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Enhancing Students' Pollution Problem-Solving Skills Through Problem-Based Learning: The Moderating Role of Mathematical Literacy

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ABSTRACT

This study examines the effectiveness of the Problem-Based Learning (PBL) model in enhancing university students' ability to solve environmental pollution problems, with mathematical literacy as a moderating variable. Conducted in Indonesia, the research adopted a quasi-experimental non-equivalent pretest-posttest control group design involving 64 biology education students from Universitas Pakuan. Participants were assessed using open-ended problem-solving tests and a rubric aligned with the PISA framework. Results from two-way ANOVA showed significant effects of the learning model ($F(1, 58) = 32.84$, $p < .001$, $\eta^2 = .216$) and mathematical literacy levels ($F(2, 58) = 29.17$, $p < .001$, $\eta^2 = .201$) on problem-solving performance. Although both groups improved by 18.75 points from the pretest to the post-test, the PBL group outperformed the control. Post hoc analysis (Tukey HSD) revealed that students with high mathematical literacy achieved the highest scores ($M = 91.8$, $SD = 3.7$), confirming its moderating effect. These findings underscore the value of integrating mathematical literacy into PBL to promote contextual learning and real-world problem-solving. Future studies should explore broader samples and longitudinal impacts across diverse educational contexts.

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1. INTRODUCTION

Environmental issues have emerged as a critical global concern, ranging from air and water pollution to plastic waste and deforestation. Ekenga et al. emphasize that environmental injustice has become a global threat with far-reaching implications [1]. According to the World Economic Forum, Indonesia ranks 54th out of 65 countries in environmental, social, and governance (ESG) indicators, reflecting low sustainability performance [2]. Lestari and Trihadiningrum further highlight that improper solid waste management in Indonesia has increased plastic pollution in coastal and marine environments [3]. In addition, forest and land fires driven by deforestation and illegal mining practices have exacerbated environmental degradation in several Indonesian provinces [4]. These environmental challenges underscore the urgent need for strategic and comprehensive responses, particularly in developing nations. These realities demand that higher education institutions proactively cultivate environmental responsibility through more contextual and applied learning approaches [5].

Nevertheless, many university students still exhibit environmentally irresponsible behaviors, such as littering and neglecting campus greenery. This reveals a disconnect between classroom knowledge and real-world application [6]. Ghozali argues that a scientific and experience-based learning approach is essential for improving student learning outcomes [7], [8]. Problem-Based Learning (PBL) is a relevant instructional strategy to address this gap. PBL is increasingly recognized for its ability to bridge theoretical understanding with experiential learning. One effective way to create meaningful learning experiences is by implementing problem-based learning (PBL).

The issues addressed in PBL are genuine challenges encountered in daily life. This approach encourages students to seek relevant knowledge, allowing them to learn directly from real-world situations [9]. PBL places real-world problems at the core of learning, encouraging students to engage in collaborative investigation and critical thinking [10], [11]. Numerous studies have demonstrated that PBL enhances students' motivation, problem-solving abilities, and environmental literacy [12], [13]. By engaging with authentic problems, students acquire knowledge and develop essential cognitive and social skills to address complex environmental issues. Problem-based learning enhances student motivation, subsequently improving problem-solving skills [13], [14].

In addition to effective teaching models, learners require specific competencies to analyze problems and make informed decisions. One such competency is mathematical literacy, which refers to the ability to formulate, apply, and interpret mathematics in various real-life contexts [15], [16]. It encompasses data modeling, quantitative reasoning, and decision-making based on evidence. Bolstad emphasizes the role of mathematical literacy in connecting theoretical knowledge to practical challenges in everyday life [17], [18]. This competency is particularly crucial when addressing multidimensional problems such as environmental pollution, often involving data analysis and quantitative evaluation.

Previous studies have separately investigated the impact of PBL on higher-order thinking skills and the role of mathematical literacy in academic performance [19], [20]. However, few studies have explored the moderating role of mathematical literacy in enhancing the effectiveness of PBL, particularly in solving environmental pollution problems [21], [22]. This indicates a lack of integrative research combining instructional models and core competencies to tackle pressing environmental issues. This reveals a significant research gap that warrants further exploration.

This study aims to examine the effect of the Problem-Based Learning model on students' ability to solve pollution-related problems and to evaluate how mathematical literacy levels moderate this effect. It seeks to determine whether variations in mathematical literacy influence the degree to which students benefit from PBL in environmental contexts.

This study hypothesizes that students with high mathematical literacy will demonstrate stronger problem-solving performance than those with moderate or low literacy when taught using the PBL model.

The findings of this research are expected to offer theoretical contributions to the development of contextual learning models integrated with mathematical literacy. Practically, the results may serve as a reference for educators in designing instructional strategies that convey knowledge and promote active engagement in addressing real-world environmental problems. Such strategies can empower students to become environmentally responsible citizens with analytical and practical problem-solving skills.

2. METHOD

This study employed a quasi-experimental design using a non-equivalent pretest-posttest control group to examine the effectiveness of the Problem-Based Learning (PBL) model in improving students' ability to solve environmental pollution problems, with mathematical literacy as a moderating variable. The research was conducted at the Faculty of Teacher Training and Education, Universitas Pakuan, Bogor, Indonesia.

Participants and Sampling Procedure

Sixty-four undergraduate students from the Biology Education Program participated in this study. The participants were selected using a purposive sampling technique based on their enrollment in a course relevant to environmental education. They were divided into two intact groups: an experimental group (n = 32) that received PBL instruction and a control group (n = 32) that received conventional teaching. Group assignments followed existing class sections without randomization.

Instruments and Validity

Students' problem-solving ability was assessed using a 5-item open-ended test to evaluate their capacity to address real-life environmental pollution issues. A rubric was developed based on the PISA (Programme for International Student Assessment) framework to measure mathematical literacy, encompassing competencies such as formulating, applying, and interpreting mathematics in real-world contexts.

Both instruments underwent expert validation by three specialists in environmental education and mathematics instruction. A pilot test with 20 students yielded a Cronbach's alpha of 0.84, indicating high internal consistency and instrument reliability.

Intervention Procedure

The intervention was conducted over five weeks. The experimental group received instruction through PBL activities, including problem identification, collaborative analysis, and solution development based on real-world environmental cases. The control group followed a traditional lecture-based format with teacher-led instruction covering the duplicate content. Both groups completed a pretest before the intervention and a post-test after completion.

All learning sessions were delivered in person in a classroom setting, and instructors used standardized lesson plans to maintain consistency across groups. Before the intervention, instructors received a brief orientation and training on the teaching model to ensure procedural fidelity.

Data Analysis

Quantitative data were analyzed using two-way ANOVA to investigate the main effects of the learning model and mathematical literacy levels and their interaction effects on problem-solving performance. Differences among literacy level groups were further examined using Tukey's Honestly Significant Difference (HSD) test. The effect size was reported using partial eta squared (η^2) to determine the practical significance of the findings.

Ethical Considerations

The Ethics Committee of Universitas Pakuan approved the study. All participants provided written informed consent, and ethical protocols followed institutional research standards and international ethical guidelines for research involving human participants.

3. RESULTS AND DISCUSSION

3.1. Results

This research collects data on mathematical literacy and the ability to solve pollution problems. Data was collected from the experimental group and the control group. To analyze the role of mathematical literacy, students' scores were classified into three categories based on predetermined thresholds. The classification is as follows:

a. Low: scores below 60
b. Medium: scores between 60 and 79
c. High: scores of 80 and above

These cutoff points were determined based on the distribution of students' scores and aligned with commonly used categorizations in previous studies on mathematical literacy [11], [23]. The following table and figure present the distribution of students' mathematical literacy levels across the experimental and control groups. Mathematical literacy scores are used to collect data about mathematical literacy classification, and the results of these abilities are shown in Figure 1 below:

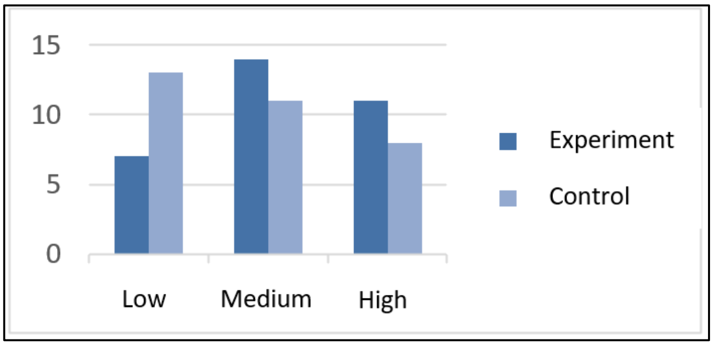

Figure 1. Frequency Distribution of Mathematical Literacy

Figure 1 above shows that the mathematical literacy of the experimental group is greater than that of the control group. Data on the ability to solve pollution problems was collected through tests, especially pretest (before treatment) and post-test (after treatment), can be seen in Table 1 below:

Table 1. Data on Ability to Solve Pollution Problems

Data	Model	P	Mean	SD
Pretest	Experiment	32	68,75	3,87
	Control	32	63,5	3,63
Posttest	Experiment	32	87,5	7,54
	Control	32	82,25	5,32

Based on this data, a hypothesis test is then carried out. From the results of the calculations carried out, the following hypothesis testing is obtained:

1. The results of the two-way ANOVA analysis for the first hypothesis revealed a significance value of 0.000 ($F = 32.84, p < 0.05$), with a partial eta squared (η^2) = 0.216, indicating a large effect. Indicating a statistically significant difference between the experimental and control groups. Consequently, the null hypothesis (H_0) was rejected, confirming that implementing the Problem-Based Learning (PBL) model significantly influenced students' ability to address pollution-related problems.
2. For the second hypothesis, the two-way ANOVA also produced a significance value of 0.000 ($F = 29.17, p < 0.05$), with η^2 = 0.201 (significant effect), which demonstrates that students' mathematical literacy levels—categorized as low, moderate, and high—had a significant impact on their pollution problem-solving ability. Due to this result's significance, further analysis was conducted using the Tukey HSD post hoc test.
3. The Tukey test results showed that students with high mathematical literacy significantly outperformed those with moderate and low literacy levels within the PBL group ($p < 0.05$). The highest mean post-test score was observed in the experimental group with high mathematical literacy ($M = 91.8, SD = 3.7$), followed by the moderate group ($M = 87.3, SD = 4.5$), and the lowest in the low-literacy group ($M = 81.4, SD = 5.2$). These results imply that mathematical literacy strengthens the effectiveness of the PBL model in solving contextual pollution problems.

A comparison of pretest and post-test scores revealed further insights. In the experimental group, the average pretest score was 68.75, which increased to 87.5 at the post-test, indicating a gain of 18.75 points. In contrast, the control group improved from 63.5 to 82.25, showing an 18.75-point gain. However, despite the similar numerical increase, the results of the two-way ANOVA revealed that the difference in performance between groups was statistically significant, with a calculated partial eta squared $(\eta^2) = 0.216$, representing a large effect size. This statistically significant difference confirms that implementing the PBL model offers more than score improvements—it provides a pedagogical advantage, contributing to deeper learning outcomes. This suggests that the PBL model produced a more substantial impact, particularly when interacting with students' literacy levels.

Furthermore, the results of hypothesis testing show that mathematical literacy also has a significant influence on problem-solving abilities. Students with a high level of mathematical literacy tend to get higher post-test scores than students with a medium or low level of literacy. This indicates that students' cognitive preparedness in mathematical reasoning plays a pivotal role in effectively engaging with and solving complex problems. These findings were strengthened through further analysis using Tukey's test, which indicated that differences between groups based on levels of mathematical literacy were statistically significant. Thus, mathematical literacy is a variable that strengthens the effectiveness of problem-based learning.

The distribution of post-test scores shows that the experimental group had more achievements, although with a slightly larger standard deviation than the control group. This shows that the variation in scores in the experimental class is still within the acceptable range and generally illustrates the success of the learning process. Such distribution patterns suggest that PBL fosters more inclusive academic progress, benefiting a wider range of student capabilities. Data visualization in Figure 1 shows that the distribution of mathematical literacy in the experimental group tends to be in a higher category than the control group, which also strengthens the results of the quantitative analysis.

In addition, students with higher mathematical literacy scored better overall and demonstrated deeper reasoning and more structured solutions during the test. These qualitative aspects of student performance reflect enhanced analytical thinking and the ability to apply concepts in novel contexts. These findings confirm the reinforcing role of mathematical literacy in enhancing the learning outcomes of students engaged in problem-based learning, especially when faced with real-world environmental issues such as pollution.

3.2. Discussion

The findings in this study confirm that model *Problem-Based Learning* (PBL) has high effectiveness in improving students' abilities to solve contextual problems, especially those related to environmental pollution issues. PBL systematically encourages students to actively identify problems, analyze information, and develop solutions through a scientific approach. This process enriches students' cognitive aspects and forms scientific attitudes and social skills relevant to 21st-century learning needs. The alignment of PBL with real-world challenges fosters a holistic learning experience that integrates knowledge, attitudes, and values essential for sustainability education.

The Problem-Based Learning (PBL) learning paradigm improves students' ability to participate in learning activities, making them more active, responsible, and capable of tackling pollution-related problems. The PBL phases stimulate information acquisition, skill development, and critical thinking. These findings are consistent with Karyatin's research, which found that PBL can assist students in enhancing their ability to create mind maps that aid in problem-solving [24]. This highlights how PBL fosters academic understanding and supports the development of metacognitive strategies essential for lifelong learning.

The Problem-Based Learning (PBL) approach supports students in enhancing a range of mathematical literacy competencies, including conceptual understanding, mathematical representations, logical reasoning, effective communication, and the ability to make connections between mathematical ideas. It also promotes students' skills in solving real-world problems and tackling non-routine tasks [23]. Students with excellent mathematical literacy in number processing, such as reading, writing, and manipulating symbols, have a greater capacity to tackle pollution problems. Such literacy empowers students to interpret quantitative data and apply mathematical thinking when engaging with environmental phenomena. Furthermore, pupils with excellent mathematics literacy are the major talent in learning, applying, and building good character to overcome pollution concerns [25], [26].

The involvement of mathematical literacy as an attribute variable in this research also shows a significant contribution. Students with a high level of mathematical literacy perform better in solving pollution problems, especially in contexts that require data interpretation, mathematical modeling, and numerical-based decision-making. In this context, mathematical literacy includes basic arithmetic skills, understanding concepts, quantitative reasoning, and the ability to relate mathematical symbols to real-world phenomena. This aligns with Erria's view that mathematical literacy is a fundamental competency that supports success in various contextual problem-living domains [21]. This emphasizes the role of mathematical literacy as a cognitive tool that bridges abstract theory and environmental practice.

Theoretically, these results strengthen the constructivist approach in education, where learning is an active construction formed through real experience. Problem-based learning allows students to build their knowledge by linking theories obtained in class with environmental problems they encounter. In addition, the discussion and group collaboration process in the PBL model contributes to developing scientific communication skills, collaborative decision-making, and instilling the value of social responsibility. This integrative process reflects a learner-centered paradigm vital for cultivating competencies aligned with Education for Sustainable Development (ESD).

Practically, these findings imply that choosing the right learning model must consider the initial characteristics of students, in this case, the level of mathematical literacy. Combining the PBL approach and strengthening mathematical literacy can be an integrated learning strategy to develop high-level thinking skills, especially in learning contexts oriented toward solving environmental problems. Therefore, it is recommended for educators to integrate the PBL learning model more widely, not only in environmental-related courses but also in other fields that require analytical and problem-solving thinking skills. Such pedagogical integration can foster adaptable learners equipped to navigate interdisciplinary challenges in real-world contexts.

Although this study yielded significant results, several limitations must be acknowledged. The sample was limited to 64 biology education students from a single university, restricting the generalizability of the findings. Potential confounding factors such as prior environmental knowledge, digital literacy, and instructor variation may have influenced the outcomes. The use of open-ended assessments also introduces possible scoring bias. To address these limitations, future studies should include larger and more diverse samples, control for additional variables, and consider using mixed-methods approaches, such as performance-based tasks or structured interviews, to gain a more comprehensive understanding of students' problem-solving abilities. Moreover, longitudinal research is necessary to assess the sustained impact of PBL and mathematical literacy integration over time. Further research should also examine the application of PBL and mathematical literacy in varied educational contexts, including younger learners, vocational settings, and interdisciplinary STEM environments, and explore long-term and technology-assisted implementations for curriculum development.

4. CONCLUSION

The results of this study indicate that the Problem-Based Learning (PBL) model significantly improves students' ability to solve environmental pollution problems, particularly among those with high levels of mathematical literacy. These findings also confirm that mathematical literacy acts as a moderating variable that enhances the effectiveness of PBL in contextual learning settings.

The implications of this study offer practical guidance for educators and curriculum designers. Teachers and lecturers are encouraged to deliberately integrate mathematical literacy into problem-based learning approaches to improve students' real-world problem-solving skills. Furthermore, the results can be a reference for developing adaptive, interdisciplinary learning designs, especially in addressing environmental issues requiring critical thinking and data-informed decision-making.

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