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Meeting 21st-Century Challenges: Cultivating Critical Thinking Skills through a Computational Chemistry-Aided STEM Project-Based Learning Approach

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Abstract— This research aims to explore the impact of a computational chemistry-supported STEM Project-Based Learning (PjBL-STEM) application on fostering critical thinking competencies. The project focuses on green energy, utilizing waste cooking oil and aluminum to enhance students' critical thinking skills. A pre-experimental design was employed for this study, involving a sample of 22 students. Data were collected using the 21st-Century Skills Usage Scale, along with structured and semi-structured interview forms. Critical thinking was assessed through a descriptive test comprising 10 questions. The collected data were analyzed using the Wilcoxon Signed Rank Test and thematic analysis techniques. The analysis revealed a significant improvement in the students' 21st-century skills, such as autonomy, collaboration, environmental sensitivity, communication, problem-solving, creativity, responsibility, and IT literacy. Particularly notable was the students' ability to interpret structured and patterned graphical data, which they found easier to understand compared to image and narrative data. The N-gain test results indicated that the STEM-PjBL model had a positive impact on developing critical thinking abilities, with 50% of students achieving medium and high categories. Overall, the STEM-PjBL model positively influenced the development of critical thinking competencies.

Keywords— Critical Thinking, STEM, PjBL, Computational Chemistry.
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1. Introduction

Critical thinking has emerged as a fundamental skill for students to master in addressing the dynamic challenges of the 21st century (Alsaleh, 2020; Elder & Paul, 2020; R. H. Ennis, 1993; Evendi et al., 2022; Liu & Pásztor, 2022; Santos-Meneses et al., 2023). In an era characterized by rapid changes in technology, information, and social structures, critical thinking is increasingly essential. The abundance of information access in the digital age necessitates the ability to filter relevant data, assess its reliability, and draw accurate conclusions. Critical thinking is crucial for understanding and anticipating the impacts of new technologies and engaging in the innovation process. This involves analyzing the ethical, social, and economic implications of new technologies. Students need to develop multidisciplinary skills to tackle complex issues effectively. Critical thinking enables the integration of various concepts from different disciplines to solve complex problems prevalent in this century (Bellaera et al., 2021; Dwyer et al., 2014; Fong et al., 2017; Higgins, 2014; Hukamdad & Akbar, 2023; ŽivkoviĿ, 2016). By mastering critical thinking skills, students are better prepared to handle the complexities and dynamics of the modern world and contribute more effectively to an ever-evolving society.

Studies indicate that critical thinking skills among students in Indonesia generally fall into moderate and low categories (Billah et al., 2021; Saputri et al., 2019; Syahrial et al., 2019). This trend is mirrored by the limited science literacy skills observed in the region (Hartono et al., 2022; Ismawati et al., 2023; Safari et al., 2020). Science literacy and critical thinking are closely linked, as science literacy inherently involves applying critical thinking to evaluate and interpret scientific information (Ramírez-Montoya et al., 2022). Zarzycka & Gesek (2022) note that critical thinking aids individuals in understanding and interpreting data and issues necessary for making precise and accurate decisions. Critical thinking and science literacy skills are intimately connected, each bolstering an individual's ability to make informed and rational decisions in scientific contexts and daily life (Alsaleh, 2020). The rapid development of technology has made information dissemination exceedingly easy, leading to the widespread presence of hoaxes and myths often accepted as facts in society. This condition necessitates a more refined level of thinking, known as Critical Analytical Thinking (CAT). CAT is based on the principle that one should not readily accept justifications or claims without thorough and comprehensive evaluation of the information. The concept theory suggests that repeating hoaxes over time may establish them as facts within the community. The ability to critically analyze conspiracy issues clearly and accurately is thus increasingly essential (Swami et al., 2014).

Experts define critical thinking as an intellectually disciplined process that involves an ethical stance reflecting consistency in thinking and action (Elder & Paul, 2020; Davies & Barnett, 2015). While critical thinking can be described as a series of procedures to follow, it should not be confined to teaching these steps through metacognitive processes but rather should be taught using scientific approaches (Evendi et al., 2022; Magno, 2010). The "Freedom to Learn" curriculum emphasizes problem-based learning (PBL) and project-based learning (PjBL) as dynamic models that cater to the cognitive, affective, and psychomotor transfer processes in students, addressing 21st-century competencies and skills. Learning is expected to provide real contexts, deriving from actual realities and surrounding issues, which is crucial for meaningful learning experiences (Azila-Gbettor et al., 2022; Sobral, 1995). Educational materials with a scientific approach are increasingly developed to train and enhance critical thinking abilities (Amin et al., 2020; Childs et al., 2015). However, the challenge in education is that performing simple and structured procedures does not guarantee critical thinking (Paul & Elder, 2019). Critical thinking involves not only the ability to solve problems but also the capacity to rapidly adapt to changing situations and devise innovative solutions (Alsaleh, 2020; Oliveira et al., 2021). In facing the complexities and dynamics of the 21st century, critical thinking is not just an additional skill but a foundational necessity for individual success and societal progress. Furthermore, integrating environmental issues into learning is crucial for training students to be more adaptive and solution-oriented towards the environmental challenges they face.

Environmental issues are now a fundamental global concern. Technological innovations are continually being developed to address these problems, which have a noticeable impact. Incorporating technology into learning strategies to tackle environmental issues is crucial. The STEM-PjBL (Science, Technology, Engineering, and Mathematics-Project-Based Learning) model proves to be an effective solution in cultivating a generation that is critical and adaptive in responding to environmental challenges. Projects within the STEM-PjBL framework often challenge students to solve complex real-world problems. This requires the ability to analyze issues, identify relevant factors, and devise effective resolution strategies (Diana et al., 2021; Oktavia & Ridlo, 2020; Setyawati et al., 2022). Students are encouraged to ask questions and explore STEM topics through a series of activities that involve collecting data from both the environment and the laboratory. This process fosters the development of their ability to pose relevant questions, find trustworthy information sources, and assess the reliability of the information they gather (Baran et al., 2021).

Climate change refers to long-term shifts in global or regional weather patterns, primarily driven by the rise in Earth's average atmospheric temperature. This warming is largely attributed to greenhouse gas emissions from human activities, such as the combustion of fossil fuels and deforestation. Utilizing green energy can help minimize these emissions, thereby potentially alleviating climate change. Technologies like solar panels, wind turbines, and electric vehicles can reduce individuals' carbon footprints and lessen the environmental impact (Bhowmik et al., 2017; Guo et al., 2019; Tan et al., 2021). There is a pressing need to enhance the competence and awareness of students regarding natural resources that can serve as alternative energies to replace fossil fuels, the effects of which are profoundly felt and observed. The repercussions of climate change, particularly its impact on global food supply disruptions, are significantly felt, leading to socio-economic challenges worldwide (Hunt et al., 2020; Khan, 2012; Schernikau & Smith, 2022; Carleton & Hsiang, 2016; Gasper et al., 2011; Tol, 2018).

The massive impact of fossil fuel use underscores the urgency of finding solutions. Education that focuses on solving environmental issues is essential for students in science disciplines. Indonesia, with its rich natural potential, could prioritize alternative energies over fossil fuels. Emphasizing technological aspects while considering environmental impacts is crucial for ongoing development. The STEM-PjBL model is one effective approach that has been shown to enhance students' thinking competencies and skills (Baran et al., 2021; Diana et al., 2021; Setyawati et al., 2022). Numerous reports highlight the effectiveness of this model in fostering competencies and creativity in thinking. Studies have shown that the implementation of STEM-PjBL effectively nurtures critical thinking, logical, creative skills, evaluation, inference, and problem-solving abilities (Purwaningsih et al., 2020; Rahmawati et al., 2021; Ramírez-Montoya et al., 2022).

Research on STEM-PjBL in chemistry education has been extensively conducted. Results have proven effective in developing thinking competencies, yet studies on abstract chemical concepts remain limited. The complexity of chemical content that explores subatomic activities, particularly involving electrons and protons in chemical reactions, necessitates computational simulations to facilitate students' conceptual understanding. Computational simulation applications are crucial for describing abstract or microscopic chemical content (Basu et al., 2017; Hulyadi & Muhali, 2023; Speybroeck & Meier, 2003). Integrating computational chemistry with the scientific activities of the STEM-PjBL model is expected to build more comprehensive thinking competencies, thereby preventing misconceptions. Based on these studies, exploring the application of computational chemistry-assisted STEM-PjBL is important for developing critical thinking skills necessary to meet 21st-century challenges.

2 Method

The study was conducted using a descriptive quantitative approach. Descriptive quantitative research is a type of research aimed at depicting and analyzing a phenomenon or population through the collection and analysis of quantitative data. Unlike qualitative research, which focuses on deep understanding and interpretive analysis, descriptive quantitative research prioritizes measurement and statistical generalization across a population. This study was carried out at Mandalika University of Education with a sample of 20 individuals. The variable analyzed was the effectiveness of the computational chemistry-assisted STEM-PjBL model in developing critical thinking competencies. The projects in this study were based on the environmental issue of global temperature rise due to fossil fuel usage. Introducing new, more environmentally friendly renewable energy sources was the project topic for the students. Projects included producing hydrogen gas from aluminum processing waste and biodiesel from local waste. Biodiesel synthesis activities were conducted with a series of treatments to improve production quality. These scientific activities are expected to enhance critical thinking competencies.

2.1 Data Collection Techniques and Tools

The study employed pre-test and post-test data interpretation and environmental literacy tests as methods and tools for data collection. The test comprised 10 essay questions aimed at assessing students' critical thinking competencies. The validity, discriminative power, and difficulty level of these tests were analyzed before implementation. These tests were developed based on indicators of critical thinking competencies. Students were given the tests before and after engaging in project activities involving the production of hydrogen gas and biodiesel. After completing the projects, students' competencies were further reinforced through computational simulations related to the projects undertaken.

2.2 Data Analysis Techniques

Data collection techniques were derived from tests assessing competencies in data interpretation and environmental literacy. In data processing, this study collected pre-test and post-test data before and after the intervention. Once the data were gathered, they were processed using SPSS 22 software. The data analysis techniques used in this study included the following: The Shapiro-Wilk normality test was used to determine whether the data were normally distributed, appropriate given the sample size of fewer than 50. Subsequently, a homogeneity test was conducted to assess the uniformity in data variance from the population. The next test applied was the N-Gain test, which identified the effectiveness of the treatments given.

3. Results and Discussion

The 21st century is marked by rapid information development and widespread digitalization across nearly all aspects. In addition to technological advancements, alarming environmental and health issues have emerged, severely impacting the global economy. Amidst these vast global challenges, there is a critical need for skills to address and solve successive problems. Problem-solving skills arise from higher-level thinking abilities, among which critical thinking is essential. This research was conducted to foster critical thinking skills through a series of environmental chemistry projects. Climate change impacts, such as the decline in global food supply, have been exacerbated by the use of fossil fuels, one of the largest contributors to environmental issues (Hunt et al., 2020; Khan, 2012; Schernikau & Smith, 2022). The study explored using waste cooking oil and aluminum as more environmentally friendly alternative energy sources. Projects designed by students aimed to train scientific skills by transforming waste issues into solutions for other problems.

The ability to transform problems into solutions for other issues is crucial and must be continually developed to foster adaptive and creative students. Transforming potentially harmful waste into new compounds can be meaningful and beneficial for life. One essential 21st-century skill is the ability to analyze problems and provide solutions, which is developed through trained critical thinking. High-level critical thinking skills can lead to more effective problem-solving abilities (Belecina & Jose M Ocampo, 2018; Carlgren, 2013; Oktavia & Ridlo, 2020; Rahmawati et al., 2021). Research shows that Indonesian students' thinking abilities remain low, as reflected in their low science and mathematics rankings. The latest PISA report shows that only 0.8% of Indonesian students excel in at least one subject area—science, literacy, and mathematics—with Indonesia ranking 69th out of 79 countries participating in PISA. This score is significantly lower than Singapore, which ranks first in the PISA applied to the global education system. Consequently, the current curriculum system does not accommodate students to work on problems that encourage, stimulate, and analyze using high-level comprehension skills (Fenanlampir et al., 2019; Ismawati et al., 2023; Safari et al., 2020; Sahyar et al., 2019; Thien et al., 2015). Educational models emphasizing training in high-level thinking through deeper problem identification activities need further development. The implementation of a computational chemistry-assisted STEM-PjBL model is applied to address the low thinking abilities. Research results show that a series of activities in synthesizing hydrogen gas and biodiesel, designed within the STEM-PjBL model, have proven to enhance students' critical thinking abilities. The outcomes of critical thinking abilities are illustrated in Figure 1.

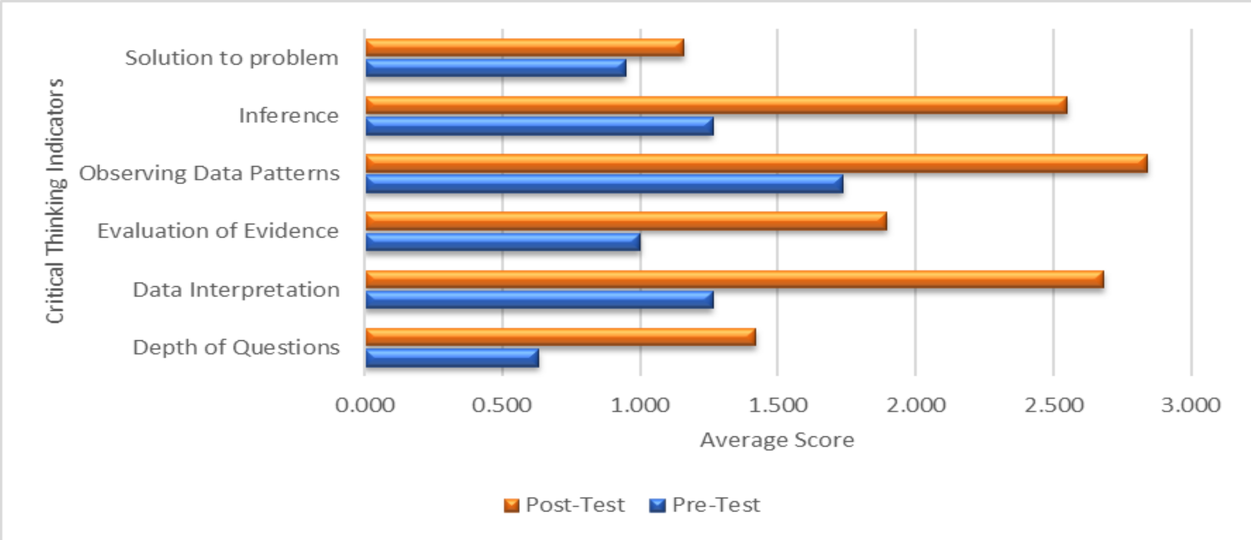

Fig. 1. The outcomes of critical thinking abilities

Overall, there was an improvement in critical thinking skills before and after the implementation of the computational chemistry-assisted STEM-PjBL model. According to Figure 1, students found it easier to interpret, pattern, and evaluate data in numerical form compared to images or narratives. (Raudenbush et al., 2020; Sermier Dessemontet et al., 2020; Wortha et al., 2023) suggest that numerical and patterned data are easier to understand because they are well-structured and organized. Numerical data are often arranged in tables or graphs with clear structures, such as columns and rows, making them easy to read and understand. They frequently exhibit specific patterns or regularities, such as increasing or decreasing numerical sequences, which facilitate conclusions or predictions based on the data. Numerical data allow for direct comparisons between different values, easing the identification of differences or patterns among various data groups. They are often linked with precise measurements, like time, distance, or quantity, making these values easier to interpret in relevant contexts. Data on the impact of fossil fuel usage on global temperature increases were more comprehensible to students. This data was presented to build student competencies about the serious impacts caused by fossil fuel use, displayed in Figure 2.

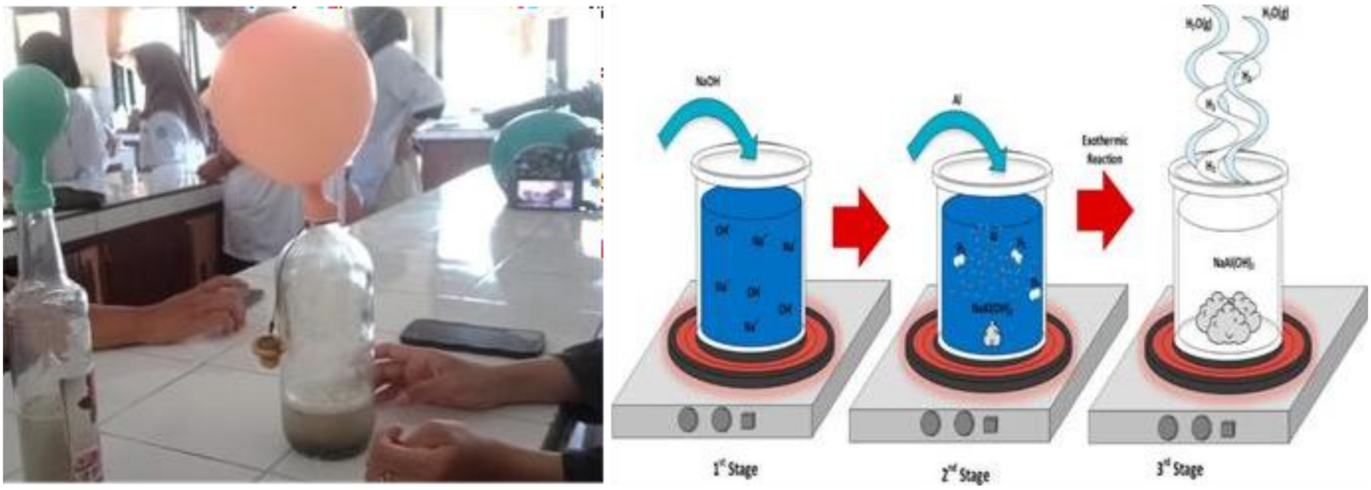

Fig. 2. Hydrogen Synthesis Process and Simulation of Occurring Reactions

Cahoon et al. (2021) reported that numerical data are often represented in forms such as graphs or diagrams, which visually demonstrate the relationships between variables or trends over time. These graphical representations facilitate quick understanding of information. Ansari (2016) and Merkley & Ansari (2016) noted that a combination of clear structure, regularity, comparability, graphical representation, and statistical analysis, makes patterned numerical data clearer and easier to comprehend. For instance, data like Figure 2 depict the comparison of hydrogen gas amounts with the same concentration and weight of aluminum waste reacted with HCl and NaOH solutions. Documentation-style data are more challenging for students to understand. To enhance critical thinking skills, this event is combined with images describing the reaction process occurring in a balloon with a larger volume, where the gas burns during a flame test. Many students still make errors in evaluating empirical evidence through images and computational simulations, which are used as tools to improve their thinking competencies.

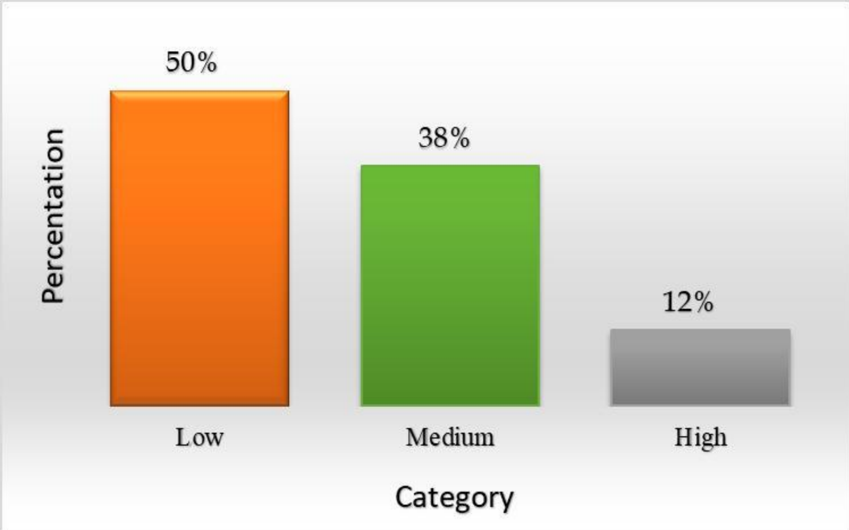

Fig. 4. N-Gain Test Results for Critical Thinking Competencies

Students still lack proficiency in presenting data in communicative and easily understandable tables and graphics. Critical thinking involves the competence to observe and evaluate data in a detailed and comprehensive manner before making inferences. The ability to meticulously document variables such as time, duration, concentration, balloon size, and the characteristics of the flame is not consistently demonstrated by students. The majority of collected data are in the form of images and video recordings from laboratory sessions. This deficiency impacts students' ability to perform low-level evaluations of evidence and data interpretation. Reflections from student projects indicate the necessity for structured guidance throughout the process, or the creation of structured learning materials (LMK) to direct students during projects. Students cannot yet be left to conduct projects independently; structured guidance and clear self-regulation are essential throughout the project duration. Overall, the implementation of the computational chemistry-assisted STEM-PjBL model has a positive impact on fostering students' critical thinking competencies. This finding is supported by N-Gain test results presented in Figure 4.

Fig. 4. depicts that 50% of students fall into moderate and high categories. The PjBL (Problem-Based Learning) model, when applied with an environmental issues approach supported by computational simulations, enhances students' data interpretation and environmental literacy. PjBL is a learning approach where students engage in various activities to develop understanding and solutions. These activities include identifying problems or questions, conducting independent research, group discussions, teamwork, experiments or simulations, presentations and discussions of results, and reflection and evaluation. Through these activities, students are encouraged to develop critical thinking, communication, collaboration, and problem-solving skills essential for achieving deep understanding and effective solutions in project-based and problem-solving learning contexts. This series of activities trains students to become solution-oriented and adaptable to challenges they face. Activities such as data collection, organizing it into tables, and describing it in graphical forms are part of a series that can enhance the ability to read data patterns and trends, fostering competencies in data interpretation (Anggereini et al., 2023; Koparan & Güven, 2015; Widakdo, 2017).

4. Conclusion

N-Gain test results indicate that the application of the computational chemistry-assisted STEM-PjBL model has a positive impact on the development of students' critical thinking competencies. The ability to understand well-structured numerical and patterned data is easier compared to data presented in image and narrative forms. This suggests that structured numerical information aids in clearer understanding and learning, enhancing critical analysis skills among students.

5. Recommendations

Based on the research findings, the researchers recommend: (1) The STEM-PjBL model requires structured learning materials (LKM) that provide clear guidance on the project mechanisms to be undertaken; (2) There is a need for self-regulation guidelines to assist students in conducting laboratory activities effectively; (3) Detailed data presentation in tables and clear graphics is necessary in the student learning materials to enhance comprehension and analysis.

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