems. Indicators include linking experimental results with particle-level explanations, accuracy in chemical notation, and creative application of concepts in problem-solving. Challenges increase when laboratory resources are limited, causing teachers to rely more on abstract explanations (Caushi et al., 2021). International assessments like PISA reveal ongoing weaknesses in applying science concepts, with Indonesia consistently scoring below the OECD average, especially on chemistry-related tasks (Musyarofah et al., 2023; OECD, 2019). Thus, improving chemical literacy is a national priority.

Indonesia's educational disparities hinder reforms. Many schools, especially rural ones, lack functional laboratories and digital resources (Susanti et al., 2017). The *Merdeka Curriculum* encourages contextualized, project-based learning (Rahmawati, 2023), but uneven teacher training and shortages threaten to widen gaps (Zahro & Lutfi, 2021). Chemistry, which heavily relies on lab work and symbolism, is particularly impacted. These conditions highlight the need for methods that can succeed despite limitations. Combining Science, Technology, Engineering, the Arts, and Mathematics (STEAM) with project-based learning (PjBL) shows promise, but its implementation in Indonesian schools remains largely unexplored.

Globally, STEAM is seen as a transformative framework that equips students with skills like creativity, problem-solving, and critical thinking (Henriksen et al., 2019). In chemistry, STEAM has been applied to tasks such as molecular modeling, infographic creation, and simulations, which enhance conceptual understanding and develop transferable skills (Perignat & Katz-Buonincontro, 2019; Yakman & Lee, 2012). However, most evidence comes from resource-rich contexts in the Global North, where laboratories and professional development opportunities are readily available (Chien & Chu, 2018). This disparity highlights a paradox: the Global South, where STEAM could help make learning more accessible, also faces the greatest implementation challenges. This shift draws attention to how educators adapt STEAM-PjBL in resource-limited settings, making the Indonesian case both timely and significant.

PjBL aligns with constructivist and experiential theories by emphasizing student agency and authentic problem-solving (Thomas, 2000). In chemistry, PjBL connects abstract concepts with meaningful projects, such as tackling environmental issues or designing affordable experiments. Evidence indicates that PjBL improves conceptual understanding, motivation, and critical thinking (Lou et al., 2014). It can also enhance representational fluency as students explore macro, micro, and symbolic levels (Kokotsaki et al., 2016). However, PjBL requires significant time and resources. In well-equipped settings, digital tools help address these challenges, but in resource-limited contexts, teachers must balance curriculum demands, exam prep, and shortages (Prajoko et al., 2023). These issues raise questions about how PjBL can be effectively implemented in Indonesian classrooms.

Sociocultural contexts also affect learning. Ethnoscience approaches include incorporating chemistry into local practices such as fermentation or dyeing, making concepts more relatable (Imansari et al., 2018). Arts integration offers creative tools, such as comics and posters, that improve representation and memory (Ardiansyah & Oktariani, 2024; Gay, 2018). Although shortages limit laboratory practice, Indonesia's cultural richness provides chances for contextualized teaching.

Teacher agency also influences success. Agency refers to teachers' ability to adapt pedagogy within systemic constraints and professional values (Priestley et al., 2015). In chemistry, agency arises when teachers develop microscale experiments, substitute natural indicators, or collaborate through professional networks such as MGMP. Evidence from the Global South shows that teacher-driven innovations are often more sustainable than top-down reforms (Sayed & Sing, 2020). Indonesian teachers have created low-cost experiments and integrated digital tools despite minimal support (Handayani et al., 2023). These practices demonstrate adaptive professionalism, but without consistent investment, innovations risk remaining fragmented.

Assessment practices add another layer. High-stakes exams focus on algorithmic problem solving and memorization, which can overshadow inquiry and representational skills. This may discourage teachers from dedicating time to PjBL (Prajoko et al., 2023). International research shows that reforming assessment is essential (Bybee, 2013). Rubrics that value both disciplinary accuracy and creative expression offer a solution (Quigley et al., 2017). In chemistry, such rubrics ensure students are evaluated on representational fluency and creativity, rather than just on procedures. Literacy initiatives, including reading programs and digital libraries, further prepare students to interpret scientific texts (Toma & Greca, 2018). Coherence across curriculum, pedagogy, and assessment is therefore crucial.

Despite worldwide enthusiasm for STEAM-PjBL, most research originates from resource-rich environments where schools have advanced labs and extensive professional development (Herro & Quigley, 2017; Krajcik & Shin, 2014). These studies highlight increased engagement, creativity, and problem-solving. However, they might overstate the universality of STEAM-PjBL by neglecting the realities faced by schools in the Global South. Ongoing equipment shortages, exam pressures, and inconsistent training affect how STEAM-PjBL can be sustained.

While much is known about the benefits of STEAM-PjBL in resource-rich contexts, little is understood about how teachers in the Global South adapt these pedagogies under systemic constraints. This study addresses that gap by highlighting the voices of Indonesian chemistry teachers in Yogyakarta, an educational hub with diverse school types and professional networks. It specifically investigates two questions: (1) How do chemistry teachers in resource-limited schools design and implement STEAM-PjBL to enhance chemical literacy and creativity? (2) What chemistry-specific strategies emerge to tackle systemic challenges, such as representational scaffolds for acid–base and buffer concepts, micro-experiments, and arts-integrated symbolic work? By examining these questions, the study not only documents teacher-driven practices but also develops the R^3 mechanism (Representations, Resources, Rubrics) as a conceptual contribution to the literature. This mechanism emphasizes how rigorous and inclusive chemistry education can flourish even amid scarcity, positioning Global South classrooms as sites of innovation rather than deficiency.

LITERATURE REVIEW

STEAM Education and Global Perspectives

STEAM education has been positioned globally as a framework that integrates disciplinary knowledge while fostering creativity, collaboration, and problem-solving (Liao, 2016). In high-income countries, extensive research demonstrates how STEAM encourages interdisciplinary inquiry, links theory to practice, and develops adaptive expertise among students (Capraro, 2008; Herro & Quigley, 2017). For instance, studies in North America highlight how STEAM supports design thinking and bridges formal and informal learning spaces (Bybee, 2013; Krajcik & Shin, 2014). European cases show gains in motivation, collaboration, and conceptual mastery when STEAM is implemented through project-based approaches (Capraro, 2008). Recent scholarship emphasizes design thinking and creativity as central outcomes, reinforcing STEAM as a critical twenty-first-century pedagogy approach (Henriksen et al., 2019).

Challenges and Innovations in the Global South

In contrast, the Global South presents a more complex picture. (Carney, 2022) emphasizes persistent disparities in access to resources, digital infrastructure, and teacher preparation. Empirical work across countries illustrates these tensions. South African schools face inequities in teacher training (Sayed & Sing, 2020); Nigerian classrooms are limited by insufficient laboratory facilities (Aina, 2022); rural Indian schools encounter digital divides that hinder inquiry-based learning (Sampath Kumar & Basavaraja, 2016); Brazilian contexts grapple with socio-economic disparities affecting sustainability of STEM initiatives (Kemechian et al., 2023); and Philippine teachers creatively adapt low-cost experiments to engage learners (Monta & Perdio, 2025). More recent studies in Southeast Asia, such as Tuong et al. (2023) in Vietnam and Kaewhanam et al., (2014) in Thailand, highlight both challenges from policy-practice gaps and innovative uses of digital tools to support STEM learning. These cases underline both the constraints and the creative practices teachers develop to adapt STEAM in resource-limited settings. Scholars increasingly warn against viewing Global South practices as deficient, emphasizing their role as sites of innovation (Chisom et al., 2024) instead.

Project-Based Learning (PjBL) as a Tool for STEAM

Project-based learning strongly aligns with constructivist and experiential theories of education (Dewey, 1986; Thomas, 2000; Vygotsky, 1978). It positions students as active participants engaging in authentic tasks, fostering deep understanding and application of concepts. Internationally, PjBL has been shown to improve collaboration, motivation, and problem-solving (English, 2019; Quigley et al., 2017). In Asia, integrating PjBL with STEM/STEAM has been found to enhance inquiry-based learning and creativity (Pramashela et al., 2023; Prasetyawati & Astuti, 2025; Retno et al., 2025; Riyadi et al., 2020). In African and Latin American contexts, teachers often adapt PjBL to local cultural stories or incorporate indigenous knowledge to contextualize learning (Sayed & Sing, 2020; Sevilla et al., 2023; Tarhan & Acar-Sesen, 2013). Additionally, recent research highlights the importance of teacher agency in shaping PjBL practices, indicating that educators actively influence curriculum implementation rather than passively following models (Biesta et al., 2019; Priestley et al., 2015). Therefore, PjBL provides not only a pedagogical framework but also a means for local STEAM adaptations to flourish.

STEAM-PjBL in the Indonesian Context

Indonesia has increasingly emphasized STEAM-PjBL through national reforms such as the *Merdeka Curriculum*. Research indicates both opportunities and challenges. Sumarni et al. (2019) demonstrated that STEM-PjBL improved students' critical thinking, though it required significant time investment. Dianti et al. (2023) reported enhanced conceptual understanding when chemistry lessons were structured through project-based STEM integration. Handayani et al. (2023) identified opportunities and constraints in using digital tools to support science classrooms. Innovative approaches have also emerged: chemistry comics to strengthen literacy (Ardiansyah & Oktariani, 2024) and ethnoscience strategies to contextualize chemistry in local cultural practices (Imansari et al., 2018). More recent scholarship also points to persistent gaps in science literacy and the importance of integrating reading strategies in science instruction (Toma & Greca, 2018). Despite these insights, little research explicitly examines how Indonesian teachers foster creativity while simultaneously managing systemic constraints such as infrastructure, time, and student diversity.

Identified Gap

Existing literature establishes the transformative potential of STEAM and PjBL globally, highlights innovations in the Global South, and documents emerging Indonesian practices. However, few studies provide a nuanced account of how teachers in Indonesia, and the Global South more broadly, navigate intersecting challenges while fostering creativity and literacy in STEAM-PjBL classrooms. This study addresses that gap by foregrounding teachers' voices, strategies, and adaptations within resource-limited contexts, thereby contributing to international debates on culturally responsive and decolonizing STEAM education.

RESEARCH METHOD

This study used a qualitative case study design to examine how chemistry teachers in Indonesian secondary schools navigate opportunities and challenges when implementing project-based STEAM learning to improve students' understanding of chemistry. A qualitative approach was chosen because it enables in-depth exploration of teachers' experiences and strategies within their institutional and cultural contexts (Creswell & Poth, 2016).

Research Context and Participants

The research was carried out in four secondary schools in Yogyakarta, Indonesia, involving six chemistry teachers (four female and two male) with 5–20 years of experience. Participants represented urban and semi-urban settings and were purposefully selected based on three criteria: (1) actively teaching chemistry, (2) prior experience with project-based or STEM/STEAM approaches, and (3) willingness to participate in extended interviews. The sample included two public and two Islamic high schools, representing different types of institutions. Yogyakarta was chosen as the research site because it is nationally recognized as an educational hub in Indonesia, featuring diverse school types, strong teacher professional networks, and a mix of urban and semi-urban environments, making it representative for studying the dynamics of STEAM-PjBL.

Data Collection

Data were collected over eight months (January – August 2025) using multiple sources. Each teacher participated in two rounds of semi-structured interviews (90–120 minutes). The first explored teachers' understandings and classroom practices; the second probed reflections on projects, strategies, and constraints. Interviews were conducted in Bahasa Indonesia, recorded with consent, and transcribed verbatim. Table 1 provides sample questions.

Table 1
Sample Interview Question

Focus Area	Example Questions
Conceptualization of STEAM-PjBL	"How do you understand STEAM and project-based learning in the context of chemistry teaching?"
Classroom Implementation	"Can you describe a project where you integrated STEAM elements into a chemistry lesson?"
Opportunities	"What opportunities have you observed when using STEAM-PjBL to support student learning?"

Challenges	"What main obstacles did you encounter (e.g., time, facilities, student readiness)?"
Creativity and Literacy	"How do you encourage students' creativity and support chemical literacy during projects?"
Adaptation Strategies	"What strategies have you used to adapt STEAM-PjBL to the constraints of your school context?"

At least one classroom observation was carried out for each teacher, focusing on project introduction, management, student engagement, use of resources, and representational practices. Table 2 outlines observation dimensions.

Table 2
Classroom Observation Focus

Dimension	Indicators
Project Introduction	How teachers introduced project goals, connections to curriculum, and STEAM integration
Classroom Management	Group formation, task distribution, and time allocation during projects
Student Engagement	Levels of participation, collaboration, and questioning
Use of Resources	Availability and creative use of laboratory tools, digital media, and local materials
Representational Practices	Evidence of macro-micro-symbolic transitions in explanations or tasks

Researchers kept journals during school visits to capture contextual details and reflections. Finally, lesson plans, worksheets, and student artifacts (posters, models, reports) were collected for analysis. Table 3 summarizes the documents analyzed.

Table 3
Document Analysis Summary

Document Type	Analytical Focus
Lesson Plans	Structure and curriculum alignment
Project Worksheets	Inquiry guidance and problem-solving
Student Artifacts (posters, models, reports)	Creativity, chemical accuracy, representational use
Assessment Rubrics	Criteria for disciplinary accuracy and creative outputs

Data Analysis

Thematic analysis followed Braun and Clarke (2006), i.e., familiarization, coding, searching, reviewing, defining, and reporting. Transcripts were read repeatedly, coded openly, and organized into categories that were later grouped into broader themes capturing opportunities, challenges, strategies, and responses. A reflexive thematic analysis approach was adopted (Braun & Clarke, 2006), emphasizing interpretive collaboration rather than quantitative reliability. Two researchers independently coded a subset of transcripts, and then refined codes through critical discussion and reflexive memoing, with an audit trail maintained to enhance transparency.

Trustworthiness

Several strategies were employed to enhance the trustworthiness of the findings. Credibility was upheld through member checking, where participants reviewed their interview summaries. Transferability was supported by providing detailed descriptions of the research context and participants. Dependability and confirmability were addressed by maintaining an audit trail of coding decisions and analytic memos, along with peer debriefings with two colleagues experienced in qualitative educational research.

Ethical Considerations

The study adhered to ethical research standards. Participants provided informed consent, were assured confidentiality, and could withdraw at any stage. To protect teachers' identities, pseudonyms were used throughout. The authors' university's institutional ethics committee reviewed and approved the study protocol.

FINDINGS

This section presents findings from interviews with six chemistry teachers in Yogyakarta, Indonesia. Results are thematically organized to align with the research questions, focusing on chemistry-specific adaptations. Teachers are identified as T1-T6 for anonymity.

Implementation of STEAM-PjBL in Chemistry Classrooms

All teachers reported applying STEAM-PjBL in topics central to chemical literacy, particularly acid-base reactions, buffer systems, molecular structures, and redox processes. T1 explained that because laboratory burettes and indicators were limited, he asked students to use a virtual titration simulator to visualize neutralization: *"Because the burettes and indicators were limited, I asked students to use a virtual titration simulator to visualize neutralization."* Similarly, T3 recounted how students tested buffer capacity using small quantities of vinegar and baking soda, noting that *"this reduced costs but still allowed them to calculate pH changes."* For symbolic language, T2 used chemistry comics and stated, *"We used comics to help students understand symbolic representations, such as balancing redox equations."* Meanwhile, T5 encouraged students to build three-dimensional molecular models of organic compounds, observing that *"they combined design and chemistry knowledge in very creative ways."* In addition, T6 connected chemistry with local cultural practices, explaining, *"I relate redox reactions to local practices such as fermentation and metal corrosion in household tools."*

Classroom observations supported these examples. For instance, in T1's class, students debated whether simulated titration curves matched textbook patterns, while T5's students showcased detailed molecular models during a mini-exhibition. Such artifacts demonstrated how STEAM-PjBL blended science, mathematics, and technology with arts and culture to enhance representational fluency. Examples of these practices are summarized in Table 4.

Table 4

Chemistry-Specific STEAM-PjBL Examples

Teacher	Example
T1	Virtual titration of acid–base systems
T2	Chemistry comics for symbolic equations
T3	Micro-experiments in buffer systems
T4	Redox projects combining symbolic and experimental tasks
T5	Molecular model building for organic compounds
T6	Ethnoscience examples (fermentation, corrosion)

Challenges in Implementation

Teachers consistently reported challenges. Time constraints were a major issue. T5 admitted: *"We can only do one major project per semester due to the time needed for lab and reporting."* Facility shortages hindered practice. T1 noted: *"Buffer reagents were expired, so we switched to online simulations."* Another common difficulty was student preparedness. T2 observed: *"Not all students were able to connect symbolic equations to particle-level models."* Limited teacher expertise also appeared. T4 reflected: *"I understand chemistry well but still struggle to integrate art and technology fully."*

Observation notes confirmed these struggles. In one school, expired indicators forced reliance on homemade extracts; in another, a redox project was postponed due to lack of lab space. These comments highlight how shortages, scheduling conflicts, and pedagogical gaps affected consistent STEAM-PjBL implementation. The challenges are detailed in Table 5.

Table 5
Reported Chemistry-Specific Challenges

Category	Example
Time	Limited projects per semester (T5)
Facilities	Expired or missing reagents (T1)
Student readiness	Difficulty with macro–micro–symbolic connections (T2)
Teacher expertise	Struggles in art-technology integration (T4)

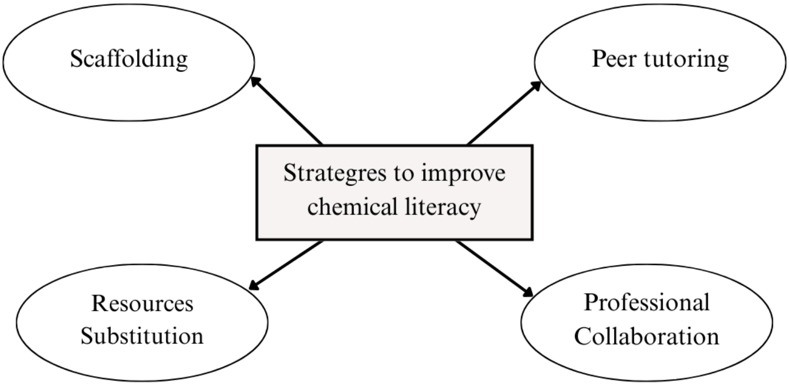
Strategies to Overcome Challenges

Despite obstacles, teachers showed resourcefulness. T1 broke projects into smaller steps: *"I broke the titration project into smaller steps, so students wouldn't be overwhelmed."* Peer collaboration also helped. T2 recalled: *"Students who grasped symbolic equations helped others balance reactions."* Substitution of resources was common. T3 explained: *"We replaced unavailable indicators with natural extracts like hibiscus."* Professional collaboration was key. T6 shared: *"In MGMP meetings, we exchanged project ideas, such as low-cost buffer experiments."*

While these substitution practices made projects feasible, issues of chemical fidelity also emerged. For example, vinegar-baking soda mixtures or hibiscus indicators can oversimplify and risk misrepresenting actual buffer chemistry. Observations highlighted both their potential and their limits: in T3's class, hibiscus extract produced a visible color change that students recorded carefully in worksheets, demonstrating engagement but also revealing the need for scientifically valid calibration. To address this, several teachers suggested safer micro-scale buffer systems (e.g., acetic acid–sodium acetate at low concentrations) combined with calibrated natural indicators, or licensed virtual labs to simulate titrations and equilibria. Such refinements ensure that substitutions are not only affordable and engaging but also valid scientifically, reinforcing the R^3 mechanism's emphasis on Resources as both practical and accurate.

In T2's class, stronger students were also observed tutoring peers during equation-balancing exercises, showing how scaffolding, peer tutoring, resource substitution, and collaboration interacted to sustain chemistry projects. Strategies are shown in Figure 1.

Figure 1
Strategies Adopted



Student Responses and Literacy Outcomes

Teachers observed that students displayed varied reactions, mostly positive. According to T2, visual media boosted engagement: *“Students became more motivated when using comics to explain redox processes.”* T5 highlighted students’ creativity in their projects, saying, *“Students produced molecular models with artistic detail, which helped improve understanding.”* T3 emphasized the development of critical thinking skills, recalling, *“Debates during micro-experiments helped students reason about buffer systems.”* However, challenges still persisted. T6 reflected on literacy gaps: *“Some students still struggled to shift between symbolic and particulate representations.”* These reports indicate that although STEAM-PjBL fostered enthusiasm and creativity, difficulties in understanding the macro, micro, and symbolic levels of chemical representation remained a major obstacle.

Observation notes confirmed these accounts. In T3’s class, small-group debates over buffer pH changes revealed reasoning strategies; in T5’s class, students proudly displayed models, and peers asked critical questions about structural accuracy. These artifacts suggest that while STEAM-PjBL fostered engagement and creativity, macro–micro–symbolic transitions remained a persistent difficulty. Student responses are outlined in Table 6.

Table 6

Student Responses and Literacy Practices

Teacher	Student Response	Literacy Practice
T1	Curious in virtual titrations	Use of simulators
T2	Motivated by comics	Symbolic literacy support
T3	Critical debates in buffer tasks	Pre-reading and group problem-solving
T4	Strong participation	Assignments with symbolic equations
T5	Creative molecular models	Model-based learning
T6	Mixed responses	Ethnoscience integration

Institutional Needs and Support

The interviews also revealed teachers' emphasis on the need for stronger institutional support to sustain chemistry-specific STEAM-PjBL. T3 stressed the importance of laboratory renewal, explaining, *"If schools provided pH sensors and online lab subscriptions, projects on buffers and titrations would be more effective."* Teachers also pointed to the need for access to technology, such as laptops, pH sensors, and internet connectivity, to support digital learning tools. T6 highlighted literacy initiatives, including programs that link reading to chemical concepts, as vital. Meanwhile, T1 underlined the urgency of professional training: *"We need special workshops on representational chemistry teaching to better connect macro, micro, and symbolic levels."* Collectively, these voices emphasize that without structural investment in facilities, technology, literacy programs, and professional development, the promise of inclusive STEAM-PjBL in chemistry remains difficult to realize.

Classroom observations echoed these calls. In one school, lack of internet access forced teachers to cancel a simulation activity. In another, limited books in the library hindered literacy tasks. Collectively, these voices emphasize that without investment in facilities, technology, literacy programs, and professional development, inclusive STEAM-PjBL in chemistry is difficult to sustain. Institutional needs are presented in Table 7.

Table 7

Reported needs for support

Area	Reported Needs
Facilities	Laboratory equipment, updated reagents
Technology	Access to laptops, pH sensors, and the internet
Literacy programs	Library books, e-books, and reading initiatives
Professional development	Training, peer collaboration, workshops

Overall, the results demonstrate how teachers in Yogyakarta are actively experimenting with STEAM-PjBL, navigating significant constraints while fostering creativity and chemical literacy in their students.

DISCUSSION

This discussion critically analyzes how STEAM–project-based learning (STEAM-PjBL) was used in chemistry classrooms with limited resources, examines the mechanisms behind the observed benefits, and considers where claims should be moderated by the disciplinary requirements of chemistry and the methodological limitations of the study.

To ground the analysis, it is important to describe the realities of the participating schools. One urban public school had a large but outdated laboratory, one semi-urban Islamic school used a repurposed storeroom as a lab, and two others operated almost completely without functional facilities. Classes averaged 32-38 students, which limited hands-on inquiry. Teachers relied on household acids and bases like vinegar or lime juice, while unstable electricity and internet disrupted digital tools. These conditions explain why improvisations, such as comics, microscale kits, or natural indicators, should be viewed as displays of professional agency in scarcity rather than as deficits relative to resource-rich models.

The discussion focuses on five tensions, namely, integration versus disciplinary rigor, representation as a bottleneck, substitution pedagogies and their validity, time-assessment misalignment, and teacher agency versus structural conditions.

Integration vs. Disciplinary Rigor: When Does STEAM in Chemistry Become Surface-Level?

Teachers used posters, comics, and model-building to incorporate STEAM into chemistry, reporting higher engagement. Similar patterns are observed in studies from Europe and North America, where arts integration boosted motivation but often risked superficial learning if not linked to disciplinary reasoning (Henriksen et al., 2019; Perignat & Katz-Buonincontro, 2019). For example, Capraro (2008) and Herro and Quigley (2017) found that students enjoyed designing products but sometimes failed to connect this work to a deeper understanding of chemistry concepts. In East Asian contexts, Conradty and Bogner (2020) showed that STEAM projects enhanced creativity but needed explicit scaffolding to maintain disciplinary rigor. Our findings reflect these concerns. In Indonesia, artistic elements were often treated as accessories rather than as tools for stoichiometric reasoning or equilibrium modeling. Compared to studies in resource-rich settings where integration was systematically aligned with curriculum goals, Indonesian teachers improvised with comics or posters without structured links to symbolic calculations or particulate models.

Correspondingly, McDaniel (2026) showed that integrating art elements through stop-motion animation in science learning can increase students' cognitive engagement while helping them visualize abstract concepts more concretely. Nonetheless, such an impact becomes meaningful only when the visualization is explicitly linked to the discipline's conceptual structure. In addition, Golegou et al. (2026) asserts that 21st-century pedagogies such as project-based learning and design thinking encourage the exploration of authentic problems as well as structured collaborative reflection, so that the strengthening of conceptual understanding does not depend on creativity alone, but rather on clear linkages between project activities and scientific reasoning. This contrast highlights the need for rigorous integration, where creative outputs are judged not just on aesthetics but also on accurate particle models, clear translation into symbolic forms such as equations, pH relationships, or oxidation states, and macro-level predictions that can be tested with data. This aligns with Gilbert and Treagust (2009) emphasis on representational coherence and connects this study to international research cautioning against viewing STEAM in chemistry as superficial decoration rather than a way to deepen disciplinary understanding. This finding is reinforced by recent research showing that STEAM integration in chemistry learning has a significant impact on conceptual understanding when creative activities are explicitly linked to submicroscopic, symbolic, and macroscopic representations through assessments that emphasize scientific argumentation and conceptual model accuracy (Bruce et al., 2022; Riyadi et al., 2025; Suchikova & Kovachov, 2024).

Representation as the Primary Constraint, Not Just a Skill Gap

Difficulties in transitioning between macro, micro, and symbolic levels are common. Prior studies confirm this as a widespread challenge (Stojanovska et al., 2017; Talanquer, 2011), but the Indonesian case demonstrates how infrastructural limitations exacerbate the problem. International research shows that students often struggle to connect symbolic procedures with particulate reasoning, even in well-resourced settings (Caushi et al., 2021; Gilbert & Treagust, 2009). In areas with greater resources, tools such as animations, dynamic simulations, and lab activities help students bridge these levels (Chien & Chu, 2018; Krajcik & Shin, 2014). Conversely, Indonesian teachers mostly relied on comics or hand-drawn visuals, which lowered entry barriers but also risked reinforcing misconceptions. Research by Alpiona (2025) shows that the use of visual media in chemistry learning is only effective when accompanied by conceptual scaffolding that explicitly directs students to translate submicroscopic representations into symbolic and macroscopic forms systematically. Similar studies in Turkey and

China found that without clear scaffolding, visual supports alone often led to ongoing misunderstandings of acid-base equilibria and redox reactions (Conradty & Bogner, 2020; Tarhan & Acar-Sesen, 2013). These similarities show that representation challenges are not just literacy issues but fundamental hurdles specific to chemistry. Our findings suggest that professional development should explicitly train teachers in “translation cycles”, shifting from particulate sketches to symbolic equations to macro-level predictions, aligned with Johnstone (1991) triplet model. Rubrics and assessments should also evaluate the quality of these translations, supporting calls in the literature for multiple external representations and linking analogies to improve representational fluency (Kozma & Russell, 2005).

Substitution Pedagogies Ender Constraint: Promise and Threats

Virtual labs and microscale experiments helped address resource shortages, but their effectiveness varied. International studies report similar substitutions, such as smartphone-based experiments in South Africa and India (Aina, 2022; Sampath Kumar & Basavaraja, 2016). Evidence from Latin America and Southeast Asia also shows that low-cost or digital alternatives can improve access but require careful validation (Sevilla et al., 2023; Tuong et al., 2023). In this context, Chu (2025) emphasizes that digital technologies and lightweight computing devices can expand access to STEM learning even in infrastructure-constrained environments. Furthermore, McDaniel (2025) in his study on the integration of artificial intelligence states that smart technology has the potential to increase the personalization of learning as well as the effectiveness of formative feedback. However, the effectiveness of technology still depends on the accuracy of pedagogical design and scientific interpretation.

Research by Rahmawati et al. (2025) shows that the use of virtual laboratories and simple experiments only has an optimal impact if it is designed by paying attention to the suitability of concepts, accuracy of procedures, and accuracy of data interpretation so as not to cause misconceptions. Our findings highlight risks: vinegar-baking soda mixtures presented as buffers can mislead students about buffer capacity, echoing concerns raised earlier that inaccurate approximations may reinforce misconceptions rather than build literacy (Caushi et al., 2021). In contrast, studies in Brazil and Thailand report successful microscale protocols when chemical validity was maintained through the use of true conjugate pairs and calibrated indicators (Kaewhanam et al., 2023; Kemechian et al., 2023). Comparative work in Europe similarly emphasizes that microscale innovations succeed when combined with clear instruction on measurement uncertainty and approximation (Hofstein & Kind, 2011). This cross-context comparison clarifies that substitution is not inherently flawed but requires adherence to disciplinary principles, accurate acid–base systems, calibrated tools, and transparent concentration approximations. Therefore, the Indonesian case illustrates both the potential and risks of substitution pedagogies under resource constraints, supporting international calls for fidelity-checked adaptations rather than impromptu improvisations.

Time and Assessment: The Impact of Structural Misalignment

Teachers limited projects to once per semester, echoing concerns in earlier research that high-stakes exams suppress inquiry-based learning (Prajoko et al., 2023). Similar issues are seen in other exam-focused systems, such as China and Turkey, where teachers revert to lecture-heavy methods despite positive attitudes toward PjBL (Conradty & Bogner, 2020; Riyadi et al., 2020; Tarhan & Acar-Sesen, 2013). Unlike in the U.S. or Singapore, where project rubrics are clearly aligned with national testing standards (Bybee, 2013; Krajcik & Shin, 2014), Indonesian exams remain centered on algorithmic problem solving and rote memorization. This misalignment discourages teachers from dedicating time to resource-intensive teaching methods. Our proposed solution of "PjBL sprints" and dual rubrics aligns with (Creswell & Poth, 2016; Quigley et al., 2017), who advocate for balancing accuracy and creativity in evaluation, and matches findings from European studies showing that shorter, well-structured projects can reduce exam pressure while maintaining conceptual learning (Kokotsaki et al., 2016). Overall, evidence from comparisons supports aligning curriculum, pedagogy, and assessment in Indonesia, emphasizing that without assessment reform, PjBL risks marginalization in chemistry classrooms.

Agency Under Constraint: Necessary but Not Sufficient

Teachers demonstrated strong agency through peer tutoring, MGMP collaboration, and resource improvisation. Similar findings in South Africa (Sayed & Sing, 2020) and the Philippines (Monta & Perdio, 2025) show that teacher-led innovations often sustain reforms better than top-down policies. Studies in Latin America also highlight how teacher collectives compensate for weak institutional support, though sustainability remains fragile without systemic investment (Sevilla et al., 2023). In Indonesia, agency resulted in creative workarounds such as microscale kits and natural indicators, echoing reports from Nigeria and Vietnam, where resource substitution enabled participation but diminished depth (Aina, 2022; Tuong et al., 2023).

In this context, teachers' agency is not only apparent in their material creativity but also in the quality of their pedagogical mentoring. In line with these findings, Ghimire and Pant (2025) reported that student engagement in project-based learning increased significantly when the mentoring process was consistent and structured throughout the project stages, from planning to final reflection. This finding confirms that teachers' agency lies not only in their improvisational ability, but also in their professional capacity to provide continuous academic mentoring. In addition, Cross et al. (2026) added that in resource-limited regions, STEM education requires an adaptive conceptual framework that maintains pedagogical integrity, ensuring innovations do not lose disciplinary direction. Furthermore, McDaniel (2025) emphasizes that the integration of smart technology in STEM learning will only be effective if teachers have pedagogical autonomy as well as structural support to implement it meaningfully.

Overall, the findings suggest that teachers' active role is a major driver of learning innovation. Nonetheless, these comparisons reinforce that agency can offset scarcity but cannot permanently replace structural support. Without basic lab renewal, digital connectivity, and ongoing professional development, local innovations risk fragmentation. This aligns with Priestley et al. (2015), who argue that agency thrives only when minimal enabling conditions are present, and positions Indonesian teachers within a broader international narrative, innovators under constraint, but reliant on policy-level support to turn creativity into systemic change.

Positioning the Contribution: The R^3 Mechanism

While much of the STEAM literature highlights outcomes in resource-rich settings, this study broadens the discussion by introducing the R^3 (Representations, Resources, and Rubrics) mechanism as a model for constraint-optimized pedagogy. Previous research has shown that STEAM-PjBL enhances motivation, creativity, and problem-solving (Capraro, 2008; English, 2019; Herro & Quigley, 2017). However, these results are mainly reported from well-equipped schools with access to labs and strong professional development programs.

Our findings demonstrate that STEAM can "work" in resource-limited environments, but its success depends on representational rigor, fidelity-checked substitutions, and aligned assessments. This aligns with recent calls in the literature to adapt global frameworks to local contexts rather than adopting them wholesale (Carney, 2022; Chisom et al., 2024).

To make the R^3 mechanism operational:

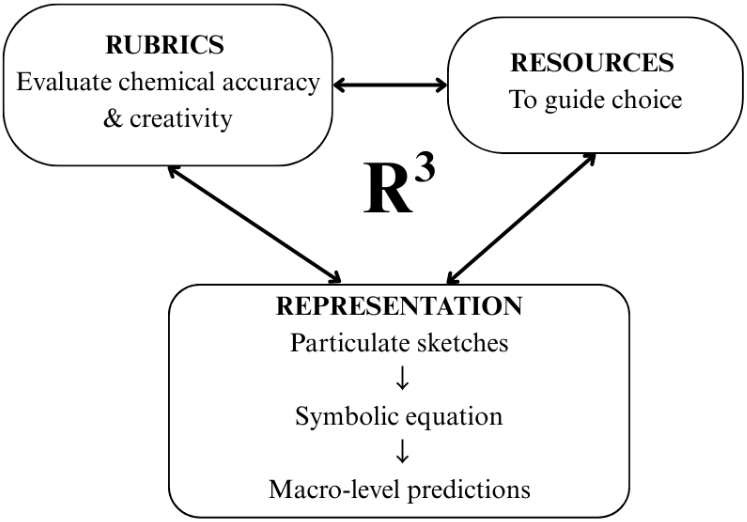
- *Representations*: Teachers and students need structured "translation cycles" (particulate sketches → symbolic equations → macro-level predictions). For instance, acid-base or redox projects should explicitly guide learners through this cycle, with rubrics evaluating how well each level is connected.
- *Resources*: Substitutions must balance affordability and validity. A resource matrix can guide choices (e.g., lab equipment → micro-scale or virtual alternatives; chemical reagents → calibrated natural indicators).

- *Rubrics*: Dual rubrics can evaluate both chemical accuracy and creativity. For example, in model-building tasks, one dimension can assess structural correctness, while another assesses originality of design.

We propose an illustrative model (Figure 2) to capture these interactions. Figure 2 depicts R³ as an interconnected system, representations at the center, resources and rubrics on either side, with bidirectional arrows showing their mutual reinforcement. This figure emphasizes that rigorous and inclusive chemistry education emerges when representational fluency, valid substitutions, and balanced assessments operate together.

Figure 2

R3 Mechanism to Implement Inclusive Chemistry Education



By demonstrating how Indonesian teachers reframe STEAM amid scarcity, this study contributes to international discussions and redefines Global South classrooms as sites of innovation rather than deficiency. The R³ mechanism shows how rigorous and inclusive chemistry education can thrive even under systemic constraints.

CONCLUSION

This study explored how chemistry teachers in Yogyakarta implemented STEAM-PjBL within systemic constraints. They adapted it to topics such as acid–base reactions, buffers, redox, and molecular modelling through comics, natural indicators, microscale experiments, and collaboration, which boosted engagement and creativity but also exposed ongoing challenges in mastering the macro–micro–symbolic triplet central to chemical literacy. The discussion identified five tensions, namely integration versus rigour, representation bottlenecks, substitution pedagogies, time–assessment misalignment, and agency versus structural support, that informed the R^3 mechanism. This framework demonstrates that successful STEAM-PjBL relies not on plentiful resources but on representational rigour, validated substitutions for resources, and rubric alignment with disciplinary standards. The study positions Indonesian teachers as innovators whose adaptive practices contribute to global efforts to decolonize and contextualize STEAM, while emphasizing that sustaining inclusive and effective implementation requires both structural support and recognition of teacher agency.

Implications

This study highlights four main implications. *First*, in classroom practice, teachers should implement STEAM-PjBL not only to boost engagement but also to enhance chemical literacy by guiding macro-, micro-, and symbolic-level representations, ensuring scientific accuracy in creative outputs, and promoting equitable collaboration. *Second*, at the institutional level, schools must support teacher agency through modest investments in laboratories, digital infrastructure, and literacy programs, alongside training focusing on representational pedagogy and fidelity-based micro-practices. *Third*, in policy, the *Merdeka Curriculum* should align with assessments that recognize accuracy and creativity, while strengthening professional learning communities such as MGMP. *Finally*, internationally, the study describes Global South classrooms as hubs of innovation through the R^3 mechanism (Representations, Resources, Rubrics), demonstrating that rigorous and inclusive STEAM-PjBL can succeed even with limited resources, challenging the notion that high-quality STEAM education requires abundance.

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