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Development of a Chemistry Learning Model through Integrated STEM Project-Based Learning Using Palm Oil Waste as a Renewable Energy Source

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Abstract: This study aimed to develop a chemistry learning model based on Project-Based Learning (PjBL) integrated with STEM, utilizing palm oil waste as a renewable energy context to enhance students' scientific literacy. The research adopted a research and development approach using the Plomp model. The developed PjBL–STEM model was implemented in senior high school chemistry classes through contextual, project-oriented activities related to palm oil waste utilization. Data were collected using tests, observations, questionnaires, and performance rubrics to examine the quality and impact of the model. The findings indicate that the developed learning model is valid and practical for classroom implementation. Its application resulted in a significant improvement in students' scientific literacy, particularly in understanding scientific concepts and applying them to real-world sustainability issues. In addition, the learning process supported the development of essential 21st-century skills, including critical thinking, collaboration, creativity, and environmental awareness. Overall, the results demonstrate that the PjBL–STEM learning model based on local renewable energy contexts is effective and feasible for chemistry instruction. The model contributes not only to improving scientific literacy but also to promoting sustainable education aligned with the Sustainable Development Goals (SDGs).

Keywords: Green chemistry; Palm oil waste; Project Based Learning; Scientific literacy; STEM.

Introduction

Chemistry education plays a fundamental role in helping students understand the structure of matter, chemical reactions, and energy transformations that underlie natural and technological phenomena (Bybee, 2014; Norris & Phillips, 2003; Toharudin et al., 2011). However, chemistry is widely perceived by students as difficult due to its abstract nature and the need to simultaneously connect macroscopic, microscopic, and symbolic representations (Fauzi & Hashim, 2020; Widodo & Riandi, 2013). As a result, students often demonstrate low motivation, weak conceptual understanding, and limited scientific literacy, particularly in applying chemistry concepts to real-life contexts (Astuti & Sudarisman, 2019; Fitriani et al., 2020).

Scientific literacy is a key goal of contemporary science education and refers to students' ability to understand scientific concepts, use scientific processes, interpret data, and make informed decisions related to socio-scientific issues (Bybee, 2014; Norris & Phillips, 2003; OECD, 2019). International assessments such as PISA indicate that many students struggle to demonstrate adequate levels of scientific literacy, especially in contextual and problem-based tasks (OECD, 2019). Research in Indonesia also shows that students' scientific literacy remains relatively low, particularly in chemistry learning that relies heavily on memorization and teacher-centered instruction (Astuti & Sudarisman, 2019; Zubaidah et al., 2018).

Traditional chemistry instruction is still dominated by lectures and algorithmic problem solving, which

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limits opportunities for students to actively construct knowledge and engage in higher-order thinking (Fauzi & Hashim, 2020; Mayer, 2004). Such approaches are inconsistent with constructivist learning theories, which emphasize that knowledge is actively constructed through meaningful learning experiences (Piaget, 1977; (Vygotsky, 1978). To address this challenge, innovative instructional models that emphasize inquiry, collaboration, and real-world problem solving are strongly recommended (Prince & Felder, 2006; Savery, 2015).

Project-Based Learning (PjBL) has been widely recognized as an effective learner-centered approach that engages students in authentic, meaningful projects connected to real-life problems (Bell, 2010; Thomas, 2000). PjBL encourages students to plan, investigate, collaborate, and reflect, thereby fostering deeper conceptual understanding and motivation (Blumenfeld et al., 1991; Krajcik & Blumenfeld, 2006). Empirical studies have shown that PjBL can improve students' scientific literacy, creativity, independence, and problem-solving skills in science learning (Afriana et al., 2016; Anazifa & Djukri, 2017).

Nevertheless, several studies report that PjBL implementation often focuses primarily on product completion and lacks systematic integration with interdisciplinary skills, particularly in science and engineering contexts (Capraro et al., 2013; Han et al., 2014). To overcome this limitation, integrating Science, Technology, Engineering, and Mathematics (STEM) into PjBL is considered a promising approach (Alam & Mohamad, 2022; Ejiwale & Lin, 2021). STEM education emphasizes the integration of scientific knowledge with technological applications, engineering design, and mathematical reasoning to solve complex real-world problems.

STEM-integrated Project-Based Learning (PjBL-STEM) has been shown to significantly enhance students' scientific literacy, critical thinking, collaboration, and learning motivation (Han et al., 2014; Huang et al., 2022). Studies conducted in Indonesia also confirm that STEM-based PjBL improves students' higher-order thinking skills and scientific literacy in science classrooms (Ardiansyah et al., 2021; Gunawan et al., 2019; Nugraha et al., 2020; Ramdani et al., 2021). These findings suggest that PjBL-STEM provides a comprehensive pedagogical framework aligned with 21st-century learning demands (Dede, 2014; Prince & Felder, 2006).

One important real-world issue that can be meaningfully integrated into PjBL-STEM is renewable energy. The global dependence on fossil fuels has resulted in environmental degradation and energy insecurity, necessitating the transition toward sustainable and renewable energy sources (Hansen et al., 2015; Lim et al., 2012). Incorporating renewable energy topics into chemistry education not only enhances conceptual understanding but also raises students' awareness of sustainability and environmental responsibility (Rahman et al., 2023).

Indonesia has enormous potential for renewable energy derived from biomass, particularly from the palm oil industry (Lim et al., 2012; Yusoff, 2006). Palm oil processing generates large quantities of biomass waste, such as empty fruit bunches, shells, and fibers, which are often underutilized despite their high energy potential (Hansen et al., 2015; Lam, 2019) Lam et al., 2019). Research shows that palm oil biomass can be effectively converted into renewable energy through processes such as combustion and pyrolysis (Lam, 2019; Rahman et al., 2023).

From an educational perspective, palm oil waste provides a highly relevant local context for chemistry learning, particularly in topics related to energy, chemical reactions, and sustainability (Hapsari et al., 2024; Sulastri & Rohman, 2021). Integrating palm oil biomass into PjBL-STEM enables students to connect chemistry concepts with technology and engineering practices, such as designing simple biomass energy prototypes (Capraro et al., 2013; Erdogan & Ciftci, 2017). This contextual approach strengthens students' understanding of chemistry as a meaningful and applicable discipline.

Several studies indicate that learning environments grounded in real-world and socio-scientific contexts contribute significantly to the development of scientific literacy and positive attitudes toward science (Fitriani et al., 2020; Zubaidah et al., 2018). Furthermore, collaborative project work aligns with social constructivist theory, which emphasizes the role of interaction and shared meaning-making in learning (Lou et al., 2011; Vygotsky, 1978).

Despite the growing body of research on PjBL and STEM, studies that explicitly integrate PjBL-STEM with renewable energy contexts—particularly palm oil waste—in chemistry learning remain limited (Alam & Mohamad, 2022; Han et al., 2014). Most existing studies focus either on PjBL or STEM separately, without emphasizing local sustainability issues as the central learning context (Anazifa & Djukri, 2017; Gunawan et al., 2019).

Therefore, there is a clear research gap in the development of a STEM-integrated Project-Based Learning model that utilizes palm oil waste as a renewable energy context in chemistry education. Addressing this gap is particularly important for Indonesia, as the world's largest palm oil producer, where sustainability education is both locally relevant and globally significant (Hansen et al., 2015; Yusoff, 2006). Consequently, this study aims to develop and evaluate a PjBL-STEM chemistry learning model based on palm oil waste to improve students' scientific literacy, 21st-century skills, and awareness of sustainable energy issues, while also supporting the achievement of the Sustainable Development Goals (SDGs), particularly SDG 4, SDG 7, and SDG 12.

Method

This study employed a Research and Development (R&D) approach using Plomp & Nieveen (2013) development model, which consists of three interrelated phases: preliminary research, development (prototyping), and assessment**.** These phases were implemented sequentially and iteratively to ensure that the developed PjBL–STEM chemistry learning model was theoretically grounded, empirically validated, and feasible for classroom implementation. A flowchart of the development procedure is provided to illustrate the connections among phases.

Preliminary Research Phase

The preliminary research phase aimed to identify instructional needs and contextual conditions. Needs analysis was conducted through classroom observations of Grade 10 science (MIPA) chemistry lessons and semi-structured interviews with chemistry teachers to identify learning difficulties, instructional gaps, and curriculum demands. A literature review was also carried out to examine previous studies on PjBL, STEM integration, and renewable energy contexts in chemistry education, which served as the basis for defining the research gap and designing the initial model framework.

Development (Prototyping) Phase

In the development phase, a prototype of the palm oil waste–based PjBL–STEM learning model was designed. This included the learning syntax, lesson plans, student worksheets, and assessment instruments. The initial prototype underwent expert validation involving three experts: a chemistry education expert, a science education expert, and a renewable energy expert. Validation was conducted using a Likert-scale validation rubric covering content relevance, instructional design, STEM integration, and contextual suitability. Validation results were categorized as *very valid, valid, needs revision,* or *invalid*. The prototype was revised based on experts' qualitative feedback before proceeding to the trial stage.

Assessment Phase

The assessment phase evaluated the validity, practicality, and effectiveness of the developed model. Practicality was assessed through teacher observation sheets and teacher practicality questionnaires, focusing on ease of implementation, time allocation, and instructional clarity. Effectiveness was examined through a single-group pretest–posttest design conducted with 32 Grade 11 science (MIPA) students. Grade 11 students were selected because they had mastered prerequisite chemistry concepts required for the energy-related projects. Data were collected using learning outcome tests, student response questionnaires, and observation rubrics for critical thinking skills. Learning outcomes were analyzed using descriptive statistics and N-Gain analysis, while observational data were quantified using rubric-based scoring.

Result and Discussion

Model Validity and Practicality

The validity analysis showed that the palm oil waste–based PjBL–STEM learning model met the criteria of valid to very valid, based on expert judgment covering content accuracy, instructional design, STEM integration, and contextual relevance. This result is consistent with Plomp & Nieveen (2013) assertion that expert validation ensures theoretical soundness and internal consistency of a developed educational product.

The practicality evaluation indicated that the model was practical and feasible for classroom implementation, as teachers were able to conduct all learning stages effectively and students actively engaged in project activities. According to Plomp & Nieveen (2013), a learning model is considered practical if it can be implemented as intended under normal classroom conditions, which was achieved in this study.

Improvement of Students' Scientific Literacy

Students' scientific literacy scores increased from an average pretest score of 55 to a posttest score of 82**,** as illustrated in Figure 1.

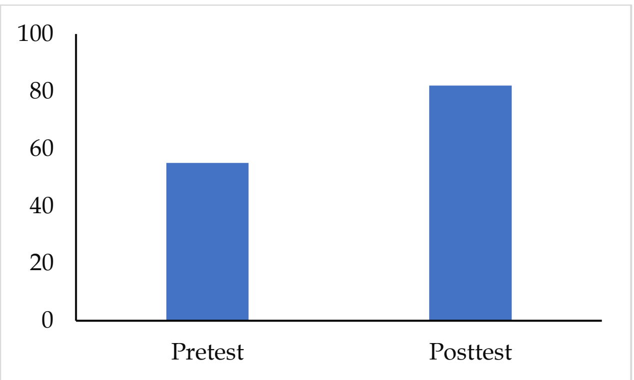

Figure 1. improving students' scientific literacy learning outcomes

This improvement indicates that the PjBL–STEM model effectively supports learning outcomes. From a constructivist perspective, meaningful learning occurs when students actively construct knowledge through direct experience and reflection. The project-based activities provided such experiences by engaging students in real-world chemistry problems related to renewable energy.

Distribution of Pretest and Posttest Scores

The distribution of pretest and posttest scores presented in Figure 2 shows that posttest scores were more homogeneous and centered at a higher median.

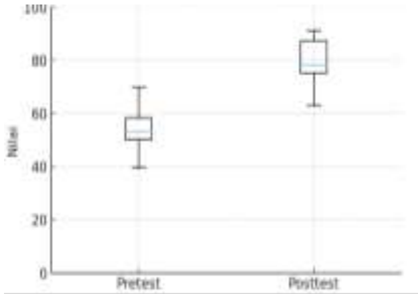

Figure 2. Distribution of Pretest and Posttest Scores

This reduction in variability suggests that the learning model helped minimize achievement gaps among students. According to Vygotsky's social constructivist theory, collaborative learning enables students to learn from peers within their zone of proximal development, leading to more evenly distributed learning outcomes (Vygotsky, 1978).

N-Gain Analysis

The average N-Gain value of 0.57 indicates a moderate to high level of improvement, confirming the effectiveness of the intervention. This finding aligns with Hake (1998) framework, which states that N-Gain values above 0.3 represent meaningful learning gains. The majority of students achieving medium to high gains (Figure 3) indicates that the learning model consistently benefited learners with varying initial abilities.

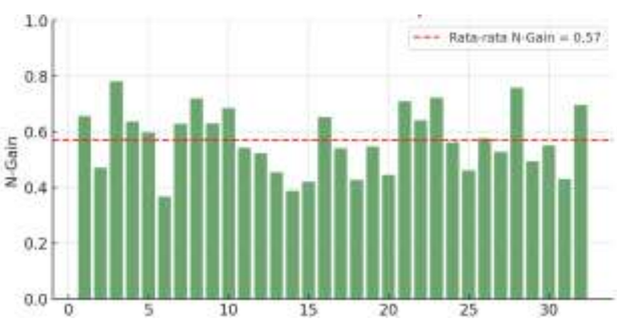

Figure 3. N-Gain Value of Students' Science Literacy

Improvement Across Scientific Literacy Indicators

Improvements were observed across all scientific literacy indicators, content, context, process, and attitude, as shown in Figure 4, with the highest gain in the process indicator.

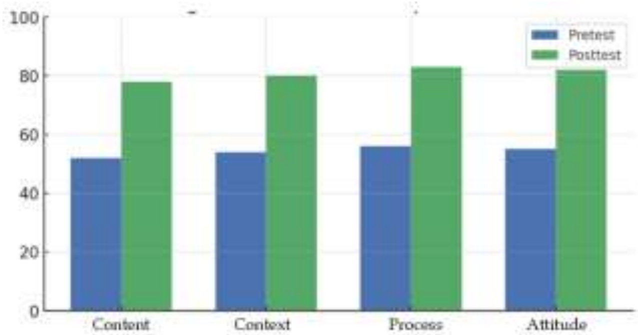

Figure 4. Improvement of students' scientific literacy in each indicator (content, context, process, attitude).

This result can be explained by the inquiry-oriented nature of PjBL–STEM, which emphasizes experimentation, data analysis, and problem-solving. According to Bybee (2014), scientific literacy development is strongest when students are actively engaged in scientific practices rather than passive content reception.

Discussion

The significant improvement in students' scientific literacy confirms that integrating PjBL with STEM in a local renewable energy context enhances conceptual understanding and scientific reasoning. This finding supports contextual learning theory, which posits that knowledge is more meaningful when connected to learners' real-life environments (Fauzi & Hashim, 2020). The strongest improvement in the process aspect indicates that students developed better inquiry and investigation skills. This aligns with the nature of PjBL–STEM, which requires students to design, test, and evaluate solutions, reinforcing higher-order thinking skills as emphasized in 21st-century learning frameworks (Huang et al., 2022).

The use of palm oil waste as a project context enhanced learning relevance and environmental awareness. According to situated learning theory, authentic contexts promote deeper understanding and long-term retention. This contextualization also helped students connect macroscopic energy phenomena with chemical principles.

Collaborative project work further supported students' communication and teamwork skills. Vygotsky (1978) emphasized that social interaction plays a central role in cognitive development, which explains the more equitable learning outcomes observed after the intervention.

Finally, the instructional-level contribution to SDG 4, SDG 7, and SDG 12 demonstrates that sustainability-oriented chemistry education can simultaneously improve academic outcomes and sustainability awareness. These contributions are pedagogical in nature and align with education for sustainable development principles.

Conclusion

This study concludes that the STEM-integrated Project-Based Learning (PjBL) model based on the utilization of palm oil waste as a renewable energy context is effective in enhancing students' scientific literacy in chemistry learning. The developed model enables students to meaningfully understand and apply chemical concepts through contextual and project-oriented learning activities. Expert evaluations indicate that the model is valid in terms of its design, learning syntax, instructional materials, and assessment components, while classroom implementation and teacher responses demonstrate that the model is practical and feasible to be applied in senior high school settings. In addition to improving cognitive learning outcomes, the PjBL–STEM model supports the development of essential 21st-century skills, including critical thinking, collaboration, creativity, and environmental awareness. Overall, the palm oil waste–based PjBL–STEM model represents a viable instructional approach that integrates chemistry education with local renewable energy issues and contributes to the promotion of sustainable education aligned with the Sustainable Development Goals (SDGs), particularly in the areas of quality education and clean energy.

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Author Contributions

Conceptualization, Zulkhairi; methodology, Zulkhairi; validation, Zulkhairi and Dzikrul Rizki; formal analysis, Zulkhairi; investigation, Zulkhairi and Dzikrul Rizki; resources, Zulkhairi; data curation, Zulkhairi; writing—original draft preparation, Zulkhairi; writing—review and editing, Zulkhairi and Dzikrul Rizki; visualization, Zulkhairi; supervision, Zulkhairi; project administration, Zulkhairi; funding acquisition, Zulkhairi. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that there are no known competing financial or personal interests that could have appeared to influence the work reported in this paper. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results. All research activities were conducted independently and in accordance with applicable ethical and academic standards.

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