Research Article

Micro-Scale Voltaic Cell Experiment Based on PjBL-STEM Using POME Waste for Sustainable Energy Education

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Abstract: *This study explores the utilization of Palm Oil Mill Effluent (POME) as an electrolyte in a micro-scale voltaic cell experiment integrated into a Project-Based Learning–Science, Technology, Engineering, and Mathematics (PjBL-STEM) framework. The primary aim is to develop an applicable green chemistry learning model that contributes to sustainable energy solutions. A quasi-experimental method was implemented with Grade XI science students at Sekolah Indonesia Kota Kinabalu, involving the stages of problem identification, experimental design, implementation, data analysis, and reflection. Results demonstrate that POME effectively functions as an alternative electrolyte, producing up to 8.71 Volts and 3.12 mA of current in a five-cell series configuration. The linear relationship between the number of POME cells and the generated voltage (Y = 17.25X + 1.85) indicates its potential as a micro-energy source for low-power electronic devices. The integration of local waste into science education not only supports the achievement of Sustainable Development Goals (SDGs) No. 7 (Affordable and Clean Energy) and No. 12 (Responsible Consumption and Production), but also fosters opportunities for renewable energy innovation grounded in local contexts. This model can be adapted in resource-limited schools to promote learning that is relevant, contextual, and environmentally conscious.*

Keywords: green chemistry, voltaic cell, POME, STEM, project-based learning, sustainability

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1. INTRODUCTION

As global demands for clean and renewable energy continue to rise (IEA, 2025), chemistry education is increasingly expected to equip students with contextual knowledge and skills that are relevant to sustainability challenges. One promising approach in this regard is green chemistry, defined as the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances (Anastas & Warner, 1998). In the context of 21st-century education, implementing green chemistry through project-based and locally contextualized learning has become a key strategy to enhance scientific literacy and environmental awareness (Avvisati, F., Echazarra, A., Givord, P., dan Schwabe, 2019).

On the other hand, the discharge of Palm Oil Mill Effluent (POME) remains a persistent environmental issue in Indonesia and Malaysia. Palm oil mill effluent (POME) is the wastewater produced during the extraction of oil from fresh fruit bunches (FFB) in palm oil mills. It is rich in organic substances, including carbohydrates, proteins, fatty acids, lipids, nitrogen-based compounds, and various minerals (Rajani et al., 2019), as shown in **Table 1**. This effluent appears as a thick, brownish liquid with elevated levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD)(Rajani et al., 2019). Ironically, despite its high energy potential, POME remains largely underutilized, particularly in marginal communities with limited infrastructure and energy access (Ng et al., 2012). This waste stream presents a valuable opportunity to serve as an alternative energy source within educational contexts.

Table 1. General characteristics of POME.

Parameter	Concentration Range
Temperature (°C)	80 to 90
pH	3.4 to 5.2
Oil and grease (mg/L)	130 to 180,000
Biochemical Oxygen Demand (BOD_3, 3 days at 30°C) (mg/L)	10,250 to 43,750
Chemical Oxygen Demand (COD) (mg/L)	15,000 to 100,000
Total Solids (SS) (mg/L)	11,500 to 79,000
Total Suspended Solids (TSS) (mg/L)	5,000 to 54,000
Total Volatile Solids (TVS) (mg/L)	9,000 to 72,000
Total Nitrogen (TN) (mg/L)	180 to 1,400
Ammoniacal Nitrogen (mg/L)	4 to 80
Colour (ADMI)	> 500
Potassium (mg/L)	1,281 to 1,928
Calcium (mg/L)	276 to 405
Magnesium (mg/L)	254 to 344
Phosphorus (mg/L)	94 to 131
Manganese (mg/L)	2.1 to 4.4
Iron (mg/L)	75 to 164
Zinc (mg/L)	1.2 to 1.8
Copper (mg/L)	0.8 to 1.6
Chromium (mg/L)	0.05 to 0.43
Cobalt (mg/L)	0.04 to 0.06
Cadmium (mg/L)	0.01 to 0.02

While various industrial-scale initiatives—such as anaerobic digestion for biogas production—have been developed to harness energy from POME (Chin et al., 2013), these methods typically require significant investment and technical expertise, posing challenges for implementation in school settings. This gap between technological innovation and accessible educational practice calls for the development of instructional models that integrate green chemistry principles, local waste utilization, and project-based learning approaches (UNESCO, 2024).

The PjBL-STEM model (Project-Based Learning – Science, Technology, Engineering, and Mathematics) has proven effective in enhancing students' scientific competencies, collaboration skills, and positive attitudes toward science (Tseng et al., 2013; Satchakett & Thana, 2019). However, most applications of PjBL-STEM have focused on general topics (Parno et al., 2020), with limited integration of real-world environmental issues such as POME utilization. This study aims to bridge chemistry education and tangible local environmental problems by providing a sustainable solution grounded in green chemistry within a STEM-integrated Project-Based Learning framework.

This research offers innovation in two key areas. First, it utilizes POME as an electrolyte in a simple voltaic cell experiment, transforming hazardous waste into a meaningful and sustainable learning medium (MacArthur, 2015). Second, it embeds the PjBL-STEM approach in a local context to holistically foster scientific literacy, environmental consciousness, and 21st-century competencies. The project aligns with the Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy) (Martínez-Borreguero et al., 2024) and Goal 12 (Responsible Consumption and Production) (Mitarlis et al., 2023).

2. METHOD & MATERIAL

This study employed a quasi-experimental approach utilizing a project-based learning-integrated STEM (PjBL-STEM) model, framed through a chemistry practicum titled "*Micro-Scale Voltaic Cell Experiment Based on PjBL-STEM Using POME Waste for Sustainable Energy Education*" The intervention was conducted from August to October 2024 at Sekolah Indonesia Kota Kinabalu, involving participants from various Community Learning Centers (CLCs) across Sabah. The project was designed as a contextual solution to environmental issues and energy limitations in marginal areas while also aiming to strengthen students' scientific literacy through the application of green chemistry principles (Anastas & Warner, 1998; Avvisati, et al., 2019).

The research subjects consisted of 11th-grade science stream students (Class XI) purposively selected based on their involvement in the chemistry learning activities. The instructional process followed five phases of the PjBL-STEM model: (1) problem identification, (2) project design, (3) experimental implementation, (4) data analysis, and (5) presentation and reflection (Satchakett & Thana, 2019; Parno et al., 2020). In the initial phase, students were introduced to the issue of environmental pollution caused by POME and the concept of green chemistry as a sustainable waste management strategy. Subsequently, students designed a voltaic cell experiment using POME as an alternative electrolyte to demonstrate the conversion of chemical energy into electrical energy in a simple and eco-friendly manner.

The experiment utilized simple and safe tools and materials suitable for a school setting. The tools included an analog wall clock, test tube racks, test tubes, crocodile clips and wires, measuring pipettes, scissors, rulers, markers, and a multimeter. The materials used were copper wire (as the cathode), magnesium ribbon (as the anode), and wet tissue (as both a salt bridge and anode covering), see **Figure 1**. The assembly procedure began by measuring and cutting one meter of copper wire, which was then coiled into a spiral using a marker as a mold. A 17 cm magnesium strip was cut, wrapped in a wet tissue, and inserted into the copper spiral. This assembly was then immersed into a test tube containing 30 mL of POME solution. The electrodes were connected using wires and crocodile clips, and a multimeter was used to measure the resulting voltage. Students recorded the data, constructed graphs, and developed a simple regression model to analyze the relationship between the number of voltaic cells and the voltage generated.

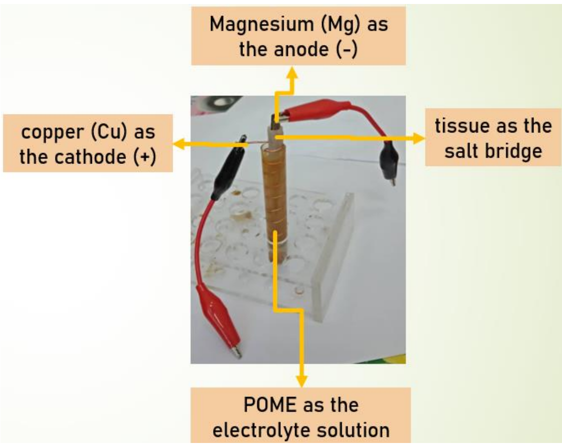

Figure 1. Modification of the voltaic cell using POME as the electrolyte solution with Cu and Mg electrodes

Data collection involved observations during the experimental process, measurements of voltage and current, and student reflections. Observation sheets were also used to assess student engagement and the implementation of each stage of the learning model. The instruments used in this study were based on previously validated rubrics and rating scales. Data analysis was carried out using descriptive techniques. Qualitative data from reflections and observations were thematically analyzed to evaluate the implementation of the learning model throughout the instructional process.

3. FINDINGS

The experimental results demonstrated that Palm Oil Mill Effluent (POME) can be effectively utilized as an alternative electrolyte in a simple voltaic cell. The student-designed voltaic cells successfully generated measurable electrical voltage, which increased proportionally with the number of series-connected cells. The relationship between the number of POME-filled test tubes and the voltage output was linear, as represented by the regression model Y = 17.25X + 1.85, where Y denotes voltage in volts and X refers to the number of POME-containing cells.

To test the circuit's effectiveness, students added 30 mL of POME solution to each test tube containing the electrode setup. The initial test using a single tube produced a voltage of 1.74 V and a current of 0.31 mA. Subsequently, two tubes produced 3.25 V and 0.88 mA, three tubes produced 5.20 V and 1.80 mA, four tubes produced 6.65 V and 2.40 mA, and five tubes produced 8.71 V and 3.12 mA. When connected to an analog wall clock, the five-cell configuration successfully powered the device, confirming the potential of this system for low-power electronic applications. The complete experimental data are presented as follows **Table 2**.

Table 2. Electrical Output of POME-Based Voltaic Cells with Varying Volume and Series Configuration

Trial	POME	Current (I)	Voltage (V)
1	30 mL	0.31 mA	1.74 V
2	60 mL	0.88 mA	3.25 V
3	90 mL	1.80 mA	5.20 V
4	120 mL	2.40 mA	6.65 V
5	150 mL	3.12 mA	8.71 V

The results of all trials were subsequently visualized using Microsoft Excel to generate a linear graph and derive the corresponding regression equation, see **Figure 2**. This helped validate the consistency and predictability of voltage output relative to the number of POME cells used in series.

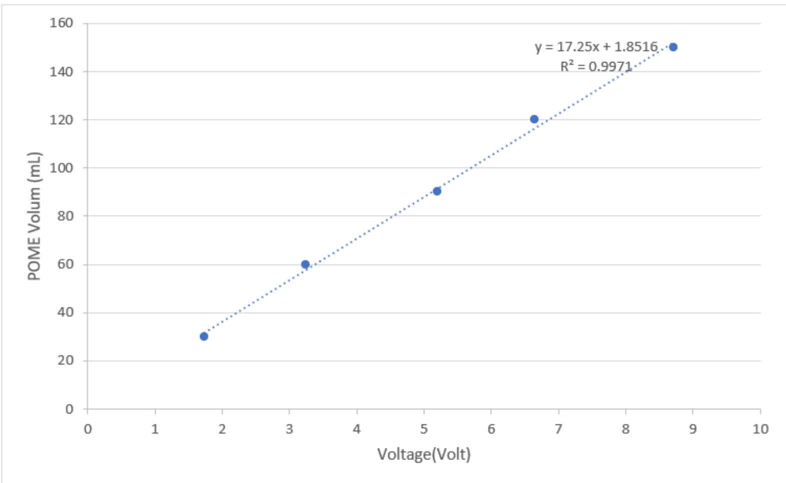

Figure 2. Linear Relationship Between the Number of POME-Based Voltaic Cells and Voltage Output

Based on the derived linear equation model, it is projected that generating 220 volts would require approximately 127 test tubes, corresponding to a total volume of 3.8 liters of POME. Although this output remains insufficient to power high-energy devices, the result underscores the potential of POME-based voltaic cells as viable micro-energy sources, especially in off-grid or energy-deprived settings.

4. DISCUSSION

The application of the PjBL-STEM (Science, Technology, Engineering, and Mathematics – Project-Based Learning) model in this chemistry learning project was designed to foster 21st-century skills such as critical thinking, collaboration, creativity, and environmental literacy (Partnership for 21st Century Learning, 2019). This model transcends cognitive learning, engaging students affectively and psychomotorically through active participation in real-world, contextually relevant projects. These findings align with previous studies, which suggest that PjBL-STEM enhances student engagement and conceptual understanding, particularly when lessons are grounded in local contexts and environmental challenges (Tseng et al., 2013; Hall & Miro, 2016).

This project successfully integrated palm oil mill effluent (POME) into a simple voltaic cell experiment as a contextual learning medium. Through the five stages of the PjBL learning process—problem identification, project design, experimental execution, data analysis, and presentation/reflection—students developed a practical understanding of redox reactions and energy conversion, while also learning about waste management and renewable energy solutions, see result **Figure 3**. The process mirrors a complete scientific inquiry cycle in which students actively participate in problem-solving, solution design, empirical testing, and evidence-based evaluation. These stages further foster environmental awareness and social responsibility, consistent with findings by Parno et al., (2020) and Satchakett & Thana, (2019).

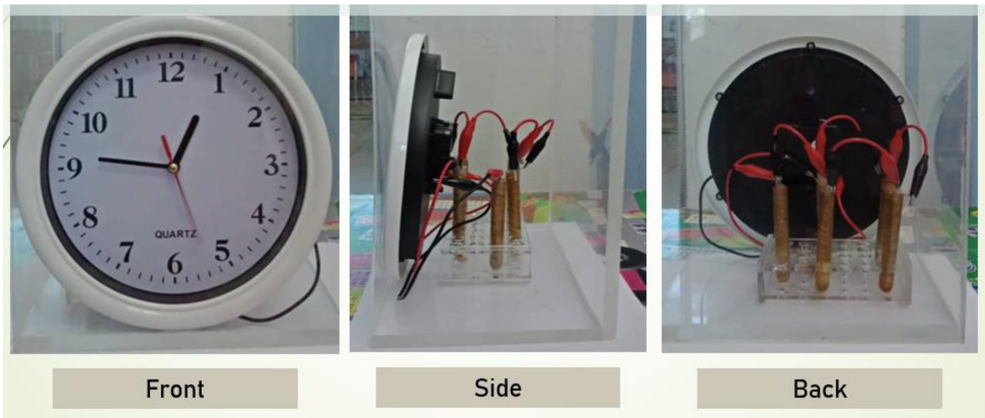

Figure 3. Trial of a voltaic cell using a wall clock

The selection of POME as an electrolyte aligns with key green chemistry principles, particularly waste minimization and the utilization of renewable resources (Anastas & Zimmerman, 2007). Moreover, involving students in projects that address local environmental problems empowers them to apply scientific principles to real-life challenges. This reinforces science education as not only a means of knowledge transfer but also a tool for empowerment and sustainable development (UNESCO, 2024).

The experimental results—demonstrating that POME-based voltaic cells could power analog clocks and low-energy devices—constitute a significant educational achievement. Students validated the transformation of waste into applicable micro-energy, while simultaneously gaining firsthand experience with electrical principles, redox reactions, and electrochemical processes. These outcomes echo the findings of Fantucci et al. (2019) and Ng et al. (2012), who assert that student involvement in sustainable chemical engineering experiments enhances scientific comprehension and global sustainability awareness.

Furthermore, this instructional model exemplifies how PjBL-STEM can be effectively implemented in resource-limited schools using inexpensive, locally sourced materials. Embedding sustainability themes in core science curricula not only improves academic outcomes but also cultivates socially and ecologically responsible citizens. This supports the conclusions of Belland et al. (2013), who found that project-based learning significantly improves chemistry concept retention and encourages the development of green laboratories in educational environments (Summerton et al., 2018).

Throughout the experimental process, students independently conducted measurements, recorded data, generated voltage–tube number graphs, and analyzed the effectiveness of POME as an alternative electrolyte. These activities facilitated contextual understanding of energy conversion principles, redox reactions, and dynamic electricity—core competencies in both chemistry and physics curricula.

Through this hands-on experiment, students directly engaged in transforming waste into energy while applying green chemistry and circular economy principles. Project-based learning (PBL) has been proven to be more effective in enhancing students' conceptual understanding of chemistry compared to conventional methods, with consistently superior learning outcomes observed in groups utilizing this approach (Delostrico, 2019), and supports the implementation of eco-friendly laboratories that are feasible for resource-constrained schools (Summerton et al., 2018).

In conclusion, this project illustrates that POME can serve as an alternative electricity source within STEM-based science education. This approach not only builds scientific competencies but also enables students to co-create solutions rooted in local problems, bridging science with societal needs and cultivating early innovation and sustainability mindsets.

5. CONCLUSION

This study demonstrates the potential of Palm Oil Mill Effluent (POME) as an alternative electrolyte in micro-scale voltaic cells, capable of generating voltages ranging from 1.74 to 8.71 volts and currents between 0.31 and 3.12 mA, with a strong linear correlation between the number of POME cells and voltage output ($Y = 17.25X + 1.85$). Projections suggest that approximately 3.8 liters of POME (127 reaction tubes) could yield up to 220 volts, while a five-cell configuration is sufficient to power a low-energy device such as an analog wall clock, highlighting its practical potential in off-grid or low-resource settings. Despite these promising outcomes, the study is limited by its small experimental scale, the use of simple apparatus, and regional variability in POME availability. Moreover, the findings are context-specific, involving only Grade XI students from a single school, thus limiting generalizability. Future research should focus on enhancing voltaic cell efficiency through electrode modification or catalyst integration, exploring other organic waste streams as electrolytes, and scaling up the application for broader use, particularly in sustainable energy solutions for remote areas.

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