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A Web-Based Edulab and Problem-Based Learning Framework for Enhancing Conceptual Understanding in Cell Biology

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Abstract: This study aims to examine the effectiveness of an integrated instructional framework combining Web-Based Edulab (WBE) and Problem-Based Learning (PBL) in enhancing students' conceptual understanding in cell biology. This study employed a quasi-experimental design using a non-equivalent control group structure. The study was conducted at a public senior high school in Malang, East Java, Indonesia. A total of 69 Grade XI students participated in the study, with 35 students assigned to the experimental group and 34 students assigned to the control group.. The experimental group received instruction through the integration of WBE and PBL, while the control group was taught using conventional methods. Data were collected through a conceptual understanding test administered as pre-test and post-test. Prior to hypothesis testing, assumption tests including normality and homogeneity were conducted. The data were then analyzed using Analysis of Covariance (ANCOVA) with pre-test scores as the covariate. The results revealed a statistically significant effect of the instructional intervention on students' conceptual understanding ($F(1,66) = 4.084$, $p = 0.047$, $\eta p^2 = 0.058$), indicating a moderate effect size. The experimental group achieved a higher adjusted mean score ($M = 83.548$) than the control group ($M = 77.820$), suggesting that the WBE–PBL framework effectively improved students' conceptual understanding in cell biology. These findings demonstrate that integrating interactive digital learning environments with inquiry-based pedagogy can promote deeper cognitive engagement and facilitate meaningful knowledge construction. This study contributes to biology education by providing empirical evidence for the effectiveness of the WBE–PBL framework. Practically, biology teachers can integrate virtual laboratory simulations, interactive visualizations, and problem-based investigations into classroom instruction to support students' exploration of abstract cellular concepts. Curriculum developers may also incorporate technology-enhanced inquiry activities into biology learning materials to strengthen conceptual understanding and promote 21st-century competencies.

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Introduction

Education in the 21st century is increasingly shaped by rapid technological advancement and the demands of the Industrial Revolution 4.0, requiring a fundamental shift from knowledge transmission to the development of higher-order thinking skills (Ferro, Sapio, Terracina, Temperini, & Mecella, 2021; Hardianto, Mahanal, Zubaidah, & Setiawan, 2024). Contemporary learning environments are expected to foster critical thinking, problem-

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solving, collaboration, and deep conceptual understanding, rather than rote memorization of content (Fatmawati, Rahardjo, & Endang Susilowati, 2024). In this context, digital technologies have transformed how knowledge is accessed, constructed, and applied, particularly in science education, where abstract concepts require meaningful representation and engagement (Achiria, Priyadi, & Hamdani, 2025; Vasilescu, 2020). Consequently, biology education must move beyond traditional instructional approaches by integrating technology-enhanced learning environments that support active learning and knowledge construction, enabling students to develop not only scientific knowledge but also the competencies necessary to thrive in an increasingly complex and knowledge-driven world (Muharni, Mahanal, Zubaidah, Susanto, & Hardianto, 2025).

Conceptual understanding plays a central role in biology education, as it enables students to grasp the relationships, processes, and underlying principles that govern living systems (Hardianto, Mahanal, Susanto, & Prabaningtyas, 2024). Unlike surface-level learning, which relies heavily on memorization of isolated facts and terminology, conceptual understanding involves the ability to organize knowledge into coherent frameworks and apply it to new situations. In the context of biology, this is particularly important because many topics such as cellular processes, physiological mechanisms, and ecological interactions are inherently complex and interconnected (Kaya, 2013; Tidemand, 2017). Students who develop strong conceptual understanding are better equipped to transfer knowledge across topics, solve problems, and engage in scientific reasoning (Hardianto, Zubaidah, & Mahanal, 2026). Conversely, a lack of conceptual understanding often leads to fragmented knowledge structures, misconceptions, and limited ability to apply biological concepts meaningfully in both academic and real-world contexts.

Learning cell biology presents significant challenges for high school students due to the abstract, microscopic, and highly complex nature of its concepts. Many cellular structures and processes such as organelle functions, membrane transport, and metabolic pathways—cannot be directly observed, requiring students to rely on mental models and symbolic representations. As a result, students often resort to rote memorization of terminology rather than developing a meaningful understanding of how cellular components interact as dynamic systems. This tendency frequently leads to misconceptions and fragmented knowledge, which hinder their ability to explain biological phenomena coherently. Moreover, previous studies have reported that students frequently struggle to articulate cellular concepts in their own words and often fail to connect them with broader biological principles, highlighting a persistent gap between knowledge acquisition and conceptual understanding (Bizimana, 2022; Ekatushabe, Nsanganwimana, Muwonge, & Ssenyonga, 2021).

Traditional instructional approaches in biology classrooms often fail to adequately support the development of conceptual understanding (Lo, Luu, & Tran, 2020), particularly for abstract topics such as cell biology. Teacher-centered methods that emphasize lectures and textbook-based explanations tend to prioritize content delivery over active knowledge construction, limiting students' opportunities to engage deeply with the material (Raharjo, Ramli, & Rinanto, 2018). In such environments, students are frequently positioned as passive recipients of information, with minimal interaction, exploration, or critical reflection (Amini, 2015; Quinn, Castéra, & Clément, 2016). Additionally, the lack of interactive and visual learning tools makes it difficult for learners to visualize microscopic processes and dynamic cellular mechanisms, further reinforcing surface-level learning. Consequently, these limitations contribute to persistent misconceptions and hinder students' ability to transform memorized information into meaningful and transferable biological knowledge.

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Web-Based Edulab (WBE) represents an innovative digital learning platform designed to support the teaching of cell biology through interactive and visually enriched features (Oliveira & Pombo, 2017). By integrating multimedia content, virtual laboratory simulations, and formative assessments, WBE provides students with opportunities to explore cellular structures and processes more dynamically and engagingly. The platform enables learners to visualize abstract concepts such as organelle functions and intracellular mechanisms through animations and simulated experiments, thereby reducing cognitive barriers associated with microscopic phenomena. In addition, embedded quizzes and interactive tasks encourage active participation and immediate feedback, which are essential for reinforcing conceptual understanding (Stevenson, 2017). As such, WBE has the potential to transform passive learning into an exploratory and meaningful learning experience in biology classrooms.

Problem-Based Learning (PBL) is a student-centered pedagogical approach that emphasizes learning through the exploration and resolution of real-world problems (Salim, Mahanal, Susanto, Hardianto, & Kusmahardhika, 2025). In this approach, students actively engage in identifying issues, formulating hypotheses, gathering and analyzing information, and proposing solutions collaboratively (Aslan, 2021; Hardianto et al., 2026; Jonassen & Hung, 2008). Such processes encourage the development of critical thinking, inquiry skills, and deeper cognitive engagement, all of which are essential for meaningful learning. In the context of biology education, PBL enables students to connect theoretical concepts with authentic contexts, thereby enhancing their ability to understand and apply scientific knowledge (Molina, Palomino, & Costilla-Legaz, 2023; Rubenstein, Callan, Neumeister, & Ridgley, 2020). By shifting the focus from passive reception to active knowledge construction, PBL fosters a deeper level of conceptual understanding and supports students in transitioning from memorizing content to interpreting and reasoning about biological phenomena (Hardianto, Mahanal, & Zubaidah, 2023).

The integration of Web-Based Edulab (WBE) and Problem-Based Learning (PBL) offers a complementary approach that combines the strengths of technology-enhanced visualization with inquiry-driven pedagogy (Salmah, Susanto, & Suwono, 2023). While WBE provides interactive simulations and visual representations that help students grasp abstract cellular processes (Pradipta et al., 2020), PBL structures the learning experience through problem-solving activities that promote critical thinking and knowledge construction (He et al., 2018). This integration allows students not only to observe and explore biological phenomena but also to analyze, interpret, and apply their understanding within meaningful contexts. By aligning digital tools with a student-centered instructional model, the combined approach is expected to facilitate deeper cognitive engagement, reduce reliance on rote memorization, and support the transition toward meaningful and transferable conceptual understanding in cell biology.

Addressing these gaps, this study integrates Web-Based Edulab (WBE) and Problem-Based Learning (PBL) into a unified instructional framework to enhance students' conceptual understanding in cell biology. Unlike previous studies that have examined either PBL or web-based learning separately, this framework combines interactive digital visualizations, virtual laboratory experiences, and inquiry-based problem solving to address persistent conceptual difficulties in understanding abstract cellular processes. By focusing specifically on conceptual understanding and controlling for students' prior knowledge, this study provides empirical evidence on the effectiveness of technology-enhanced inquiry learning in biology education and offers practical insights for 21st-century instructional design.

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Research Method

This study employed a quasi-experimental design (Cohen, Manion, & Morrison, 2018) using a non-equivalent control group structure to examine the effect of the instructional intervention on students' conceptual understanding in cell biology. Before conducting the study, permission was obtained from the school principal and biology teachers. Participants and their parents or legal guardians were informed about the purpose and procedures of the research, and participation was entirely voluntary. Written informed consent was obtained from parents or guardians before students were involved in the study. Participants were informed that they could withdraw from the study at any time without penalty. To ensure confidentiality, all student data were anonymized and used exclusively for research purposes.

Two groups were involved: an experimental group that received instruction through the integration of Web-Based Edulab (WBE) and Problem-Based Learning (PBL), and a control group that was taught using conventional instructional methods. Both groups were administered a pre-test before the intervention to assess their initial conceptual understanding, followed by a post-test after the instructional treatment to measure learning outcomes (Table 1). This design allows for the comparison of post-intervention performance while accounting for initial differences between groups.

Table 1. Research Design

Group	Pre-test	Treatment	Post-test
Experimental	O_1	WBE + PBL	O_2
Control	O_3	Conventional Instruction	O_4

***Notes:** **O_1 and O_3**: Pre-test scores (initial conceptual understanding), **O_2 and O_4**: Post-test scores (learning outcomes after intervention), **WBE + PBL**: Web-Based Edulab integrated with Problem-Based Learning, **Conventional Instruction**: Traditional teaching methods without intervention.

The study was conducted at SMA Negeri 3 Malang, a public senior high school in Malang City, East Java Province, Indonesia. The participants consisted of 69 Grade XI students, including 35 students in the experimental group and 34 students in the control group. The selection of participants was based on criteria such as comparable learning abilities, similar instructional schedules, and the same subject teacher, to minimize potential confounding variables and ensure the validity of the comparison between groups.

The treatment procedure was conducted over several instructional sessions covering the topic of cell biology. In the experimental group, learning was implemented through the integration of Web-Based Edulab (WBE) with Problem-Based Learning (PBL). The instructional process followed the main stages of PBL, including problem orientation, problem investigation, data collection, analysis, discussion, and conclusion. During these stages, students actively engaged with WBE features such as virtual laboratory simulations, interactive visualizations, and embedded quizzes to explore cellular structures and processes. In contrast, the control group received conventional instruction, which primarily consisted of teacher-centered explanations, textbook-based learning, and limited use of interactive media. This procedure was designed to compare the effectiveness of the WBE–PBL framework with traditional teaching approaches in enhancing students' conceptual understanding.

The primary instrument used in this study was a conceptual understanding test administered as both a pre-test and a post-test. The test consisted of 15 items, including 10 multiple-choice questions and 5 essay questions, designed to measure students' understanding of key concepts in cell biology. Prior to implementation, the instrument was empirically tested for validity and reliability. The validity of the items was assessed using Pearson product–moment correlation, with all items showing correlation coefficients ranging

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from 0.412 to 0.782, exceeding the critical value (r-table=0.361, n = 30, p-value < 0.05), indicating that all items were valid. The reliability of the instrument was evaluated using Cronbach's Alpha, yielding a coefficient of 0.873, which indicates a high level of internal consistency. These results confirm that the test instrument was both valid and reliable for measuring students' conceptual understanding.

The data collection and analysis procedures were conducted systematically to ensure the validity and reliability of the findings. Initially, a pre-test was administered to both the experimental and control groups to assess students' initial conceptual understanding. This was followed by the implementation of the instructional treatment, where the experimental group received learning through the integration of Web-Based Edulab (WBE) and Problem-Based Learning (PBL), while the control group was taught using conventional methods. After the intervention, a post-test was administered to measure students' learning outcomes. The collected data were then analyzed using both descriptive and inferential statistics. Prior to hypothesis testing, prerequisite analyses were conducted, including tests of normality (Kolmogorov–Smirnov) and homogeneity of variance (Levene's test). To examine the effect of the instructional intervention while controlling for initial differences, an Analysis of Covariance (ANCOVA) was employed with pre-test scores as the covariate. If significant differences were found, a post hoc test using the Least Significant Difference (LSD) method was conducted to identify differences between groups. The level of significance was set at $\alpha = 0.05$, and effect size was interpreted using Partial Eta Squared (η^2). The effect size, as indicated by the partial eta squared value ($\eta p^2 = 0.058$), was interpreted according to Cohen's (1988) criteria, where values of 0.01, 0.06, and 0.14 represent small, medium, and large effects, respectively. The obtained value was therefore considered to be close to a medium effect, indicating that the integration of Web-Based Edulab (WBE) with Problem-Based Learning (PBL) had a meaningful impact on improving students' conceptual understanding.

Results and Discussion

Table 2 presents the descriptive statistics of students' conceptual understanding in cell biology for both groups. The control group, which received conventional instruction, obtained a mean pre-test score of 31 and a post-test score of 78. Meanwhile, the experimental group, taught using the integration of Web-Based Edulab (WBE) and Problem-Based Learning (PBL), demonstrated a higher mean pre-test score of 43 and a higher post-test score of 84. These results indicate that the experimental group consistently outperformed the control group in both initial and final assessments. However, the observed difference in pre-test scores suggests that the two groups were not equivalent at baseline. Therefore, further inferential analysis using covariance techniques is required to control for initial differences and accurately determine the effect of the instructional intervention.

Table 2. Descriptive Statistics of Students' Conceptual Understanding

Group	N	Pre-test Mean	Post-test Mean
Control (Conventional)	34	31.00	78.00
Experimental (WBE + PBL)	35	43.00	84.00

Before conducting the main analysis, preliminary tests were performed to examine baseline equivalence and to ensure that the data met the assumptions required for parametric analysis. An independent samples t-test was conducted on the pre-test scores to assess whether there were initial differences between the control and experimental groups. The results indicated that the experimental group had a higher initial mean score compared to the

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control group, suggesting that the two groups were not equivalent at baseline. This condition justifies the use of Analysis of Covariance (ANCOVA) to control for initial differences in conceptual understanding. Furthermore, assumption testing was carried out to validate the use of ANCOVA. The normality of residuals was examined using the Kolmogorov–Smirnov test, which showed that the data were normally distributed, $D (69) = 0.091$, $p = 0.200$ ($p > 0.05$). In addition, Levene's test of homogeneity of variance indicated that the variances between groups were homogeneous, $F(1,67) = 2.250$, $p = 0.138$ ($p > 0.05$). These findings confirm that the data satisfied the required assumptions, allowing for further inferential analysis using ANCOVA.

The effect of the instructional intervention on students' conceptual understanding was examined using Analysis of Covariance (ANCOVA), with pre-test scores treated as a covariate. As presented in Table 3, the results revealed a statistically significant effect of the instructional model on students' conceptual understanding, $F (1,66) = 4.084$, $p = 0.047$, $\eta p^2 = 0.058$. This indicates that, after controlling for initial differences, there was a significant difference between the experimental and control groups. The effect size, as indicated by the partial eta squared value ($\eta p^2 = 0.058$), can be interpreted as a moderate effect, suggesting that the integration of Web-Based Edulab (WBE) with Problem-Based Learning (PBL) had a meaningful impact on improving students' conceptual understanding. In contrast, the covariate (pre-test scores) was not statistically significant, $F(1,66) = 2.965$, $p = 0.090$, indicating that the observed differences in post-test scores were primarily attributable to the instructional treatment rather than initial ability differences.

Table 3. Results of ANCOVA on Students' Conceptual Understanding

Source	SS	df	MS	F	p-value	Partial Eta Squared
Corrected Model	1063.616	2	531.808	3.951	0.024	0.107
Intercept	56288.408	1	56288.408	418.197	0.000	0.864
Pre-test (Covariate)	399.047	1	399.047	2.965	0.090	0.043
Group	549.747	1	549.747	4.084	0.047	0.058
Error	8883.457	66	134.598			

Further analysis using the Least Significant Difference (LSD) test was conducted to compare the adjusted mean scores between groups. As shown in Table 4, the experimental group achieved a higher adjusted mean score ($M = 83.548$, $SD = 8.45$) compared to the control group ($M = 77.820$, $SD = 14.41$). The different notations assigned to each group indicate that the difference was statistically significant. These findings confirm that the WBE–PBL framework was more effective than conventional instruction in enhancing students' conceptual understanding of cell biology.

Table 4. Adjusted Means and Post Hoc Comparison (LSD)

Group	Adjusted Mean	SD	Notation
Control (Conventional)	77.820	14.41	a
Experimental (WBE + PBL)	83.548	8.45	b

Discussion

The findings of this study indicate that the integration of Web-Based Edulab (WBE) with Problem-Based Learning (PBL) has a significant positive effect on students' conceptual understanding in cell biology. Although the difference in adjusted mean scores between the experimental group (83.548) and the control group (77.820) may appear moderate, it is educationally meaningful in the context of biology learning. Conceptual understanding in cell biology involves more than the acquisition of factual knowledge; it requires students to explain relationships among cellular structures and processes, interpret biological

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phenomena, and apply concepts to new situations. Therefore, even a moderate increase in conceptual understanding scores may reflect substantial improvements in students' ability to construct coherent biological explanations and transfer knowledge beyond rote memorization. Furthermore, the higher achievement of the experimental group suggests that students were better able to attain the intended learning competencies related to conceptual reasoning, problem-solving, and scientific inquiry.

The effectiveness of the WBE–PBL framework can be explained through several complementary learning theories that emphasize active knowledge construction and multimodal processing. From a constructivist perspective, students learn more effectively when they actively engage in building their own understanding through inquiry and problem-solving activities, as facilitated by PBL (Shongwe, 2024). In this context, WBE supports this process by providing visualizations and interactive simulations that help students concretize abstract cellular concepts. This aligns with the cone of experience theory, which posits that learning is enhanced when information is presented through both visual and verbal channels, allowing learners to integrate and organize knowledge more effectively (Masters, 2020). Additionally, the use of visual representations in WBE is consistent with the Dual Coding Theory, where combining visual and textual information strengthens memory and understanding (Clark & Paivio, 1991). Together, the integration of WBE and PBL facilitates deeper cognitive processing, enabling students to move beyond memorization toward meaningful conceptual understanding.

The positive impact of the WBE–PBL framework on students' conceptual understanding can also be interpreted through socioconstructivist and cognitive learning perspectives. From a socioconstructivist viewpoint, learning occurs through active participation, dialogue, and the co-construction of knowledge within a social context (Vygotsky, 1978). During the PBL process, students collaboratively analyzed biological problems, exchanged ideas, evaluated alternative explanations, and negotiated meaning with their peers. These interactions provided opportunities for students to operate within their zones of proximal development, where conceptual understanding could be extended through peer discussion and teacher facilitation. Consequently, learning became a socially mediated process rather than an individual act of memorization.

From a cognitive perspective, the integration of Web-Based Edulab (WBE) and PBL supports meaningful learning as proposed by Ausubel's Theory of Meaningful Learning. The visualizations, simulations, and virtual laboratory activities available in WBE helped students connect new cellular concepts with their existing knowledge structures, facilitating the development of more organized cognitive schemas (Ausubel, 1968). Simultaneously, the problem-solving activities embedded within PBL required students to apply, analyze, and evaluate biological information, promoting higher-order cognitive processing. Through this combination of visualization and inquiry, students were encouraged to reorganize their prior knowledge and construct deeper conceptual relationships among biological concepts.

Furthermore, the effectiveness of the intervention can be explained through Mayer's Cognitive Theory of Multimedia Learning, which posits that learning is enhanced when information is processed through both visual and verbal channels (Mayer, 2021). The interactive animations and simulations provided by WBE enabled students to develop mental representations of abstract cellular processes that are difficult to observe directly. When these multimedia experiences were integrated with collaborative problem-solving activities, students were better able to integrate information, reduce misconceptions, and achieve a more coherent understanding of cell biology concepts. Therefore, the observed improvement in

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conceptual understanding is likely the result of the complementary interaction between cognitive processing, multimedia-supported visualization, and socially mediated knowledge construction.

An important aspect to consider in interpreting these findings is the presence of initial differences between the experimental and control groups, as indicated by the higher pre-test scores in the experimental group. Such baseline differences are common in quasi-experimental designs and may influence the interpretation of raw learning outcomes if not properly controlled. In this study, the use of ANCOVA played a critical role in adjusting for these initial disparities, allowing for a more accurate estimation of the treatment effect. The results demonstrate that, even after controlling for students' prior conceptual understanding, the experimental group still achieved significantly higher post-test performance. This suggests that the observed improvement is attributable to the instructional intervention rather than pre-existing differences, highlighting the robustness of the WBE–PBL framework in enhancing conceptual understanding.

The findings of this study are consistent with a growing body of research demonstrating the effectiveness of both Problem-Based Learning (PBL) and technology-enhanced learning environments in improving students' conceptual understanding (Salim et al., 2025; Zakaria & Nawi, 2020). Previous studies have shown that PBL promotes active engagement and critical thinking, enabling students to construct knowledge through inquiry and real-world problem solving (Hardianto et al., 2026). Similarly, research on web-based and virtual learning environments indicates that interactive visualizations and simulations can significantly enhance students' ability to understand abstract biological concepts (Chu & Chang, 2008). The present study extends these findings by demonstrating that the integration of Web-Based Edulab (WBE) with PBL provides a more powerful learning approach than conventional instruction. Unlike studies that examine these strategies in isolation, this research highlights the added value of combining digital visualization with inquiry-based pedagogy to produce more meaningful learning outcomes in cell biology.

The effectiveness of the WBE–PBL framework can be further understood by examining the underlying learning mechanisms at the cognitive, engagement, and problem-solving levels. At the cognitive level, the use of interactive visualizations and simulations in WBE helps reduce learners' cognitive burden by making abstract cellular processes more concrete and easier to process, which is consistent with Cognitive Load Theory. This allows students to allocate more cognitive resources to understanding relationships between concepts rather than struggling with mental representation (Houdé, 2019). At the engagement level, the interactive nature of WBE combined with collaborative problem-solving in PBL fosters active participation and sustained attention during learning. Meanwhile, at the problem-solving level, PBL encourages students to analyze complex biological phenomena, evaluate information, and construct explanations, thereby promoting deeper reasoning (Tawfik & Lilly, 2015; Tsalapatas et al., 2021). These interconnected processes collectively support the transition from surface learning to meaningful conceptual understanding.

The findings of this study have important implications for educational practice, particularly in the teaching of complex and abstract topics such as cell biology. For teachers, the results suggest that integrating Web-Based Edulab (WBE) with Problem-Based Learning (PBL) can serve as an effective instructional strategy to enhance students' conceptual understanding by combining visualization with inquiry-based activities. This approach encourages more active and student-centered learning environments, where learners are engaged in exploring and constructing knowledge rather than passively receiving

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information. At the curriculum level, the integration of digital learning tools with pedagogical models such as PBL supports the development of 21st-century skills, including critical thinking, problem-solving, and digital literacy (Hardianto et al., 2023; Hardianto, Mahanal, Zubaidah, et al., 2024). Therefore, the adoption of technology-enhanced, inquiry-based learning frameworks should be considered as a strategic direction for improving the quality of biology education.

This study also contributes to the theoretical advancement of biology education by proposing an integrative framework that combines digital learning environments with inquiry-based pedagogy to enhance conceptual understanding (Hafiza, Rahayu, & Pasah Kahar, 2022). Specifically, the integration of Web-Based Edulab (WBE) and Problem-Based Learning (PBL) extends existing perspectives on constructivist learning by demonstrating how technology can function not only as a supportive tool but as an active component in facilitating knowledge construction. The findings provide empirical support for the synergistic relationship between multimedia-based learning and problem-oriented instruction, reinforcing the idea that meaningful learning occurs when students are engaged in both visual exploration and cognitive inquiry (McCoy, 2016). Thus, this study offers a conceptual contribution by bridging the gap between technology integration and pedagogical design in the context of biology education.

Conclusion

This study confirms that the integration of Web-Based Edulab (WBE) and Problem-Based Learning (PBL) is effective in enhancing students' conceptual understanding in cell biology. The findings demonstrate that combining interactive digital learning environments with inquiry-based pedagogy provides a meaningful instructional approach that supports deeper cognitive processing and knowledge construction. The results address the research objective by showing that the WBE–PBL framework offers a more effective alternative to conventional instruction in facilitating students' ability to understand complex and abstract biological concepts. This suggests that instructional designs that align technology with student-centered pedagogical strategies can significantly contribute to improving the quality of biology learning. The study highlights the importance of integrating digital tools with active learning approaches to promote conceptual understanding, providing both empirical support and practical direction for future instructional development in science education.

Recommendation

To address the limitations related to technological infrastructure and digital readiness, biology teachers should be supported through continuous professional development in technology-enhanced pedagogy, while school principals should ensure adequate access to digital devices, reliable internet connectivity, and technical support for classroom implementation. At the policy level, educational authorities should promote equitable access to digital learning resources through targeted funding, infrastructure development, and teacher training programs. Such coordinated efforts are essential to ensure the effective and sustainable implementation of innovative instructional frameworks such as WBE–PBL across diverse educational contexts.

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