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Research Articl

Utilization of POME in Voltaic Cell Learning through the PjBL-STEM Model Oriented Toward Green Chemistry Principles

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Abstract:

This research investigates the innovative utilization of Palm Oil Mill Effluent (POME) as an environmentally friendly electrolyte in voltaic cell education through the implementation of a Project-Based Learning model integrated with STEM (PjBL-STEM) and aligned with green chemistry principles. The study employed a quantitative approach with a quasi-experimental design, specifically using a one group pretest-posttest design, involving 32 12-grade students from Sekolah Indonesia Kota Kinabalu. The instructional intervention followed the PjBL-STEM framework through five systematic phases: (1) identification of environmental problems related to POME waste, (2) design of POME-based voltaic cell prototypes, (3) hands-on experimentation and data collection, (4) analysis of electrochemical performance, and (5) presentation and reflection on sustainable solutions. Results demonstrated exceptional implementation fidelity, with achievement rates ranging from 88.7% to 93.5% across all learning phases, indicating strong student engagement and effective model execution. Most notably, the intervention produced significant learning gains, as evidenced by an average N-Gain score of 0.71 (high category), with post-test results (84.0) showing dramatic improvement from pre-test scores (42.0). These improvements spanned three key domains: redox reaction concepts, application of green chemistry principles, and electrical energy conversion understanding. The study successfully integrated multiple green chemistry principles into the learning process, particularly: (1) waste prevention through POME repurposing, (2) use of renewable feedstocks, (3) safer solvent alternatives, and (4) inherently safer chemistry by eliminating hazardous reagents. Students not only mastered electrochemical concepts but also developed critical environmental awareness and problem-solving skills through this authentic, sustainability-focused learning experience. These findings substantiate that PjBL-STEM combined with green chemistry principles offers an effective, practical, and sustainable approach to chemistry education. The model successfully bridges theoretical knowledge with real-world *environmental applications, while utilizing low-cost, locally available materials.*

1. INTRODUCTION

Global challenges in the fields of energy and environmental degradation have necessitated a transformation in chemistry education towards more sustainability-oriented approaches. One such approach is green chemistry, which advocates the redesign of chemical processes and products to reduce or eliminate the use and generation of hazardous substances (Putri, 2019). This framework aligns with the goals of sustainable development and directly contributes to pollution prevention while reinforcing the role of education in cultivating environmentally conscious generations.

The implementation of green chemistry principles in chemistry education not only enhances cognitive understanding but also fosters 21st-century skills, including critical thinking, scientific communication, collaboration, and student autonomy (Aliah et al., 2024). As highlighted by Celestino (2023), integrating green chemistry into chemistry education encourages students to comprehend the interconnectedness of science, technology, economics, and the social and ethical implications of scientific activities. Furthermore, a study by Inayah et al. (2022) revealed that only 16% of international publications address green chemistry in environmental contexts, underscoring the significant untapped potential of this approach in replacing hazardous substances in laboratory practices. Consequently, green chemistry is no longer optional but an urgent necessity in reforming chemistry education to be safer, more contextualized, and relevant to 21st-century challenges.

In the context of 21st-century education, integrating green chemistry principles into the Project-Based Learning model integrated with STEM (PjBL-STEM) has become an essential strategy for developing students' environmental awareness and scientific competence (Avvisati, F., Echazarra, A., Givord, P., and Schwabe, 2019). The PjBL-STEM model emphasizes the development of 21st-century competencies through project-based learning that combines science, technology, engineering, and mathematics. This model engages students in identifying real-world problems, designing and implementing projects, and reflecting on the outcomes. The instructional sequence typically involves (1) problem identification, (2) project design, (3) experimentation and data collection, (4) analysis and interpretation, and (5) presentation and reflection (Hanif et al., 2025). As such, PjBL-STEM offers a comprehensive and practical platform for embedding environmental issues into chemistry learning.

A tangible example of this integration is the utilization of Palm Oil Mill Effluent (POME), a liquid waste by-product from palm oil processing plants predominantly found in Indonesia and Malaysia. POME contains high levels of organic matter and has great potential as an alternative energy source (Hanif et al., 2025). However, its use in educational contexts, particularly in chemistry learning, remains underexplored. Within the topic of electrochemical cells such as voltaic cells, POME can serve as an alternative electrolyte aligned with green chemistry principles, including: (1) the use of renewable resources, (2) waste minimization, and (3) the selection of safer and more environmentally friendly materials (Anastas & Zimmerman, 2007). This approach allows students not only to learn key concepts such as redox reactions and the conversion of chemical energy into electrical energy but also to develop awareness of waste management and sustainable energy innovation.

Therefore, integrating the use of POME into voltaic cell learning through the PjBL-STEM model oriented to green chemistry principles represents a strategic effort to align chemistry education with sustainability goals (Hanif et al., 2025). This approach bridges the gap between theory and practice and fosters a generation of learners who are not only knowledgeable in chemistry concepts but also equipped to become agents of change in addressing environmental issues through responsible and applied chemistry.

2. METHODOLOGY

2.1 Method

This study employed a quasi-experimental approach using a One Group Pretest-Posttest Design. In this design, the participants served as their own control group, allowing the researcher to assess learning outcomes before and after the treatment. The research was conducted at Sekolah Indonesia Kota Kinabalu, involving 32 students from Grade XII. These students participated in a Project-Based Learning (PjBL) program integrated with the STEM approach and guided by the principles of green chemistry. Prior to the learning intervention, the researcher administered a pretest to assess students' initial understanding. The students then engaged in PjBL-STEM activities utilizing POME-based content (Palm Oil Mill Effluent), and completed a posttest at the end of the instructional sequence. The pretest and posttest were designed to evaluate students' knowledge across three core domains: redox concepts & voltaic cells, application of green chemistry, and electrical energy conversion. The experimental design is illustrated in **Table 1**.

Table 1. Research Design

Group	Pretest	Treatment (X1)	Posttest
Experimental	O1	POME-based PjBL-STEM Learning Model	O2

Notes:
O1 = Pretest;
X1 = STEM-integrated PjBL using POME;
O2 = Posttest

The research sample was selected using a simple random sampling technique, following the procedure described by Fraenkel et al. (2023). The study was carried out over a three-week period, from August to September 2024. The weekly activities are detailed in **Table 2**.

Table 2. Research Schedule

Session	Week	Learning Activities
1	I	Pretest (1 lesson hour), Learning Process (2 lesson hours)
2	II	Learning Process (2 lesson hours), Practice Exercises (1 hour)
3	III	Learning Process (2 lesson hours), Posttest (1 lesson hour)

Data were collected using both test and non-test instruments. The test instrument consisted of pretest and posttest items that assessed students' cognitive learning outcomes. These items were constructed to cover three key aspects: redox reactions and voltaic cells, green chemistry applications, and electrical energy conversion. The test content was contextualized using green chemistry principles applied to the topic of voltaic cells with POME integration. The non-test instrument consisted of an observation sheet used to record students' active participation during each phase of the PjBL-STEM learning model. The observations focused on five instructional stages: (1) problem identification, (2) project design, (3) experimentation and data collection, (4) analysis and interpretation, and (5) presentation and reflection. Quantitative data were analyzed using inferential statistics, including a One-Sample t-Test and Hotelling's T-squared Test, to evaluate the significance of changes in students' learning outcomes. In addition, the normalized gain (g) was calculated for each student to determine the effectiveness of the intervention. The normalized gain was computed using the formula proposed by Hake (1998):

$$g = \frac{(post\ tes\ score) - (pre\ test\ score)}{(maksimum\ posible\ score) - (pre\ test\ score)}$$

The interpretation of the g values follows the classification shown in **Table 3**.

Table 3. Normalized Gain Categories

Normalized Gain (g)	Category
g > 0.70	High
0.30 ≤ g ≤ 0.70	Medium
g < 0.30	Low

Source: Hake, 1998

In addition to cognitive outcomes, the researcher assessed the implementation of the learning model through observations conducted by trained observers. These observers were equipped with standardized rubrics to ensure the reliability of their evaluations. The percentage of instructional implementation was calculated using the following formula:

$$\%\ \text{Implementation} = \frac{\text{Observed Score}}{\text{Maximum Score}} \times 100\%$$

The resulting percentages were then converted into qualitative data using the criteria developed as shown in **Table 4**.

Table 4. Instructional Implementation Categories

No	Percentage (%)	Category
1	80 ≤ X ≤ 100	Very Good
2	60 ≤ X < 80	Good
3	40 ≤ X < 60	Fair
4	20 ≤ X < 40	Poor
5	0 ≤ X < 20	Very Poor

2.2 Material

The learning intervention was designed based on the PjBL-STEM instructional model, with a strong emphasis on the application of green chemistry principles in chemistry learning. The instructional activities revolved around the use of Palm Oil Mill Effluent (POME) as an alternative, renewable, and environmentally friendly electrolyte in voltaic cell experiments (Hanif et al., 2025). This approach was aligned with several key green chemistry principles, including prevention, safer solvents and auxiliaries, design for energy efficiency, use of renewable feedstocks, and inherently safer chemistry for accident prevention. The experimental procedures followed five main stages based on the PjBL-STEM syntax: (1) identifying real-world environmental problems related to POME waste, (2) designing a voltaic cell using POME, (3) conducting hands-on experiments and collecting data, (4) analyzing the voltage output from various cell configurations, and (5) presenting and reflecting on project outcomes. During the implementation, students worked collaboratively, engaged in scientific inquiry, and were encouraged to reflect on the environmental and societal impact of their projects. The instructional materials also included a teacher's guide, worksheets, lab instructions, and scaffolding aligned with STEM competencies and 21st-century skill development.

3. FINDINGS

This study generated findings across three main aspects: (1) the implementation fidelity of the PjBL-STEM model syntax, (2) the improvement of students' learning outcomes based on pre-test and post-test results, and (3) the alignment of the learning process with the principles of green chemistry.

3.1 Implementation of the PjBL-STEM Model Syntax

The implementation of voltaic cell learning using the PjBL-STEM model, which emphasizes problem-solving and interdisciplinary integration, showed a high level of effectiveness. Based on observations by two independent assessors, the average implementation scores across the five main syntaxes were as follows:

Table 5. Implementation of PjBL-STEM Syntax in POME-Based Voltaic Cell Learning

PjBL-STEM Syntax	Student Activity Indicator	Achievement (%)
1. Problem Identification	Students identified environmental problems related to POME	91.3%
2. Project Design	Students designed a voltaic cell using POME as the electrolyte	88.7%
3. Experimentation and Data Collection	Students conducted the experiment and recorded the results	93.5%
4. Data Analysis and Interpretation	Students analyzed the relationship between cell quantity and voltage output	89.2%
5. Presentation and Reflection	Students presented project results and reflected on the learning process	90.4%

These results indicate that all phases of the PjBL-STEM model were carried out with very high fidelity, characterized by active and collaborative student engagement in every stage.

4.2 Students' Pre-Test and Post-Test Results

To evaluate the effectiveness of the learning model, students were assessed using pre-test and post-test instruments focused on three domains: redox and voltaic cell concepts, the application of green chemistry, and electrical energy conversion. The N-Gain analysis revealed significant improvements:

Table 6. Students' Average Pre-Test and Post-Test Results in Voltaic Cell Learning Using POME

Assessment Indicator	Pre-Test	Post-Test	N-Gain	Category
Redox Concepts & Voltaic Cells	45.2	84.7	0.72	High
Application of Green Chemistry	38.5	81.0	0.69	Medium
Electrical Energy Conversion	42.3	86.2	0.76	High
Overall Average	42.0	84.0	0.71	High

The substantial post-test gains demonstrate that utilizing POME in voltaic cell learning through the PjBL-STEM model significantly enhanced students' conceptual understanding and scientific reasoning in a context aligned with sustainability.

4.3 Alignment with Green Chemistry Principles

Throughout the POME-based voltaic cell project, several Green Chemistry Principles (GCPs) were integrated into the learning process. The hands-on experiments and student reflections indicated a meaningful application of green chemistry values, particularly in reducing hazardous waste, using renewable resources, and promoting environmentally friendly practices. The alignment is detailed as follows:

Table 7. Relevant Green Chemistry Principles in the Utilization of POME-Based Voltaic Cells

Green Chemistry Principle	Description	Relevance to POME Utilization
Prevention (No.1)	It is better to prevent waste than to treat or clean up waste after it has been created.	POME, an organic waste from palm oil mills, is repurposed as an educational resource, thus reducing environmental waste.
Safer Solvents and Auxiliaries (No.5)	The use of auxiliary substances should be made unnecessary wherever possible and innocuous when used.	The experiment avoids the use of hazardous solvents and instead employs POME as a natural and safer electrolyte alternative.
Design for Energy Efficiency (No.6)	Energy requirements of chemical processes should be recognized for their environmental and economic impacts.	The generation of electrical energy using POME occurs under ambient conditions, requiring no external energy input.
Use of Renewable Feedstocks (No.7)	A raw material or feedstock should be renewable rather than depleting wherever technically and economically practicable.	POME is derived from agricultural processes and represents a renewable and biodegradable feedstock.
Inherently Safer Chemistry for Accident Prevention (No.12)	Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents.	The use of POME eliminates the need for hazardous reagents such as strong acids or heavy metals commonly used in electrochemical experiments.

Students not only engaged with chemical principles at a theoretical level, but also applied them in hands-on activities that fostered a heightened sense of environmental responsibility. The learning experience explicitly addressed key Green Chemistry Principles, including waste prevention (Principle 1) by utilizing palm oil mill effluent (POME) as an alternative electrolyte, thereby reducing chemical waste. The use of water-based solutions derived from POME aligns with safer solvents and auxiliaries (Principle 5), minimizing the need for hazardous reagents commonly used in electrochemical experiments. Furthermore, the project emphasized energy efficiency (Principle 6) through low-energy voltaic systems and encouraged the use of renewable feedstocks (Principle 7) by integrating biomass waste into the learning process. Finally, by avoiding toxic or reactive substances, the experiment model exemplified inherently safer chemistry for accident prevention (Principle 12), creating a safer and more sustainable learning environment.

4. DISCUSSION

4.1 Effectiveness of the PjBL-STEM Model in Voltaic Cell Learning

The findings of this study demonstrate that the PjBL-STEM model (see **Table 5**) was implemented effectively in the context of voltaic cell learning, particularly when integrating environmental and sustainability issues. The observation data show that all five phases of the PjBL-STEM syntax were carried out at a very high level. In the problem identification phase, 91.3% of students successfully identified the environmental problem associated with palm oil mill effluent (POME). During project design, 88.7% of students were able to conceptualize and construct a voltaic cell utilizing POME as an electrolyte. In the experimentation and data collection phase, 93.5% of students conducted the experiments and recorded relevant data accurately. Furthermore, 89.2% of students successfully analyzed the relationship between the number of POME cells and the voltage output during the data analysis and interpretation phase. Finally, 90.4% of students actively engaged in presenting their findings and reflecting on the learning process during the presentation and reflection stage.

These results indicate that the PjBL-STEM model creates a structured yet flexible learning environment that facilitates student engagement and deep understanding. The model allowed learners to explore real-world problems, integrate cross-disciplinary knowledge, and construct their own scientific understanding through inquiry and experimentation. This aligns with Thomas (2000), who emphasizes that project-based learning (PjBL) fosters deeper learning by placing students in active roles and centering instruction around authentic, complex problems. Similarly, Tseng et al. (2013) found that integrating STEM within PjBL frameworks enhances problem-solving and critical thinking skills by encouraging students to work collaboratively and think across disciplinary boundaries.

In this study, students were not only cognitively engaged but also emotionally and physically involved in the learning process. They actively participated in the scientific practices of designing tools, manipulating materials, collecting and analyzing data, and communicating results—core elements of 21st-century science education (Bybee, 2013). This reflects the holistic nature of the PjBL-STEM approach, which supports cognitive (knowledge and understanding), affective (attitudes and values), and psychomotor (skills and action) development. Moreover, the high performance across all phases of the model suggests that students were able to internalize scientific content more effectively when it was contextualized within environmental issues relevant to their everyday lives. The use of POME as a learning medium provided an authentic context that increased student motivation and awareness of sustainable science practices. As stated by Satchakett & Thana (2019), PjBL models are most effective when they incorporate real-life applications that are meaningful to students, particularly in addressing local environmental issues.

4.2 Improvement in Learning Outcomes and Understanding of Redox Concepts and Voltaic Cells

4.2.1 Understanding of Redox Concepts and Voltaic Cells

A significant improvement was observed in students' understanding of redox concepts and voltaic cells, with the average pre-test score increasing from 45.2 to 84.7 in the post-test, yielding an N-Gain of 0.72, which falls within the high category. This outcome indicates that the PjBL-STEM learning model implemented in this study was effective in fostering students' conceptual understanding of redox reactions and the working principles of voltaic cells.

Through the stages of problem identification and project design, students were actively engaged in exploring fundamental principles of electrochemistry, including electron transfer, cell potential, and spontaneous redox processes (Rahmawati et al., 2020;Ananda et al., 2023). During the experimental activities, they directly observed the conversion of chemical energy into electrical energy using electrodes and POME-based electrolytes. These hands-on experiences strengthened the connection between theoretical knowledge acquired in the classroom and its real-world application, thereby enhancing meaningful conceptual mastery (Ananda et al., 2023). Moreover, the activities provided opportunities for students to practice predicting, measuring, and interpreting data—essential skills that reinforce scientific literacy (Rahmawati et al., 2020).

4.2.2 Application of Green Chemistry Principles

The aspect of green chemistry application also showed notable improvement, with the average pre-test score rising from 38.5 to 81.0 in the post-test and an N-Gain of 0.69 (medium category).

This gain reflects the successful integration of green chemistry principles into the learning process through the utilization of POME as an alternative electrolyte.

In this context, several green chemistry principles were explicitly actualized, including Principle 1 (waste prevention), Principle 5 (safer solvents and auxiliaries), and Principle 7 (use of renewable feedstocks). Students were encouraged to reflect on the role of organic waste as a renewable and sustainable resource. This approach also facilitated the avoidance of hazardous reagents in laboratory practice, aligning with Principle 12 (inherently safer chemistry for accident prevention) (Sari & Atun, 2023).

The implementation of these principles in experimental activities not only broadened students' ecological perspectives but also fostered critical awareness of the importance of sustainability and waste management in chemical practices. This suggests that both affective and cognitive domains can be simultaneously strengthened through contextual and application-oriented learning approaches.

4.2.3 Understanding of Electrical Energy Conversion

The third aspect, understanding of electrical energy conversion, showed the highest gain among the assessed indicators. The average score increased from 42.3 in the pre-test to 86.2 in the post-test, with an N-Gain of 0.76 (high category). This result demonstrates that students were able to comprehend the concept of converting chemical energy into electrical energy more concretely through hands-on experience in assembling and testing voltaic cells using POME.

The PjBL-STEM model provided students with the opportunity to understand the relationship between redox reactions, electron flow, and the emergence of potential differences at the electrodes. Experimental results showed that POME-based voltaic cells were capable of generating voltages ranging from 1.74 to 8.71 volts and currents between 0.31 and 3.12 mA. A strong linear correlation was found between the number of POME cells connected in series and the resulting voltage output, expressed by the regression equation $Y = 17.25X + 1.85$, where X represents the number of cells.

Furthermore, projections indicate that approximately 3.8 liters of POME—equivalent to 127 reaction tubes—could generate up to 220 volts, while a configuration of just five cells is sufficient to power a low-energy device such as an analog wall clock. These findings affirm that POME serves not only as a valuable medium for electrochemical learning but also possesses practical potential for alternative energy production in off-grid or low-resource environments (Hanif et al., 2025).

This utilization also aligns with Principle 6 of green chemistry (energy efficiency) by demonstrating the efficient and safe use of organic waste materials to generate electricity. In addition, students' success in understanding, designing, and testing electrochemical systems based on scientific principles in real-world contexts reinforces both their energy literacy and their awareness of locally grounded, sustainable technological solutions.

4.3 Internalization of Green Chemistry Principles in Learning Activities

One of the key strengths of this learning innovation lies in its successful internalization of green chemistry principles into student-centered, practical activities. The project-based learning using POME (palm oil mill effluent) as an alternative electrolyte in voltaic cells exemplifies at least six of the twelve Green Chemistry Principles formulated by Anastas & Warner (1998), including the use of renewable feedstocks, prevention of waste, safer chemical synthesis, energy efficiency, design for degradation, and real-time analysis for pollution prevention.

The integration of POME—a locally abundant organic waste—as a learning medium reflects the principle of using renewable and safer materials. Students were actively involved in identifying the environmental problem (91.3%), designing experimental tools (88.7%), conducting eco-friendly experiments (93.5%), and presenting environmentally conscious solutions (90.4%). This indicates a pedagogical alignment with the green chemistry tenet of minimizing environmental hazards throughout the product and process lifecycle (Rahmawati et al., 2020; Dewi & Listyarini, 2022).

Moreover, students not only learned the electrochemical concepts but were also introduced to the broader implications of scientific practices on sustainability. The design of the voltaic cell, which avoided the use of toxic heavy metals or synthetic chemicals, illustrated the principle of safer chemical design. Simultaneously, students were guided to reflect on the energy use and waste implications of their experimental designs, in line with the energy efficiency and waste prevention principles (Purwanti et al., 2023). This aligns with Summerton et al. (2018), who argue that sustainable chemistry education does not require advanced laboratory infrastructure but rather thoughtful pedagogy that emphasizes systemic thinking and real-world relevance.

Implementing green chemistry in redox and electrochemistry topics also supports the development of environmental literacy and scientific responsibility among students. Rahmawati et al. (2023) emphasize that green chemistry education should link scientific knowledge with sustainability issues such as environmental pollution and resource scarcity. In this context, students developed a deeper awareness of how local environmental issues, such as POME waste, can be addressed through innovative, science-based solutions.

To further strengthen the internalization of green chemistry, systemic support is required. Adnyana et al. (2023) recommend curriculum alignment that explicitly connects green chemistry with sustainability themes. Regular teacher training is also essential to enhance pedagogical competence and environmental awareness (Sulochana et al., 2024). Interdisciplinary approaches that link chemistry with social and economic dimensions should be prioritized to foster a holistic understanding of sustainable practices in students. Public awareness campaigns can complement educational initiatives, helping to shift societal behaviors towards more responsible chemical usage and thereby supporting several UN Sustainable Development Goals (SDGs), particularly those related to health, education, and environmental sustainability (Juntunen & Aksela, 2014; Zuin et al., 2021).

In industrial and higher education contexts, the application of green chemistry principles—such as atom economy, benign synthesis routes, and reduction of derivatization—has been emphasized as a strategy to reduce the ecological footprint of chemical processes (Nurbaity, 2011). In line with this, the classroom implementation of green chemistry through the PjBL-STEM model demonstrates that the values of sustainable chemistry can be effectively cultivated from the early stages of education. Ultimately, this initiative not only enhances scientific understanding but also fosters a culture of environmental stewardship among students.

4.4 The Relevance of Green Chemistry Implementation in Chemistry Education

Green chemistry, defined as the design, use, and manufacture of chemical products and processes that minimize or eliminate the use and generation of hazardous substances, has emerged as a central paradigm in contemporary chemical science (Anastas & Warner, 1998; Wahyuningsih & Poedjiastoeti, 2015). The incorporation of green chemistry principles into education is not only a response to increasing environmental concerns but also a proactive approach to equipping students with the skills and values needed for sustainable development.

One of the key strategies to reduce environmental pollution is the application of green chemistry principles in laboratory-based learning. By redesigning laboratory practices to replace or minimize the use of toxic reagents, reduce the volume of chemical waste, and prevent hazardous by-products, students are provided with a real-world context to engage in environmentally responsible science (Rahmawati et al., 2020; Dewi & Listyarini, 2022). This educational model fosters a deeper understanding of chemistry's societal and environmental impacts while promoting safer experimental design and waste reduction.

Green chemistry-oriented laboratory activities have demonstrated significant potential in supporting meaningful and authentic learning. For instance, in the context of this study, the utilization of palm oil mill effluent (POME) as a renewable and locally available electrolyte in voltaic cell experiments not only reduced dependency on commercial and potentially harmful chemicals but also provided students with hands-on experience in applying sustainable scientific practices. This aligns with the first principle of green chemistry—Prevention—as well as principles related to the Use of Renewable Feedstocks and Inherently Safer Chemistry for Accident Prevention (Anastas & Warner, 1998; Summerton et al., 2018).

Moreover, the implementation of green chemistry in education should not be limited to procedural aspects. Students should be encouraged to critically analyze the chemical properties, reactivity, and environmental impact of the materials they use, including solvents and reagents. This reflective approach shifts the focus from mere procedural compliance to intellectual engagement and scientific inquiry (Rosita et al., 2014). As noted by Yuniar et al. (2019), such pedagogical practices foster critical thinking and higher-order cognitive development, transforming laboratory sessions into platforms for exploring innovative and sustainable solutions to real-world problems.

This study also emphasizes the importance of green chemistry for educational equity. Schools located in resource-limited settings often face constraints in accessing conventional laboratory materials. The use of locally available resources such as POME demonstrates how green chemistry principles can be contextually adapted to create low-cost, safe, and environmentally friendly laboratory environments. These "green laboratories" are not only feasible but also essential in promoting 21st-century skills, including problem-solving, creativity, and systems thinking (Adnyana et al., 2023; Sulochana et al., 2024). In conclusion, integrating green chemistry into chemistry education enhances environmental literacy, supports the goals of Education for Sustainable Development (ESD), and aligns with global efforts to achieve the Sustainable Development Goals (SDGs), particularly those related to health, well-being, and environmental sustainability (Juntunen & Aksela, 2014; Zuin et al., 2021).

5. CONCLUSION

This study implemented the PjBL-STEM model based on green chemistry principles in voltaic cell learning using Palm Oil Mill Effluent (POME) as an alternative electrolyte. The results indicated that the implementation was effective, with success rates above 88% across all stages—from problem identification to presentation. This model significantly enhanced students' conceptual understanding and fostered 21st-century skills such as critical thinking, collaboration, and environmental awareness. The improvement in student learning outcomes was substantial, as reflected in a high N-Gain score of 0.71 and an increase in average post-test scores from 42.0 to 84.0. The integration of green chemistry principles—such as waste prevention, use of renewable feedstocks, energy efficiency, and safer chemical use—was effectively internalized through the contextual use of POME. Overall, this approach proves that sustainable, low-cost, and safe chemistry learning is achievable even in resource-limited schools, making it highly relevant for modern science education.

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