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MOOC-Based PBL Model to Improve Chemical Literacy Skills In Content, Procedural and Epistemic Knowledge Aspects

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ABSTRACT

This study explores the effectiveness of a MOOC-based Problem-Based Learning (PBL) model in enhancing chemical literacy across three dimensions—content, procedural, and epistemic knowledge—among grade 10 high school students. Employing an explanatory sequential mixed-methods design, the research gathered data through chemical literacy tests, interviews, and observations. The participants comprised 80 students from three districts in Central Java, Indonesia. Quantitative analysis using Rasch modeling revealed a significant improvement in scores, with an average pretest score of 44.82 increasing to 66.50 post-intervention. The effect size of 1.1819 was categorized as "good," indicating the model's potential for fostering learning. However, the average posttest score remained below the minimum completion criterion of 75.80. Qualitative findings highlighted weaknesses in the problem orientation stage of the PBL model, particularly in connecting students' prior knowledge to new learning objectives. This stage is critical for setting the foundation for subsequent PBL phases, suggesting that insufficient scaffolding may have hindered optimal learning outcomes. To enhance the effectiveness of MOOC-based PBL, the study recommends restructuring the problem orientation stage to align better with students' initial knowledge levels. These findings underscore the promise of integrating MOOC-based PBL in chemistry education while emphasizing the need for refinements to address identified challenges. By bridging gaps in problem orientation and fostering deeper connections between prior and new knowledge, this approach could more effectively support the development of chemical literacy, providing valuable insights for educators and policymakers.

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1. INTRODUCTION

As a branch of natural science, chemistry has extensive daily applications. Beyond its contributions to material production and engineering for practical use, a deep understanding of chemistry is pivotal for sustainable living and addressing global challenges (Wang et al., 2018). Chemical literacy, which encompasses the ability to understand chemical concepts, apply them in everyday life, and make informed decisions on chemistry-related issues, is a critical competency. In an increasingly complex world, chemical literacy is essential for navigating and resolving various societal challenges (Eilks & Hofstein, 2013).

To promote chemical literacy, chemistry education must integrate theoretical concepts with pressing global issues such as environmental degradation and sustainability. Educators worldwide have widely adopted this approach (Haack & Hutchison, 2016; Nabuasa et al., 2020). However, achieving meaningful and measurable outcomes requires using clear indicators and learning models designed to effectively develop and enhance chemical literacy skills.

Chemical literacy comprises three essential dimensions: content, process, and context (OECD, 2018). The content dimension emphasizes key concepts that enable students to understand natural phenomena and human-induced environmental changes. The process dimension equips students to apply scientific knowledge and reasoning to solve problems effectively (Rahayu, 2015). The context dimension connects scientific principles to real-life issues, encouraging students to utilize their knowledge in addressing practical challenges. Collectively,

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these dimensions empower students to comprehend and tackle everyday problems through the framework of scientific literacy (Celik, 2014).

Innovative learning designs are critical to address the needs of modern education. These designs should incorporate approaches, methods, and strategies that prioritize the development of chemical literacy skills. Emphasizing cognitive engagement and social collaboration, they should enable students to undertake tasks that mirror real-world complexities. Among the numerous pedagogical frameworks available, Problem-Based Learning (PBL) is particularly effective for nurturing critical thinking and problem-solving abilities. By encouraging students to engage deeply with real-world problems, PBL fosters the essential skills required for meaningful learning and application.

This study integrates the MOOC-based Problem-Based Learning (PBL) model to enhance chemical literacy across three dimensions: content, procedural, and epistemic knowledge. Previous research has consistently shown that PBL significantly improves critical thinking skills when applied in traditional classroom settings (Berman & Kuden, 2017; Rillero & Camposeco, 2018). Building on these findings, this study investigates how the flexibility and accessibility of MOOCs can complement PBL to strengthen chemical literacy further.

MOOCs offer students the autonomy to manage their learning while allowing educators to design learning scenarios tailored to the PBL framework (Babori, 2020). Studies have demonstrated that MOOCs enhance students' engagement with module content and improve the clarity of instructional materials (Hamid et al., 2021). Additionally, MOOCs provide diverse and interactive resources—such as videos and animations—that effectively clarify abstract and microscopic concepts, particularly in complex subjects like chemistry and physics (Leito et al., 2015). However, the successful implementation of MOOCs relies heavily on meticulous planning and aligning learning activities with pedagogical goals (Kartimi et al., 2021). Combining PBL's emphasis on critical thinking with MOOCs' interactive and flexible nature, this study aims to provide a transformative approach to advancing chemical literacy.

In Indonesia, the implementation of the "Kurikulum Merdeka" highlights the necessity of incorporating innovative teaching methods such as Problem-Based Learning (PBL) and Project-Based Learning (PjBL) to meet 21st-century educational objectives (McMillan et al., 2019). This curriculum aligns with global trends, emphasizing literacy-focused teaching, especially in the sciences, where chemical literacy is critical (Rahayu, 2015; PISA, 2021; Sothayapetch et al., 2013). Within this framework, the development of problem-solving and critical thinking skills is prioritized as essential elements for fostering well-rounded student growth.

Chemical literacy, a specific domain within scientific literacy, enables individuals to apply scientific knowledge, investigate complex questions, and derive evidence-based conclusions. It is vital to understand natural phenomena and human-induced environmental changes (Rahayu, 2017). While scientific literacy encompasses a broad spectrum of integrative skills, chemical literacy focuses on specialized chemistry-related knowledge essential for students (Kohen et al., 2020). According to Schwartz et al. (2006), chemical literacy comprises four critical aspects: context, knowledge, competence, and attitude. The context addresses local and global challenges like technology, health, and the environment. The knowledge aspect emphasizes foundational concepts and explanatory theories. The competence aspect involves explaining scientific phenomena, designing investigations, and engaging in high-level thinking. Finally, the attitude aspect reflects students' interest in science and their awareness of its societal impact.

Problem-Based Learning (PBL) is a learner-centered pedagogical approach that positions students as active participants in their educational journey. It fosters creativity, collaboration, and critical thinking by engaging students in solving real-world problems (Ulger, 2018). This method promotes scientific literacy by encouraging students to ask meaningful questions, explore diverse solutions, and interact deeply with the subject material. Recent studies highlight PBL's widespread adoption in K-12 education as an effective tool for enhancing critical thinking skills (Rillero & Camposeco, 2018). Furthermore, PBL optimizes scientific literacy by giving students the time and resources to analyze and elaborate on complex problems (Barrett, 2017).

This study seeks to advance chemical literacy among high school students by integrating the accessibility and interactivity of Massive Open Online Courses (MOOCs) with the structured problem-solving approach of PBL. By merging these two innovative methods, the study addresses gaps in existing pedagogical strategies while offering a scalable and impactful solution to modern challenges in chemistry education. This integration provides a dynamic learning environment that equips students with essential skills, bridging theoretical understanding and practical application to prepare them for future scientific and societal demands.

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2. MATERIAL AND METHOD

Research Design

This study employed a pre-experimental, one-group pretest-posttest design to evaluate the impact of a MOOC-based Problem-Based Learning (PBL) model on students' chemical literacy skills. The design involved assessing students' initial knowledge with a pretest, implementing the MOOC-based PBL intervention, and measuring knowledge gains through a posttest. The study adopted a parallel explanatory convergent strategy to provide a comprehensive analysis, integrating quantitative and qualitative data collection methods (Creswell, 2018). The quantitative data offered measurable outcomes of the intervention, while qualitative observations and interviews provided insights into students' engagement and learning processes. The structure of this design, illustrated in Figure 1, demonstrates how these data types were combined to thoroughly analyze the intervention's effectiveness.

This design effectively aligned with the study's objectives by directly measuring knowledge improvements resulting from the intervention. However, the lack of a control group presented a limitation, reducing the ability to compare outcomes with those of students not exposed to the intervention. To address this limitation, triangulation was employed, utilizing multiple data sources such as pretests, posttests, virtual observations, and interviews. This approach enhanced the validity and robustness of the findings, ensuring that the results accurately reflected the impact of the MOOC-based PBL model on students' chemical literacy.

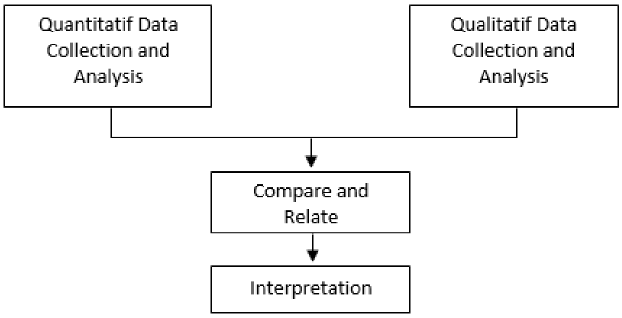

Figure 1. Parallel Explanatory Convergent Research Design

Participants

The study included 80 10th-grade students from three high schools in Central Java, Indonesia, selected based on specific criteria to ensure uniformity and relevance. Schools were chosen using accreditation data from the National Accreditation Board (BAN-PDM), with all three institutions rated "A." This selection ensured comparable educational quality and resources, reducing student baseline performance variability. Participants, aged 15 to 16, came from diverse backgrounds within the selected schools and were distributed as follows: 25 students from SMA (A), 30 from SMA (B), and 25 from SMA (C). The sample comprised 28 male and 52 female students, all enrolled in chemistry courses and demonstrated sufficient digital literacy to use the MOOC platform involved in the intervention. A detailed gender and school distribution of the participants is presented in Table 1. The focus on Central Java was strategic, representing typical Indonesian educational settings with varying levels of technological access. This regional focus provided a context to assess the MOOC-based Problem-Based Learning (PBL) model's effectiveness within Indonesia's "Kurikulum Merdeka." This curriculum emphasizes digital literacy and problem-solving skills, making Central Java a relevant setting to evaluate the model's alignment with national educational goals.

Table 1. Distribution of Respondents Across Schools

Number	School Name	Male	Female	Total
1	SMA (A)	9	16	25
2	SMA (B)	11	19	30
3	SMA (C)	8	17	25
Total		28	52	80

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Instruments

The primary instrument used in this study was a chemical literacy test comprising 45 multiple-choice questions designed to assess students' knowledge across three critical dimensions: content, procedural, and epistemic knowledge. The test was adapted from validated instruments cited in prior studies (Alwathoni et al., 2020b) to comprehensively align with the objectives of comprehensively evaluating chemical literacy. The content knowledge section assessed students' understanding of core chemical principles, including chemical reactions, properties of matter, and the periodic table. The procedural knowledge segment evaluated students' ability to interpret experimental data, apply scientific methods, and predict outcomes in chemical scenarios. Meanwhile, the epistemic knowledge component measured students' comprehension of scientific inquiry, such as evaluating evidence and differentiating between hypotheses and theories.

The test underwent expert review and statistical validation to ensure the instrument's reliability and validity. A panel of chemistry educators reviewed the questions to confirm alignment with chemical literacy constructs. Additionally, the test demonstrated high internal consistency, with a Cronbach's alpha score exceeding 0.85. This rigorous validation process ensured that the test was robust and capable of capturing nuanced insights into students' competencies across all dimensions of chemical literacy

Procedure

The research procedure followed a structured step-by-step approach to ensure systematic implementation and accurate data collection. Initially, students completed a pretest administered online via the MOOC platform to establish a baseline for their chemical literacy skills across content, procedural, and epistemic domains. The intervention phase applied a MOOC-based Problem-Based Learning (PBL) model over eight weeks, following the established PBL syntax. This phase consisted of five stages: problem orientation, student organization, individual and group investigation, presentation, and analysis and evaluation.

In the problem orientation stage, students were introduced to real-world chemical problems, such as environmental pollution and sustainable energy solutions, to spark interest and stimulate critical thinking. Participants were divided into virtual groups during the student organization phase to encourage collaboration and peer interaction. The investigation stage facilitated individual and group research, supported by resources available on the MOOC platform, including videos, animations, and digital reading materials. Students participated in discussion forums to share findings, exchange ideas, and seek clarification to deepen their understanding. In the presentation phase, groups showcased their findings to peers and instructors, receiving constructive feedback to refine their conclusions. Finally, the analysis and evaluation stage enabled students to reflect on their learning journey, link their findings to real-world applications, and connect their results to the assessed dimensions of chemical literacy.

After the intervention, students completed a posttest, identical to the pretest, to evaluate knowledge gains and determine the effectiveness of the intervention. In addition, a subset of students participated in semi-structured interviews to explore their experiences with the MOOC-based PBL model. The interview questions focused on their engagement with MOOC resources, the dynamics within their collaborative groups, and their overall impressions of the problem-based learning approach. Virtual observations were conducted via the Moodle platform to enrich the qualitative data further. These observations captured real-time interactions, contributions during group discussions, and engagement with learning activities.

Despite the comprehensive design, the virtual nature of the study posed challenges, including inconsistent internet connectivity and varying levels of digital literacy among students. These issues were mitigated through detailed user guides and troubleshooting sessions to provide technical support and ensure students were adequately equipped to participate effectively in the program. These measures helped maintain the integrity of the research process and supported participants in navigating the virtual learning environment.

Data Analysis

The study employed quantitative and qualitative data analysis techniques to fully understand the intervention's impact. Quantitative data, derived from pretest and posttest scores, were analyzed using **paired t-tests** to assess the statistical significance of observed changes in chemical literacy. To quantify the magnitude of these changes, **Cohen's d** was calculated, with values above 0.8 interpreted as large effect sizes. Additionally, **Rasch modeling** was applied to evaluate item difficulty and student performance trends, providing deeper insights into the alignment between test items and student abilities (Sumintono, 2018).

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Qualitative data from interviews and virtual observations were analyzed through thematic coding, identifying key themes such as student engagement, collaboration, and problem-solving approaches. The findings were triangulated with quantitative results to ensure consistency and depth. This mixed-methods approach enabled the study to measure improvements in chemical literacy while exploring the nuanced experiences of students engaging with the MOOC-based PBL model. By integrating quantitative and qualitative data, the study provided a comprehensive perspective on the intervention's effectiveness and highlighted its potential for broader application in similar educational contexts.

3. FINDINGS

The findings of this study underscore the effectiveness of the MOOC-based Problem-Based Learning (PBL) model in improving students' chemical literacy. The pretest and posttest data analysis revealed substantial knowledge gaps before the intervention, which were significantly addressed through the structured PBL approach. Qualitative observations further enriched the results, providing insights into students' engagement and the processes contributing to their improved understanding and application of chemical concepts. The study demonstrates the model's capacity to foster meaningful learning outcomes in diverse educational settings.

Pretest Result

The pretest results revealed considerable gaps in students' chemical literacy before implementing the MOOC-based PBL model. The average pretest score across all three schools was 44.82, indicating a generally low understanding of chemical concepts. Standard deviations varied moderately, ranging from 14.91 in School C to 17.95 in School A, reflecting differences in student performance. The lowest recorded score was 9.00, particularly in School A, indicating that some students lacked almost any foundational knowledge of chemistry. Conversely, the highest score of 78.00 in School C suggests that a small subset of students had comparatively stronger prior exposure or understanding of chemical literacy, emphasizing the diversity in baseline knowledge levels among participants.

Table 2. Pretest Scores for Chemical Literacy Abilities

Information	School A	School B	School C	Total
Number of Respondents	25	30	25	80
Average	45.60	44.50	44.36	44.82
Standard Deviation	17.95	17.73	14.91	-
Minimum Score	9.00	22.00	18.00	-
Maximum Score	76.00	76.00	78.00	-

The data point to systemic challenges in foundational chemical education, further amplified by the shift to online learning during the COVID-19 pandemic. Contributing factors include limited access to digital resources, inadequate teacher preparedness for virtual instruction, and disruptions in traditional classroom engagement. These challenges hindered the consistent delivery of chemistry education, resulting in gaps in students' foundational knowledge. The observed variability in scores across schools underscores disparities in learning environments, access to quality instruction, and the availability of supportive resources, highlighting the unequal impact of the pandemic on educational outcomes.

Further analysis of the pretest results, utilizing a Wright Map as depicted in Figure 2, offers valuable insights into the alignment between student abilities and test item difficulties. The Wright Map visually represents student abilities on the left and item difficulties on the right, allowing for a comparative analysis. The findings indicate that only 32.5% of students scored in the upper logit range, highlighting that the majority faced challenges even with moderately difficult questions. This struggle was especially pronounced in epistemic knowledge questions, which demand advanced reasoning and a thorough understanding of scientific inquiry processes (Prandika & Amrullah, 2021). These results underscore the need for targeted instructional strategies to address gaps in higher-order cognitive skills essential for chemical literacy.

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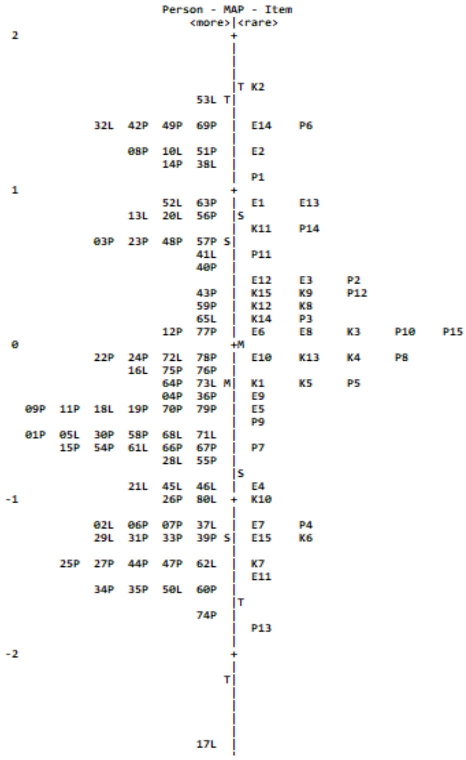

Figure 2. Wright Map of Pretest Result

The Wright Map highlights a significant clustering of students at the lower end of the ability scale, with only a few achieving scores in the upper logit range. Item K2, which evaluated the scientific process of systematically acquiring knowledge through evidence, emerged as the most challenging among the test items. This item required students to identify the correct response, "The scientific process for obtaining knowledge systematically is through physical evidence or facts," from a set of distractors that included unsupported claims or less rigorous scientific methods. The high placement of Item K2 on the difficulty scale underscores its complexity and reveals gaps in students' understanding of core epistemic principles, particularly their grasp of systematic scientific inquiry.

The low average scores across schools highlight significant gaps in students' foundational understanding of chemistry, impeding their ability to comprehend complex concepts and engage in scientific reasoning. The wide score range, with some students achieving near-zero results, reflects stark disparities in educational quality and access to resources. Analysis using the Wright Map reveals that students struggled most with epistemic knowledge, which requires logical reasoning, justification of scientific processes, and critical evaluation of evidence. For instance, the difficulty of question **K2**, which assessed familiarity with the scientific method and the role of evidence in knowledge construction, underscores the inadequacy of traditional instructional methods in fostering higher-order cognitive skills.

Disparities in scores between schools and within classrooms further point to unequal access to quality education. Schools with better resources and more experienced educators provided stronger foundational instruction, while others struggled, particularly during the disruptions caused by the COVID-19 pandemic. The challenges of remote learning exacerbated existing inequities in chemical literacy, as many students lacked reliable internet access, digital devices, and interactive learning materials, leading to reduced engagement and knowledge retention. Often unprepared for the rapid transition to online platforms, teachers faced challenges in delivering effective instruction, leaving many students underprepared for advanced learning.

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Posttest

The post-test results demonstrated significant improvements in students' chemical literacy after implementing the MOOC-based Problem-Based Learning (PBL) intervention. The overall average score increased to 66.50, reflecting a 32.60% improvement from the pretest average of 44.82, emphasizing the intervention's effectiveness in enhancing students' understanding and application of chemical concepts and processes.

Improvements were consistent across all three schools, with the highest average score in School B at 67.30, School A at 66.80, and School C at 65.40. The relatively narrow range of scores across schools indicates the intervention's uniform impact, regardless of contextual differences. Additionally, standard deviations ranging from 13.00 to 14.08 highlight reduced variability in student performance compared to the pretest, suggesting the intervention successfully addressed knowledge disparities among diverse student groups. A notable improvement was observed in the minimum score, which rose to 40.00 from the pretest's lowest score of 9.00, demonstrating the intervention's capacity to uplift low-performing students. Similarly, the maximum score increased to 91.00, compared to the pretest high of 78.00, indicating substantial gains for high-performing students. These findings affirm the PBL approach's potential to benefit students across the performance spectrum.

Table 3. Postest Scores for Chemical Literacy Abilities

Information	School A	School B	School C	Total
Number of Respondents	25	30	25	80
Average	66.80	67.30	65.40	66.50
Standard Deviation	14.08	13.00	13.74	-
Minimum Score	40.00	44.00	42.00	-
Maximum Score	89.00	89.00	91.00	-

The data in Table 3 highlight the effectiveness of the MOOC-based PBL model in driving substantial and consistent improvements across all schools. The notable increases in minimum scores demonstrate that students who initially struggled with basic chemical concepts were able to achieve foundational competence. Similarly, the rise in maximum scores underscores the intervention's success in challenging high-performing students, enabling them to attain advanced levels of understanding and applying chemical literacy.

Furthermore, the reduced standard deviations across schools indicate a narrowing of performance gaps, emphasizing the equitable nature of the intervention. This consistency suggests that the MOOC-based PBL model supports diverse learners and ensures that improvements are evenly distributed, regardless of initial performance levels. By fostering foundational competence and advanced understanding, the intervention proves its potential as a versatile and inclusive approach to enhancing chemical literacy.

To confirm the significance of these improvements, a paired samples t-test was conducted, and the results, presented in **Table 4**, provide robust statistical evidence supporting the impact of the MOOC-based PBL intervention. The mean difference between pretest and posttest scores was calculated as **-23.062**, with a standard deviation **5.616**. A t-value of **-23.22** was obtained, accompanied by a highly significant p-value of **0.000**.

These findings confirm that the observed improvements in students' chemical literacy were not due to random variation but were directly attributable to the intervention. The statistical significance of these results underscores the effectiveness of the MOOC-based PBL model in enhancing students' understanding and application of chemical concepts, providing a reliable basis for its potential broader implementation.

Table 4. Paired Sample T-Test Result

Paired Difference	Mean	Std. Dev	t	df	Sig (2-tailed)
Pretest - Posttest	-23.062	5.616	-23.22	79	0.000

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The statistical validation presented in Table 4 confirms that the improvements in students' chemical literacy were substantial and meaningful. The large mean difference highlights the effectiveness of the intervention, demonstrating significant gains in students' understanding and application of chemical concepts. Additionally, the narrow standard deviation of the differences indicates consistent benefits across the sample, suggesting that the intervention's impact was equitable and not confined to a specific subset of students.

The highly significant p-value further reinforces the reliability of these findings, eliminating the possibility that the observed improvements were due to random variation. These results validate the MOOC-based PBL approach as a robust and effective educational tool capable of enhancing chemical literacy consistently across diverse student groups.

The uniformity in average post-test scores across the three schools underscores the effectiveness of the MOOC-based PBL intervention in diverse educational contexts, highlighting its adaptability and potential for broader implementation. The dramatic increase in minimum scores, from 9.00 to 40.00, demonstrates the intervention's success in helping students with initially low chemical literacy achieve foundational competence. Simultaneously, the rise in maximum scores to 91.00 reflects the intervention's capacity to challenge high-performing students, encouraging engagement with more advanced concepts.

The reduced standard deviations further indicate that the intervention narrowed performance gaps, fostering a more equitable learning environment. The paired samples t-test results provide robust statistical evidence of the intervention's significant impact, ensuring the observed improvements are valid and reliable. Supported by detailed analyses in Table 3 and Table 4, the findings highlight the MOOC-based PBL model's success in enhancing students' chemical literacy. This approach increased overall performance and addressed equity by uplifting underperforming students while challenging high achievers. The strong statistical validation reinforces its potential as a scalable and effective solution for improving chemical literacy in varied educational settings.

Effect Size

The effect size analysis demonstrates the substantial impact of the MOOC-based Problem-Based Learning (PBL) intervention on students' chemical literacy. As detailed in Table 5, the calculated effect sizes across the three schools were all categorized as large, highlighting the intervention's consistent and meaningful benefits.

Effect sizes ranged from **1.**0823 in School B to 1.3452 in School C, with School C exhibiting the strongest response to the intervention, reflecting its significant influence on students' learning outcomes. School A recorded an effect size of **1.1819**, further underscoring the intervention's effectiveness in fostering chemical literacy. These values, derived using Cohen's d, confirm the intervention's robust positive impact, regardless of initial knowledge levels or contextual differences among the schools. This analysis affirms the MOOC-based PBL model as a powerful tool for advancing educational outcomes in diverse learning environments.

Table 5. Effect Size for Chemical Literacy Abilities

School Name	Effect Size	Criteria
School A	1.1819	Large
School B	1.0823	Large
School C	1.3452	Large

The consistently large effect sizes across all schools affirm the effectiveness of the MOOC-based PBL model in improving chemical literacy. The slightly higher effect size observed in School C may be attributed to factors such as enhanced student engagement, more seamless integration of the MOOC platform, or more effective teacher facilitation during the intervention. These uniformly high effect sizes underscore the scalability of the MOOC-based PBL approach and its potential for broader implementation across diverse educational

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settings, demonstrating its adaptability and efficacy in varied learning environments.

The large effect sizes across all three schools demonstrate the consistent effectiveness of the MOOC-based PBL intervention, irrespective of contextual variations such as location, resources, or students' initial abilities. The highest effect size of 1.3452 in School C suggests that factors like greater teacher involvement, higher student engagement, or smoother integration of the PBL model may have amplified the benefits for this group.

Effect sizes exceeding the 1.0 threshold in all schools confirm that the MOOC-based PBL model delivered gains far beyond those typically expected from standard instructional methods. This highlights its transformative potential as a tool for enhancing chemical literacy. The detailed analysis in Table 5 provides compelling evidence of the intervention's substantial and widespread impact. The consistently large effect sizes across diverse contexts reinforce the scalability and validity of this approach, establishing it as a powerful model for improving chemical literacy in varied educational settings (Alwathoni et al., 2020a).

Qualitative Observations

Qualitative observations revealed significant insights into the implementation and impact of the MOOC-based Problem-Based Learning (PBL) model on student engagement. The intervention engaged students through the structured five-stage PBL framework delivered via the Moodle platform. These stages—problem orientation, student organization, investigation, presentation, and evaluation—successfully fostered participants' collaboration, critical thinking, and problem-solving skills. The alignment of these stages with established PBL principles highlights the model's ability to actively involve students in meaningful and interactive learning processes (Arends, 2012; Alwathoni et al., 2020a).

Students accessed the MOOC platform via a user-friendly login interface, as shown in Figure 3. The platform's design facilitated sequential learning, enabling students to systematically navigate the Problem-Based Learning (PBL) stages. This structured approach ensured clarity and guided students in focusing on their learning objectives, promoting an organized and goal-oriented learning experience.

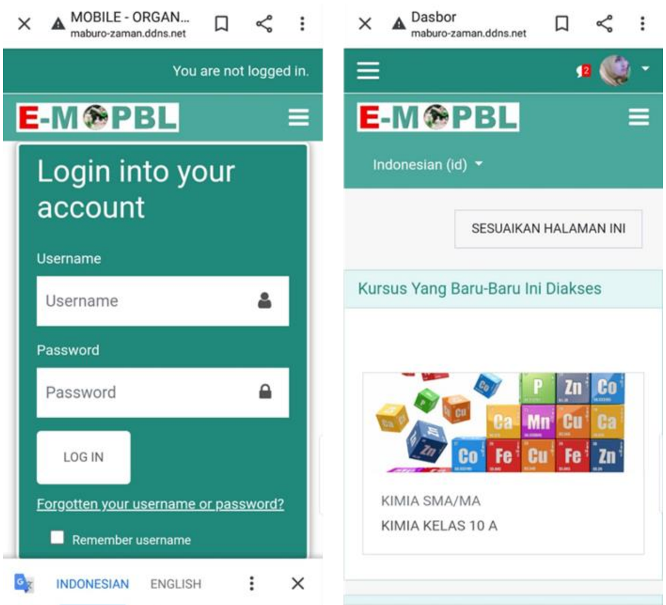

Figure 3. Screenshot of the MOOC-Based PBL Login Page

The MOOC platform proved highly effective in facilitating group discussions and collaborative activities, fostering active student participation. Virtual observations revealed consistent engagement, with most students logging in regularly and utilizing the available resources and activities. However, technical challenges, such as

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occasional navigation difficulties and issues with uploading assignments, were highlighted in student feedback. These challenges underscore the importance of further optimizing the platform to enhance user experience and ensure seamless participation.

The problem orientation stage, depicted in Figure 4, effectively engaged students in exploring real-world challenges, such as rising sea levels and their implications for sustainability. These discussions were conducted through Zoom and seamlessly integrated with the MOOC platform, enabling dynamic and interactive learning experiences. Students responded enthusiastically to multimedia resources, including videos and narratives, which added context and relevance to the problems being addressed. This approach fostered a deeper understanding and connection to the material, enhancing their engagement.

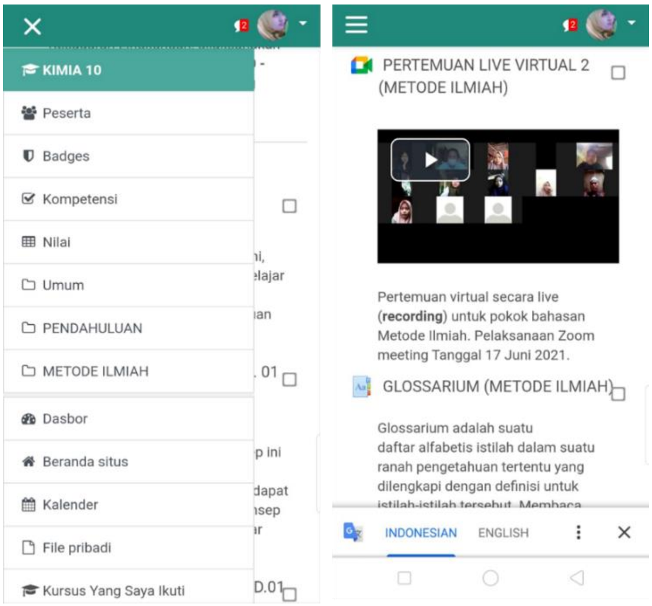

Figure 4. Problem Orientation Stage via Zoom

While most students actively participated in discussions during the problem orientation stage, some encountered difficulties connecting the presented challenges with their prior knowledge. This issue was more pronounced among students with weaker foundational understanding, emphasizing the need for additional scaffolding. Pre-orientation activities, such as concept-mapping exercises or brief primers, could bridge this gap and better prepare students for the learning process.

During the investigation stage, students collaborated in virtual groups to explore resources and develop solutions to the assigned problems. The platform's discussion forums and document-sharing tools facilitated effective communication, while teachers actively guided discussions and ensured that students remained focused.

In the reporting stage, student presentations showcased creativity and critical thinking. Groups presented their findings using various formats, including PowerPoint slides and videos. These presentations were evaluated by peers and teachers, fostering an environment of constructive feedback and reinforcing students' understanding of the material. This process encouraged active participation and enhanced students' collaborative and analytical skills.

4. Discussion

Effectiveness of the MOOC-Based PBL Model

The findings from the post-test scores highlight the significant effectiveness of the MOOC-based Problem-Based Learning (PBL) model in improving students' chemical literacy. With an average score increase of

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32.60%, the intervention effectively addressed foundational gaps in chemical literacy while fostering higher-order thinking skills. Consistently large effect sizes, ranging from 1.0823 to 1.3452, underscore the intervention's meaningful and statistically significant impact across diverse educational settings. These results validate the MOOC-based PBL approach as a robust and adaptable educational tool for enhancing students' understanding and application of chemical concepts (Qin et al., 2016).

The structured stages of the PBL model (problem orientation, investigation, group discussions, presentations, and evaluations) were pivotal in achieving significant learning outcomes. These stages promoted active learning and deep engagement with chemical concepts. During the problem orientation stage, students delved into real-world challenges such as rising sea levels, contextualizing their learning and enhancing their motivation to bridge theoretical knowledge with practical applications, as supported by Hendarwati et al. (2021). This approach strengthened their understanding and encouraged a more meaningful connection to the subject matter.

The MOOC platform provided a collaborative and inquiry-driven environment, leveraging features such as discussion forums and multimedia resources to foster student interaction and teamwork. These tools enabled students to collaboratively investigate problems, share solutions, and engage in reflective learning processes. The group discussions cultivated critical thinking and teamwork. At the same time, presentations and evaluations reinforced learning through articulation and feedback, aligning with Dost et al. (2020), who emphasize the effectiveness of integrating PBL within online platforms to improve motivation and outcomes. Furthermore, the adaptability of the MOOC-based PBL model during the COVID-19 pandemic highlights its flexibility and scalability. Karahan et al. (2022) noted that transitioning PBL to online formats ensured educational continuity, reinforcing the model's potential as a resilient approach for modern education systems (Saqr et al., 2020; Alwathoni et al., 2020a).

The large effect sizes observed across all schools underscore the MOOC-based PBL model's scalability and robustness. School C, which recorded the highest effect size (1.3452), illustrates how effective teacher facilitation and heightened student engagement can enhance the model's impact. These results emphasize optimizing implementation strategies to harness the model's potential and fully maximize educational outcomes.

The MOOC-based PBL model proved significantly effective in improving chemical literacy by fostering active engagement, collaboration, and the practical application of knowledge. Its integration with digital platforms enhanced accessibility and adaptability, effectively addressing challenges posed by the pandemic and providing a sustainable approach for future education. These findings align with the broader goals of equipping students for collaborative and real-world problem-solving scenarios, as highlighted by Yin and Zhang (2023). Refining pre-orientation scaffolding and addressing technical limitations will be critical to enhance further the efficacy and reach of this innovative educational framework.

Challenges in Problem Orientation

While the MOOC-based Problem-Based Learning (PBL) model demonstrates significant promise in enhancing chemical literacy, the problem orientation stage posed notable challenges. Virtual observations indicated that while many students actively engaged in discussions, a significant portion struggled to relate new problems to their prior knowledge. The Wright Map analysis (Figure 2) highlighted the difficulty of epistemic questions, underscoring deficiencies in students' foundational understanding of scientific processes. These findings emphasize the necessity of implementing additional scaffolding strategies, such as pre-orientation activities or advanced organizers, to better prepare students for the cognitive demands of problem-solving tasks (Yang et al., 2021).

Research highlights the inherent complexity of online group discussions, where additional time and more detailed explanations are often required compared to face-to-face interactions. Lytovchenko et al. (2022) noted that online discussions demand greater cognitive effort, as students must articulate their ideas explicitly,

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lacking immediate feedback or non-verbal cues to aid communication. This increased cognitive load can be especially challenging for students with weaker foundational knowledge, exacerbating their struggles to integrate new concepts with prior understanding. Such challenges underscore the need for targeted support mechanisms to facilitate more effective online learning experiences (Alwathoni et al., 2020a).

Moreover, observations during the problem orientation phase align with broader research emphasizing the importance of planning and support in online PBL environments. Teachers play a crucial role in facilitating discussions; however, many educators encounter challenges such as insufficient preparation time and ineffective instructional modeling. Yang et al. (2021) suggest that connecting educators with experienced PBL practitioners can foster a supportive community, offering valuable insights and strategies to enhance student readiness for PBL activities.

Addressing these challenges requires targeted interventions to improve the problem orientation phase. Pre-orientation scaffolding, such as concept mapping and structured review sessions, can help students bridge the gap between their prior knowledge and new problems. This preparation equips students to engage more confidently in discussions and problem-solving tasks, leading to better learning outcomes. Additionally, integrating interactive tools and real-time feedback mechanisms within the MOOC platform can alleviate difficulties associated with online discussions. Features like live Q&A sessions or automated feedback for initial problem responses can provide timely support, enabling students to effectively address knowledge gaps during the PBL process's early stages.

While the problem orientation stage presents significant challenges, these obstacles are addressable through scaffolding techniques and enhanced educator collaboration. By implementing these measures, educators can better support students in connecting prior knowledge with new concepts, thereby strengthening the overall effectiveness of the MOOC-based PBL model. This approach improves the problem orientation stage and amplifies the model's impact on developing critical thinking and problem-solving skills.

Engagement with Epistemic Knowledge

The findings from the Wright Map analysis (Figure 2) underscore the significant challenges students face with epistemic knowledge, as only 32.5% performed in the upper logit range. This indicates substantial difficulty with questions requiring higher-order reasoning skills, aligning with existing research identifying epistemic knowledge as a demanding cognitive domain that necessitates explicit instruction (Cunningham & Kelly, 2017). Epistemic knowledge involves understanding how knowledge is acquired, justified, and critically evaluated—skills fundamental to scientific literacy and critical thinking (Brownlee et al., 2022). The complexity of these tasks underscores why students often struggle without targeted instructional support.

To address these challenges, instructional strategies must emphasize enhancing epistemic reasoning abilities. For example, integrating critical evaluation exercises can help students assess the validity and reliability of scientific information, promoting a deeper understanding of methodologies and data interpretation (Campbell & Carayannis, 2016). Such activities encourage analytical thinking and improve students' capacity to evaluate how knowledge is constructed and applied. Additionally, embedding tasks emphasizing scientific methodologies and evidence-based reasoning can further strengthen students' abilities to analyze and synthesize information, enhancing their performance on assessments of epistemic knowledge (Sertler, 2020). These targeted strategies support epistemic learning and contribute to broader gains in scientific literacy and critical thinking.

Incorporating epistemic tools into the curriculum offers significant potential to foster deeper engagement and improve students' epistemic cognition. Research indicates that such tools, which help students visualize and interact with knowledge processes, enhance their ability to understand and critically evaluate scientific information (Kelly & Cunningham, 2019). For instance, in engineering education, epistemic tools have been shown to mediate the learning process, enabling students to approach complex problems with greater confidence and clarity. Applying these tools within the MOOC-based PBL framework could create a more

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interactive and supportive learning environment, encouraging students to engage actively with challenging epistemic tasks.

Pre-orientation scaffolding activities, such as concept mapping and structured review sessions, can also prepare students to connect prior knowledge with new epistemic concepts. This preparation reduces the cognitive load associated with epistemic reasoning and enhances students' readiness for critical thinking and problem-solving. Furthermore, integrating immediate feedback mechanisms into the MOOC platform could provide students timely guidance and reinforcement, ensuring they remain on track while navigating complex content.

In summary, addressing the challenges of engaging with epistemic knowledge requires targeted instructional strategies and tools to enhance student's critical thinking and understanding of scientific processes. Activities such as critical evaluation exercises and exploring scientific methodologies, combined with epistemic tools and scaffolding, can significantly improve students' engagement and proficiency in this demanding cognitive domain. These interventions are essential for equipping students with the skills necessary to meet the challenges of scientific literacy and higher-order thinking.

Students Feedback and Practicality of the System

Student feedback on the MOOC platform underscored its practicality and accessibility, particularly in providing digital resources for learning. As illustrated in Figure 3, the platform's user-friendly interface enabled students to easily navigate sequentially organized learning steps. However, challenges such as difficulty submitting assignments and a notable preference for printed materials (as indicated in Table 3) highlight areas requiring refinement to improve user experience and educational effectiveness.

Research suggests that blending digital tools with traditional learning methods can address these challenges and enhance learning outcomes. While students valued the convenience and flexibility offered by the MOOC platform, they expressed a need for more interactive and engaging elements similar to face-to-face learning experiences. Edgington and Holbrook (2010) emphasize that students in blended learning environments benefit from in-person discussions and hands-on activities, which foster a deeper understanding of course materials. Likewise, Korkealehto et al. (2021) observed that oral interaction and engagement improved significantly when classroom-based activities complemented digital learning. These findings align with the students' feedback, suggesting that a hybrid approach combining digital and traditional methods, as supported by Kahveci and Orgill (2015), could enhance the overall learning experience by integrating the strengths of both modalities.

Moreover, the logistical difficulties faced by some students in navigating the digital platform underscore the need for robust instructional design that accommodates diverse learning preferences. Uz and Uzun (2018) highlighted that the success of blended learning lies in effectively integrating online and face-to-face components to engage learners actively. This integration can address practical issues, such as submission errors while fostering a more interactive and supportive learning environment tailored to individual needs.

Blended learning strategies also promote self-regulated learning by enabling students to take greater ownership of their educational journey. Yudhana (2021) demonstrated that blended approaches significantly enhance students' reading and comprehension skills, showcasing their potential to meet varied educational requirements. By combining the accessibility and flexibility of MOOC platforms with the personalized interaction of traditional teaching methods, educators can create a holistic and effective learning experience. While the MOOC platform offers substantial benefits in terms of accessibility and resource availability, integrating blended learning approaches is essential to address student concerns and maximize engagement. By merging the strengths of digital and in-person learning, educators can enhance the practicality, inclusivity, and overall effectiveness of the MOOC-based PBL system, ensuring improved academic outcomes and heightened user satisfaction.

Statistical Significance and Effectiveness

The statistical analysis confirmed the significant effectiveness of the MOOC-based Problem-Based Learning (PBL) model in enhancing students' chemical literacy. The paired samples t-test results (Table 4) demonstrated a highly significant improvement, with a p-value of 0.000, affirming the robustness of the findings.

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The intervention yielded an average posttest score increase of 32.60% across all schools, effectively addressing foundational gaps in chemical literacy. Additionally, the large effect sizes reported across schools (Table 5), ranging from 1.0823 to 1.3452, further validate the substantial and consistent impact of the MOOC-based PBL intervention on student learning outcomes (Kahveci & Orgill, 2015). These findings underscore the efficacy of this approach as a transformative tool in chemistry education.

This effectiveness aligns with prior research highlighting the transformative potential of digital learning environments to improve educational outcomes. Febrian et al. demonstrate that MOOCs provide accessible and flexible learning opportunities tailored to diverse student needs, making them an ideal platform for implementing Problem-Based Learning (PBL). By integrating digital tools within the MOOC framework, this approach fosters self-directed learning while providing the structure necessary to guide students through complex concepts. Furthermore, Azzahro et al. (2023) underscore the importance of digital literacy in enhancing cognitive learning outcomes, further validating the utility of MOOC-based PBL in modern education (Arends, 2012).

The systematic design of the PBL stages (problem orientation, investigation, group discussions, presentations, and evaluations) was pivotal in the improvements. These stages developed critical thinking and problem-solving skills by immersing students in deep engagement with scientific concepts and their real-world applications. The intervention's structured yet flexible framework enabled students to explore and apply knowledge collaboratively, fostering a supportive learning environment. The MOOC platform's accessibility and collaborative features were instrumental in achieving these educational gains, underscoring its effectiveness in enhancing critical thinking and chemical literacy.

However, refining digital resources and instructional strategies is crucial to optimize the learning experience further. Automated feedback, interactive assessments, and pre-orientation scaffolding could bridge initial knowledge gaps and maintain sustained student engagement throughout the learning process. These enhancements would significantly amplify the scalability of the MOOC-based PBL model, making it an even more robust tool for advancing scientific literacy across diverse educational contexts.

The statistical significance of the results and the large effect sizes validate the effectiveness of the MOOC-based PBL model as a scalable and impactful approach to enhancing chemical literacy. This model addresses foundational learning deficits and equips students to navigate the complexities of modern scientific inquiry and critical thinking. Future implementations should prioritize refining the digital infrastructure and integrating blended learning opportunities to maximize educational outcomes further and broaden the model's applicability.

5. CONCLUSION

Online learning cannot fully replicate the benefits of face-to-face classroom learning, where direct social interaction, clear instructions, collaboration, and real-time discussions significantly enhance the learning process by helping students receive information and construct knowledge effectively. However, the demands of future learning necessitate robust integration with information technology. The Problem-Based Learning (PBL) model has proven effective in empowering chemical literacy skills by fostering elaboration, evaluation, exploration of learning resources, and collaborative problem-solving. Traditionally, PBL has been confined to in-class applications, but this study provides empirical evidence that PBL can be successfully implemented online using a MOOC-based approach. This study demonstrates that the sequential and systematic arrangement of PBL learning steps on a MOOC platform allows students to access learning resources independently and interact virtually to complete assignments. The findings confirm that MOOC-based PBL significantly enhances chemical literacy across content, procedural, and epistemic knowledge dimensions. However, the improvements, while notable, are not yet extraordinary. A critical recommendation is strengthening the problem orientation stage by ensuring a well-structured learning organization that connects students' prior knowledge with new concepts. Looking ahead, MOOC-based PBL can be integrated into blended learning models, combining online and face-to-face sessions to reinforce and deepen the knowledge acquired during classroom activities.

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