An empirical and theoretical investigation using PBL: Students' mental models in understanding capillary rise

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Abstract
Students' low achievement and persistent misconceptions in physics, particularly on capillary rise phenomena, suggest that conventional instruction is often insufficient for developing scientifically accurate mental models. Understanding capillary rise requires students to connect microscopic interactions, such as adhesive and cohesive forces, with observable macroscopic phenomena. Although this concept is important in physics and closely related to everyday experiences, research investigating students' mental models of capillary rise remains limited, especially within Problem-Based Learning (PBL) contexts. Previous studies have focused mainly on conceptual understanding and learning outcomes rather than on the development of topic-specific mental models. This study aimed to examine the effect of PBL on students' mental models of capillary rise concepts. A quasi-experimental method with a pretest–posttest non-equivalent control group design was employed. Participants were 78 eleventh-grade science students from two public senior high schools in Central Maluku, Indonesia, divided equally into an experimental group and a control group. Data were collected through mental model tests, interviews, and classroom observations. Quantitative data were analyzed using Analysis of Covariance (ANCOVA). The results showed a significant effect of the instructional model on students' mental models ($F = 8.793$; $p = 0.004$; Partial $\eta^2 = 0.116$). Students who learned through PBL demonstrated greater improvement in constructing scientifically appropriate mental representations than those who received conventional instruction. These findings indicate that PBL promotes active engagement in problem-solving and collaborative inquiry, enabling students to build and refine conceptual understanding. This study contributes to physics education research by providing empirical evidence that problem-based learning supports the development of meaningful mental models in conceptually complex physics topics such as capillary rise.

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1. Introduction

Over the past three decades, various studies have identified and proposed explanations for students' misconceptions regarding physical phenomena (Babari et al., 2023). This issue has become a global concern because it contributes to low student achievement in science, particularly physics education at the secondary school level (Barmby et al., 2008; Oon & Subramaniam, 2011; Keller et al., 2017). Several international studies have reported declining student performance and reduced interest in physics learning. This condition has implications not only for academic achievement but also for students' future career pathways in science and technology-related fields (Taangahar et al., 2021; Othoo, 2019). In higher education contexts, challenges are also reflected through high dropout rates and increased stress among physics students (Lahme et al., 2024). Such findings indicate that difficulties in understanding physics concepts remain a persistent issue across different educational levels (Belay, 2025; Kotsis, 2026).

This condition is often associated with traditional teaching practices that focus primarily on information delivery while paying insufficient attention to students' prior conceptions and cognitive structures (Kwarikunda et al., 2020). As a result, students tend to retain intuitive ideas that are inconsistent with scientifically accepted explanations (Hull et al., 2021; Batlolona, 2025). Previous studies suggest that even after formal instruction, many students continue to maintain alternative conceptions or misconceptions alongside scientific concepts (Meltzer, 2004; Batlolona et al., 2024).

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Furthermore, Buabeng et al. (2014) emphasized that teaching quality and instructional approaches significantly affect students' conceptual understanding and learning outcomes. Therefore, selecting effective instructional approaches becomes crucial for improving students' understanding and minimizing misconceptions in physics learning.

One of the concepts frequently associated with misconceptions is capillarity. Capillary phenomena are introduced repeatedly across different educational levels, beginning in elementary education and continuing into secondary and higher education with increasing levels of abstraction and mathematical complexity. Capillary rise is a phenomenon in which liquid moves upward through a narrow tube due to interactions among adhesive forces, cohesive forces, surface tension, viscosity, and gravitational forces. Although this topic has strong relevance to everyday phenomena and various scientific applications, studies consistently report that students experience difficulties in understanding the underlying mechanisms governing capillary action (Erceg et al., 2021). Students frequently rely on memorizing formulas rather than constructing conceptual understanding regarding the interactions among variables involved in capillary phenomena.

From a constructivist perspective, students actively construct knowledge based on prior experiences and cognitive structures. Understanding physical phenomena therefore depends on students' ability to develop and reconstruct mental models. Mental models represent internal cognitive structures that individuals use to explain, predict, and interpret various phenomena (Furlough & Gillan, 2018). During learning processes, students often develop personalized interpretations that differ from scientifically accepted models. Once these conceptions become established, they tend to persist and become difficult to modify. Consequently, identifying and understanding students' mental models becomes essential because they provide insight into students' conceptual understanding and learning difficulties.

To address misconceptions and improve conceptual understanding, constructivist-based instructional models have been increasingly implemented in science education (Qarareh, 2016). One learning approach that has attracted considerable attention is Problem-Based Learning (PBL). PBL promotes active engagement by encouraging students to investigate authentic problems, collaborate with peers, and develop problem-solving skills through meaningful learning experiences (Denizhan, 2020). Previous studies have demonstrated that PBL positively affects students' motivation, critical thinking skills, problem-solving abilities, and conceptual understanding (McCrum, 2017; Salari et al., 2018). Additionally, several studies suggest that PBL contributes to the development of students' mental models in various learning contexts.

However, despite the growing literature regarding PBL and mental models, several important gaps remain. First, previous studies have predominantly focused on general cognitive outcomes, problem-solving abilities, or conceptual achievement, while limited studies have specifically examined the development of students' mental models in physics learning contexts. Second, empirical investigations regarding students' mental models associated with capillary rise concepts remain scarce despite the conceptual complexity of this topic. Third, studies exploring how PBL facilitates the development of students' mental models in understanding capillary phenomena are still limited. Furthermore, the relationship between students' mental models and conceptual understanding within capillarity learning contexts remains insufficiently explored. Therefore, this study aims to investigate the effect of Problem-Based Learning on students' mental models in understanding capillary rise concepts and to analyze the relationship among students' mental models during learning. The findings of this study are expected to contribute both theoretically and empirically to physics education literature by providing a deeper understanding of how PBL can facilitate the development of scientific mental models in conceptually challenging topics.

2. Method

2.1. Research Design

This study employed a quasi-experimental method to investigate the effect of the PBL model on students' mental models. The study utilized a pretest–posttest non-equivalent control group design involving two groups, namely an experimental group and a control group. At the beginning of the study, both groups were administered a pretest to assess students' initial abilities. Furthermore, the experimental group received instruction using the PBL model, while the control group was taught using a conventional learning approach. The research design was adapted from Capili & Anastasi (2025), as presented in Table 1.

Table 1. Pretest–posttest control group research design

Group	Pretest	Treatment	Posttest
Experimental	O_1	X	O_2
Control	O_3	-	O_4

Consistent with the work of Capili & Anastasi (2025), this study adopted a quasi-experimental design, which resembles a true experimental approach but does not require random assignment of participants into experimental and control groups. The design involved two intact groups: an experimental group that received instructional treatment and a control group that underwent regular classroom instruction. This approach enabled the comparison of learning outcomes between groups under naturally existing classroom conditions. In the experimental class, a PBL model integrated with a mental model approach was implemented as the instructional treatment. This student-centered learning approach engaged students in solving authentic and meaningful problems related to real-life situations while facilitating the development and reconstruction of their mental representations of capillary rise concepts. Throughout the learning process, students were encouraged to actively participate in discussions, identify problems, formulate possible explanations, investigate relevant information, and connect new knowledge with their prior cognitive structures. Such learning activities were expected to strengthen students' mental models and promote a deeper conceptual understanding of capillary rise phenomena.

Meanwhile, students in the control group received instruction through a conventional teaching approach characterized by teacher-centered practices. Classroom activities mainly consisted of lectures, direct explanations of concepts, textbook-oriented learning, and teacher-guided question-and-answer sessions. Students generally acquired information directly from the teacher and completed individual exercises based on provided materials, with relatively limited opportunities for collaborative interaction, independent investigation, and active exploration of problems. Unlike the instructional procedures implemented in the PBL class, the conventional approach did not actively engage students in problem identification, hypothesis generation, investigation, or knowledge construction processes. Following the completion of the treatment period, a post-test was administered to both groups to assess students' mental models after the instructional intervention. The comparison of pre-test and post-test results allowed the researchers to determine the effects of the learning models applied to each group. To ensure the quality of the research findings, the study was conducted systematically through several stages, including preliminary preparation, implementation of instructional treatments, and data analysis procedures. Applying these stages carefully is essential to obtaining valid and reliable findings, as data validity and reliability contribute significantly to the credibility and trustworthiness of research outcomes (Oluwatayo, 2012; Karnia, 2024).

2.2. Participants

The participants in this study consisted of 78 eleventh-grade science students (Grade XI IPA) selected from two public senior high schools in Central Maluku, namely SMA Negeri 47 Maluku Tengah and SMA Negeri 6 Maluku Tengah. The participants were divided equally into two groups: 39 students in the experimental class and 39 students in the control class. The average age of the participants was approximately 17 years. The students had completed three semesters of study and possessed relatively similar academic backgrounds. The experimental group received instruction through the PBL model, whereas the control group was taught using a conventional learning approach. The sampling technique used in this study was purposive sampling. This technique was employed because the selection of participants was based on specific criteria relevant to the research objectives. The selected classes had comparable academic characteristics, were at the same educational level, and had similar learning experiences in physics. Since the study adopted a quasi-experimental design, random assignment of students into experimental and control groups was not conducted. Instead, intact classes were selected and assigned as experimental and control groups to maintain naturally existing classroom conditions and ensure the feasibility of the instructional intervention.

2.3. Research Instrument

The primary instrument used in this study was a mental model test designed to assess students' mental models in understanding the concept of capillary rise. The instrument consisted of ten test items developed based on indicators of students' mental model characteristics. The assessment rubric referred to the mental model framework developed by Ifenthaler (2006), which categorizes students' mental models into three levels: surface mental models, matching mental models, and deep mental models. Surface mental models represent limited and fragmented understanding, matching mental models indicate partially appropriate conceptual understanding, while deep mental models reflect comprehensive and scientifically accurate conceptual structures. Prior to implementation, the instrument underwent expert judgment to establish content validity. The validation process involved two experts in theoretical physics and physics education to evaluate the relevance, clarity, and appropriateness of the instrument items. The results of the content validity assessment showed that the instrument met the validity criteria with an average validity score of 0.89, indicating that the instrument was appropriate for use in the study. Furthermore, instrument reliability was examined using Cronbach's Alpha, and the results demonstrated a reliability coefficient of 0.87, indicating that the instrument had an acceptable level of internal consistency and reliability for data collection. In addition to the mental model test, interview guidelines and observation sheets were employed to support data collection and provide a more comprehensive understanding of students' mental model development during the learning process. Interviews were conducted with selected students to clarify their responses and explore their reasoning processes, while observation sheets were used to monitor students' learning activities and participation throughout the instructional implementation.

2.4. Research Procedure

The research procedure in this study was conducted systematically through several stages, including preparation, implementation of treatment, data collection, and data analysis. In the preparation stage, the researchers developed the research instruments, particularly the mental model test used to measure students' mental models regarding the concept of capillary rise. Prior to implementation, the instrument was validated to ensure its validity and reliability. The implementation stage began with administering a pre-test to both the experimental and control groups to determine students' initial mental models. Following the pre-test, the experimental group received instruction using the PBL model, while the control group was taught using a conventional learning approach. During the instructional process, students in the experimental class actively participated in problem identification, discussion, investigation, and problem-solving activities designed to facilitate the development of their mental models. After the completion of the instructional treatment, a post-test was administered to both groups using the same mental model instrument to measure changes in students' mental models after the intervention. The obtained data were then analyzed quantitatively to determine the effect of the PBL model on students' mental models. Prior to hypothesis testing, prerequisite tests, including normality and homogeneity tests, were conducted to ensure that the data met the assumptions for further statistical analysis.

2.5. Data Analysis Techniques

The data obtained in this study were analyzed quantitatively to determine the effect of the PBL model on students' mental models. Descriptive statistical analysis was initially performed to summarize the data, including the mean scores, standard deviation, minimum scores, and maximum scores of both the pre-test and post-test results. Before conducting hypothesis testing, prerequisite analyses were performed to examine whether the data met the required statistical assumptions. A normality test was conducted to determine whether the data were normally distributed, while a homogeneity test was used to examine the equality of variance between the experimental and control groups. The results indicated that the data met the assumptions of normality and homogeneity, allowing further parametric statistical analysis to be performed. To examine the effect of the instructional model on students' mental models while controlling for initial differences between groups, Analysis of Covariance (ANCOVA) was employed using pre-test scores as covariates and post-test scores as dependent variables. Statistical analyses were conducted using SPSS version 23.0 for Microsoft Windows with a significance level of 0.05. The decision criteria for hypothesis testing were based on the significance value (p-value), where a significance value lower than 0.05 indicated that the instructional model had a significant effect on students' mental models.

3. Results and Discussion

The mental model test was administered twice using the same instrument. The first administration was conducted before the treatment was implemented, while the second administration was carried out after the completion of the treatment. The interval between the pre-test and post-test administrations was eight weeks. A summary of the ANCOVA results regarding the effect of the learning model on students' mental models is presented in Table 2.

Table 2. Homogeneity test results using levene's test

Levene's Test of Equality of Error Variancesa
Dependent Variable: Posttest_MM

F	df1	df2	Sig.
3.507	1	68	.065

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.
a. Design: Intercept + XMM + Class

The results of the homogeneity test using Levene's Test showed a significance value of 0.065, which was greater than the alpha level of 0.05. This result indicates that the pre-test and post-test data of students' mental models were homogeneous. Next, normality test result can be seen in Table 3.

Table 3. Normality test results using kolmogorov–smirnov test

Test of Normality

	Kolmogorov-Smirnov			Saphiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual for YMM	.088	70	.200	.969	70	.082

a. Lilliefors Significance Correction
*. This is a lower bound of the true significance

The results of the normality test using the Kolmogorov–Smirnov test showed a significance value of 0.200, which was greater than the alpha level of 0.05. This finding indicates that the pre-test and post-test data of students' mental models were normally distributed. Next, Hypothesis testing results can be seen in Table 4.

Table 4. Hypothesis testing results using ANCOVA (one-way analysis of covariance)

Tests of Between-Subjects Effects
Dependent Variable: Posttest_MM

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	8399.914[a]	2	4199.957	18.474	.000	.355
Intercept	5271.736	1	5271.736	23.188	.000	.257
XMM	5123.554	1	5123.554	22.536	.000	.252
Kelas	1999.024	1	1999.024	8.793	.004	.116
Error	15232.469	67	227.350			
Total	147053.590	70				
Corrected Total	23632.383	69				

a. R Squared = .355 (Adjusted R Squared = .336)

a. H_0: There is no difference in students' mental models between students taught using the Problem-Based Learning (PBL) model and those taught using a conventional learning model.

b. H_a: There is a difference in students' mental models between students taught using the Problem-Based Learning (PBL) model and those taught using a conventional learning model.

Based on Table 4, the significance value for the class variable was 0.004, which was lower than the alpha level of 0.05. Therefore, H_0 was rejected and H_a was accepted. This result indicates that there was a significant difference in students' mental models between students who received instruction through the PBL model and those who were taught using the conventional learning model. In other words, the Problem-Based Learning (PBL) model significantly affected students' mental models. This is because the PBL model has several advantages in its implementation, including involving students in learning activities to ensure that their knowledge is thoroughly absorbed, preparing students to work together with other students, and allowing students to learn problem-solving from various sources (Lin et al., 2025). The advantages of PBL include motivating students to be able to solve problems in real-world situations, enabling students to develop their own knowledge through learning activities, focusing learning on problems rather than unrelated material, involving students in scientific activities through group work, and habituating them to use knowledge sources from libraries, the internet, interviews, and observations. The participants stated that the PBL approach had increased their capacity for collaboration as a group, had the confidence to express opinions, became more engaged, had better communication skills, and showed more critical thinking after just one session (Lee & Blanchard, 2019; Korpi, 2019).

Moreover, PBL is a pedagogical method that effectively develops problem-solving skills by involving students in solving complex real-world problems. Often integrated with collaborative or cooperative learning strategies, PBL emphasizes teamwork and group dynamics in the problem-solving process. Problem-based learning uses complex real-world problems as a context for students to acquire and apply knowledge (Solomon, 2020). PBL emphasizes collaborative problem-solving, which requires students to work in groups to address and solve problems. This approach facilitates the development of teamwork skills because students must negotiate, communicate, and collaborate to achieve a solution (Valdez & Bungihan, 2019). By engaging in PBL, prospective teachers not only tackle real-world problems but also train and hone their ability to work effectively with others, which is crucial for effective teaching and classroom management. This learning approach leverages complex problems as a catalyst for learning, driving the acquisition of key concepts and principles (Feng et al., 2025). Within the PBL framework, problems do not merely serve as exercises but as a primary motivator for learning, driving the development of critical thinking skills, effective communication, and teamwork. One of the hallmarks of PBL is its structure, which introduces learners to problems before they fully grasp the relevant knowledge. This approach encourages learners to collaboratively formulate an understanding of the problem, conduct investigations, and ultimately derive solutions. As a result, learners acquire not only content knowledge but also essential problem-solving competencies (Abdelkhalek et al., 2010). Problem-solving, as described by Strohfeldt & Khutoryanskaya (2015), is a process where individuals navigate and overcome obstacles in pursuing specific goals. Furthermore, Monrad & Mølholt (2017) emphasize that individuals' perceptions of their problem-solving abilities significantly influence how they view and tackle various challenges. The PBL approach not only facilitates a deep understanding of problems but also encourages learners to explore and design innovative solutions. Research indicates that PBL enhances various skills, including group collaboration, communication, creativity, logical thinking, and overall academic achievement (Akinoğlu & Tandoğan, 2007). The comprehensive development of these skills underscores the effectiveness of PBL in preparing students to face the complexities of real-world challenges and fostering lifelong learning. A study from Thailand shows that this highly suitable and feasible learning model significantly enhances the teamwork and collaborative problem-solving skills of prospective teachers, achieving an increase of 82.06%, with the highest positive perceptions and satisfaction among the teachers. These results significantly surpass the set criteria of 80%, indicating the high effectiveness of the model in advancing these essential competencies (Anchunda & Kaewurai, 2025).

The second objective of PBL is collaborative learning. In PBL, collaborative learning is a learner-centered process aimed at engaging PBL members in in-depth analysis and synthesis of the issues faced. PBL is a way for teachers to consider individual learners' issues as well as broader systematic issues, such as assessment and evaluation. This differs from cooperative learning approaches, which are more teacher-oriented regarding learning issues and problem-solving procedures. Furthermore, in cooperative learning, the goal of group members is to achieve a shared understanding of the task and content, with mutual responsibility and ensuring that all group members have mastered the content (Simone et al., 2014). Additionally, Chernobilsky et al. (2004) found that students who solve problems in PBL groups improve their professional vocabulary and become more cautious in their explanations, using discipline-specific terms and limiting their explanations to the information and resources they have as the semester progresses. In PBL, group members verbally express what they know and what they still need to learn, which assists them in the development and flexible application of knowledge when solving problems. This, in turn, fosters collaboration within communities of practice, creating a forum for teachers to address problems effectively and engage in dialogue (Harvey et al., 2005). Conversely, in the PBL realm, collaborative inquiry needs to be facilitated by a PBL mentor skilled in content and communication skills. This facilitation can take the form of smaller groups working on PBL tasks so that issues related to collaborative engagement can be more easily managed.

The results of this study are relevant to the findings of Kaliampos et al. (2020) which strongly indicate that the majority of children have different mental representations from the scientific models taught in education. Additionally, many of them can make predictions regarding capillary rise, although they cannot analyze their thought processes. Lastly, the study found differences in capillary rise. Based on relevant research, this study aims to capture the mental representations of young children regarding thermal phenomena and concepts. Traditionally, this research has had a limited scope but has produced various findings that collectively form a more comprehensive picture. Generally, only a small number of children have mental representations that align with accepted scientific knowledge in school environments. These representations, on one hand, allow children who use them to develop their thinking systematically and, on the other hand, serve as an indicator that with appropriate teaching methods, we can guide other children toward similar cognitive pathways (Ioannou et al., 2023). Other studies show that computer-assisted PBL has a significant impact on the mental models of elementary school students (Fitria & Zen, 2023).

Thus, a conceptual space is created for reasoning that allows for the formulation of assumptions for a more holistic approach, i.e., a transition from separate exploration and teaching activities that emphasize material, change, and transformation to a broader change with the same background, where the systemic nature of phenomena and the unifying character of concepts apply. In this context, one of the most striking examples is the question regarding the possibility of a systematic approach and understanding of the transition from discrete changes in the state of water to the water cycle in nature. However, research aimed at such large-scale interventions requires a comprehensive design of a series of teaching activities whose development can be reflected in the program and take place over time.

Models are created through a process of simplification and reduction of structure, which depicts the relationships between elements in a system (Bhalwankar & Treur, 2021). Mental models are internal or cognitive representations of a system and show aspects that are privatized with a focus on predictive and descriptive features (Zhang et al., 2021). Individuals use mental models to explain, understand, and observe real-world behavior and develop new mental models within existing frameworks according to personal context. Essentially, mental models originate from how individuals perceive the world through their actions. Meanwhile, external or conceptual models can be developed by interpreting perceptions into codes (Altman, 2023). Thus, an individual's mental model can be identified based on expressions and actions that reflect understanding of certain concepts. Since the learning process involves the construction of mental models (Shepardson et al., 2007), and there is a risk of lack of understanding or misperception due to inadequate learning environments, it is essential to examine robust mental models in students within those learning environments. Mental models can greatly assist teachers in understanding and addressing students' learning difficulties (Toikka & Tarnanen, 2024).

The results of Bartell (2001) one of the professors of chemistry at Hebata, over more than 40 years of teaching physical chemistry at Iowa State University and the University of Michigan, often find that students come to class having heard scary stories about how boring and difficult it is to understand thermodynamics and physical chemistry. In fact, the campus newspaper, the Michigan Daily, published an article stating that physical chemistry is the most challenging course at the university. Of course, this becomes a significant challenge to create a more enjoyable atmosphere. He found that the best way to make students more interested and open to ideas in lectures on thermodynamics and related fields is to share stories from time to time. These stories illustrate various principles, introduce important figures in the development of thermodynamics and related fields, and review steps and mistakes in the development of this discipline. It turns out that these stories are much easier for students to remember than just memorizing principles and facts, so I feel that this is a good approach. He also introduced some scientific puzzles (1), which encourage students to use their imagination in seeking solutions based on the basic framework discussed. Sometimes, he even provides extra credit for correct answers. In evaluations of students regarding my teaching methods, the stories I shared received the highest praise. Findings in Tanzania show that an increase in math competence can have a direct and positive impact on physics performance, offering valuable insights for educators and policymakers seeking to improve academic outcomes in this important subject (John, 2024).

4. Conclusion

The findings of this study indicate that the PBL model has a significant effect on students' mental models in understanding capillary rise concepts. Students who received instruction through the PBL model demonstrated better development of mental models compared to students who experienced conventional learning approaches. The implementation of PBL encouraged students to actively participate in learning activities through problem identification, investigation, discussion, and collaborative problem-solving processes. These learning experiences facilitated the construction and reconstruction of students' cognitive structures, enabling them to develop deeper and more scientifically appropriate mental representations of physics concepts. The findings also suggest that the development of students' mental models is influenced not only by instructional approaches but also by students' prior knowledge, learning experiences, and the opportunities provided during the learning process to actively construct understanding. Students who engage directly with authentic and meaningful problems tend to develop more coherent conceptual structures than students who primarily receive information through teacher-centered instruction. Therefore, the learning process should provide sufficient opportunities for students to connect prior knowledge with new information in order to strengthen conceptual understanding and minimize misconceptions.

From a theoretical perspective, this study contributes to the development of learning theories, particularly constructivist learning theory and mental model theory. The findings support the constructivist assumption that knowledge is actively constructed by learners through interaction with learning experiences and cognitive processes rather than passively received from external sources. Furthermore, this study extends previous findings concerning mental models by providing empirical evidence that problem-based instructional approaches can facilitate the development of more accurate and scientifically meaningful mental representations. The study also reinforces the idea that students' mental models are dynamic cognitive structures that can be modified and reconstructed through meaningful learning environments. Regarding the development of physics education, the results of this study provide important implications for instructional practice, curriculum development, and learning design. The findings suggest that physics learning should move beyond traditional teacher-centered practices and emphasize student-centered learning environments that encourage active participation and inquiry processes. The use of PBL can help students understand abstract physics concepts more effectively by connecting theoretical concepts with real-life situations. This approach also supports the development of higher-order thinking skills, including critical thinking, problem-solving ability, communication skills, and collaboration.

In addition, the findings imply that physics teachers should function not only as information providers but also as facilitators who guide students in constructing conceptual understanding through meaningful learning experiences. Teacher professional development programs should therefore provide training related to the implementation of PBL strategies, classroom facilitation techniques, and the assessment of students' mental models. Furthermore, the results may contribute to curriculum improvement by emphasizing the integration of real-world problems and mental model development into physics instruction. Future studies are recommended to investigate students' mental models across different physics topics, educational levels, and cultural contexts to provide a broader understanding of mental model development in science education. Further research may also explore the relationship between mental models and other learning variables such as critical thinking, creativity, conceptual understanding, and problem-solving skills to strengthen the theoretical and practical contributions to physics education.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

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