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Development of a Digital Technology-Based Biology Learning Model to Enhance Conceptual Understanding

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ABSTRACT

This qualitative study aims to develop a digital technology-based biology learning model to enhance students' conceptual understanding of abstract and complex biological concepts. The study responds to the problem that biology learning often still relies on verbal explanation, textbook images, and memorization, while many biological processes require visual, interactive, and contextual representation. This research used an instrumental case study design conducted in a senior high school that had implemented digital technology in biology learning. Data were collected through semi-structured interviews, limited participatory observation, documentation, and researcher reflective notes. The participants included biology teachers, eleventh-grade students, a vice principal for curriculum affairs, and learning or digital media experts selected through purposive sampling. The data were analyzed using reflexive thematic analysis. The findings revealed four main themes: digital visualization helped students understand abstract concepts, student engagement increased when technology was integrated with inquiry-based activities, teacher facilitation determined the quality of conceptual understanding, and digital learning faced constraints related to access, readiness, and classroom management. Based on these findings, the study developed a five-stage model consisting of orientation, visualization, exploration, conceptual construction, and reflection. This study contributes to the understanding of digital biology learning by showing that technology becomes meaningful when it supports active concept construction, teacher scaffolding, and reflective learning. The findings imply that schools need to support digital learning through infrastructure, teacher training, and pedagogically grounded technology integration. Further studies can test this model in broader contexts and specific biology topics.

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1. Introduction

Digital transformation has changed how biology learning is designed, implemented, and evaluated. Digital technology no longer serves only as a presentation tool. It has become part of a learning ecosystem that supports visualization, interaction, simulation, collaboration, and flexible formative assessment. In the global context, the integration of digital technology in schools has changed the role of teachers, patterns of student interaction, and the capacity of schools to manage more adaptive learning (Timotheou et al., 2023). This shift is also visible in science education because biological concepts often require visual representation and learning experiences that cannot always be delivered through lectures or textbooks. Haleem et al. (2022) explain that digital technology gives education the opportunity to provide more interactive, personalized, and data-driven learning. Therefore, developing a digital technology-based biology learning model is an important need in responding to changes in how students understand scientific information.

In biology learning, one of the main problems is students' weak conceptual understanding of abstract, complex, and dynamic topics. Topics such as cell division, genetics, organ systems, ecology, plant tissue, and molecular processes require students to connect structure, function, process, and relationships among biological components. Suprapto et al. (2024) show that plant anatomy learning requires visuospatial transformation support so that students can understand tissue structures and their relationships more meaningfully. Difficulties also occur because many biological processes cannot be observed directly in real time in the classroom. Miller and Yoon (2023) explain that agent-based simulations can help students understand complex biological systems because students can observe patterns, causal relationships, and system dynamics through modeling. This condition shows that conceptual understanding in biology cannot be built only through memorizing terms. It must be facilitated through learning experiences that help students construct relationships among concepts.

At the national level, the use of digital technology in biology learning in Indonesia has grown through e-modules, mobile learning, learning management systems, interactive videos, augmented reality, virtual laboratories, and digital quiz applications. Hadi et al. (2025) found that ICT-based biology learning in Indonesia has developed through various forms of media, but its implementation still faces challenges related to teacher readiness, facility availability, pedagogical design, and sustainability of use. Other findings show that mobile learning in biology education continues to increase and is widely used for concept visualization and practical learning activities (Sangur et al., 2025). However, the use of technology in classrooms often remains limited to media use. It has not yet become a complete learning model that systematically regulates objectives, syntax, student activities, teacher roles, assessment, and learning reflection. This condition shows the need to design a digital learning model that is not only visually attractive but also able to strengthen concept construction.

Previous studies have shown that digital technology can support biology learning. Weng et al. (2020) found that augmented reality can improve biology learning outcomes at certain cognitive levels because students gain more concrete visual experiences. Vekli and Çalık (2023) also show that web-based biology learning environments have a positive effect on academic performance, although their effectiveness depends on experimental design, educational level, and learning context. Liono et al. (2021) explain that augmented reality helps students understand abstract concepts through three-dimensional visualization. Virtual reality has also been shown to help students gain a more immersive learning experience, especially in online biology courses (Majewska & Vereen, 2023). These findings show that digital technology has strong potential in biology learning. However, this potential can work optimally only when technology becomes part of instructional design, not merely an additional tool.

Empirical findings also show field problems that need deeper investigation. Yapıcı and Karakoyun (2021) found that prospective biology teachers viewed augmented reality as useful for making abstract material more concrete, increasing attention, and supporting retention. However, they also highlighted technical constraints, device access, and the risk of passive student participation if learning activities are not well designed. Sattar et al. (2025) show that augmented reality can increase student engagement in biology learning, especially when the technology is adapted to classroom conditions and resource limitations. In a broader context, Al-Ansi et al. (2023) emphasize that augmented reality and virtual reality in education continue to develop, but their implementation is still influenced by institutional readiness, devices, cost, and teacher competence. This means that the main issue is not only the availability of technology, but also how teachers and students experience, interpret, and use technology in the process of building conceptual understanding.

Previous studies still leave an important gap. Many studies focus on the effectiveness of technology on learning outcomes, motivation, or engagement, while qualitative studies that explore the model development process, teacher experiences, student experiences, and the meaning of digital learning remain limited. Faria and Miranda (2024) show that augmented reality in science and biology learning affects learning outcomes, motivation, understanding, and cognitive load. However, studies that examine implementation contexts and pedagogical strategies still need to be strengthened. Indrati and Masing (2025) found that research trends on augmented reality in biology learning from 2020 to 2024 mostly focused on learning outcomes, motivation, and critical thinking. Wilsa et al. (2025) also show that augmented reality studies in biology have mainly moved toward content mapping and bibliometric analysis. Stanič and Špernjak (2025) add that AR in biology education is widely used in human anatomy, genetics, cells, botany, ecology, and molecular processes, but pedagogical integration remains an important issue. This gap strengthens the need for qualitative research that explores processes, experiences, and design principles in digital technology-based biology learning models.

Based on this background, this study aims to develop a digital technology-based biology learning model to enhance students' conceptual understanding. The study focuses on learning needs, teacher and student experiences, model design principles, and strategies for integrating digital technology into abstract and complex biology concepts. This study is grounded in constructivist theory, multimedia learning, visuospatial learning, and experiential learning. Afnan and Puspitawati (2024) explain that augmented reality can be examined through a constructivist perspective because technology gives students space to construct knowledge through interaction with digital representations. Mansour et al. (2025) also show that augmented reality-based learning can strengthen engagement and understanding when students take an active role in learning experiences. Theoretically, this study enriches the discussion on digital instructional design in biology education. Practically, this study provides guidance for teachers in designing biology learning that is more visual, interactive, contextual, and oriented toward conceptual understanding.

2. Materials and Methods

This study uses a qualitative approach with an instrumental case study design. This design was selected because the study aims to understand in depth the development process of a digital technology-based biology learning model, including teacher experiences, student experiences, classroom needs, and pedagogical principles that support conceptual understanding. An instrumental case study is appropriate when researchers seek to understand an issue through a specific context, namely digital biology learning in schools. Defensor et al. (2024) show that qualitative case studies can explore experiences, challenges, and future directions in virtual education programs. Therefore, the case study design in this research enables the researcher to examine the relationship between technology, classroom activities, teacher roles, student participation, and the formation of conceptual understanding.

The study will be conducted in the even semester of the 2025/2026 academic year at a senior high school or Islamic senior high school that has implemented digital technology in biology learning. The research site will be selected purposively because the school has biology teachers who actively use digital media, provides supporting learning devices, and teaches biology topics that require visualization of abstract concepts. The school context becomes an important part of this study because the success of digital learning is not determined only by technological devices. It is also shaped by learning culture, teacher readiness, curriculum support, and student participation. Amrianto (2025) shows that 21st-century biology learning faces challenges related to student engagement, technological readiness, and teachers' ability to design meaningful learning experiences. Therefore, this study positions the school as a social space where the digital learning model is examined contextually.

The research participants consist of biology teachers, eleventh-grade students, the vice principal for curriculum affairs, and learning or digital media experts. The main informants are one to two biology teachers who teach abstract topics, such as genetics, the coordination system, the immune system, cell division, or ecosystems. Twelve to eighteen students will be selected by considering academic ability, learning engagement, and experience in using digital technology. Supporting informants include one vice principal for curriculum affairs and two experts who understand biology instructional design or educational technology. The number of participants may develop according to data adequacy, especially when the information obtained becomes repetitive and no longer produces new substantive themes.

The informants will be selected using purposive sampling. Teachers will be selected based on at least three years of biology teaching experience, experience in using digital technology, and willingness to participate in the model development process. Students will be selected based on active participation in learning, ability to explain learning experiences, and variation in responses to the use of digital technology. Campbell et al. (2020) explain that purposive sampling helps researchers select participants who have information relevant to the research objectives. If the initial data indicate the need to expand the source of information, this study may use snowball sampling through teacher recommendations to identify students who have distinctive digital learning experiences, either positive experiences or experiences of difficulty. This strategy helps the researcher obtain rich, deep, and relevant data.

Data will be collected through semi-structured interviews, limited participatory observation, documentation, and researcher reflective notes. Semi-structured interviews with teachers will explore their experiences in designing digital learning, reasons for selecting technology, strategies for explaining abstract concepts, implementation barriers, and changes observed in students' conceptual understanding. Interviews with students will focus on their experiences in using digital technology, parts of the material that became easier to understand, learning barriers, interaction patterns with teachers and peers, and the meaning of technology for understanding biology concepts. Lobe et al. (2020) state that qualitative interviews can be conducted face-to-face or online as long as researchers maintain ethics, data security, and participant comfort. In this study, each interview with key informants will last approximately 30 to 45 minutes and will be recorded after obtaining participant consent.

Observation will be conducted in three to five biology learning meetings that use digital technology. The observation will focus on learning syntax, teacher activities, student responses, interaction patterns, digital media use, forms of questioning, the way students explain concepts, and situations in which technology helps or hinders understanding. Documentation will be collected from teaching modules, presentation materials, e-modules, interactive videos, student worksheets, assignments, screenshots of digital activities, assessment instruments, and teacher evaluation notes. Onowugbeda et al. (2024) show that biology learning becomes more meaningful when technology is connected to students' contexts and experiences. Therefore, documentation will not only be used as supporting data, but also as material to understand the alignment between learning design, classroom implementation, and student responses.

Data validation will be carried out through source triangulation, method triangulation, member checking, and audit trail. Source triangulation will be conducted by comparing information from teachers, students, the vice principal, experts, and learning documents. Method triangulation will be conducted by comparing interview data, observation data, documentation, and reflective notes. Member checking will be conducted by returning interview summaries and initial interpretations to informants to ensure meaning accuracy. Ahmed (2024) explains that the quality of qualitative research can be strengthened through credibility, transferability, dependability, and confirmability. The audit trail will be maintained by storing interview transcripts, observation notes, learning documents, coding matrices, analytical decision notes, and revisions of the model design. This process ensures analytical transparency and allows limited replication in schools with similar characteristics.

Data will be analyzed using reflexive thematic analysis. The first stage involves repeated reading of interview transcripts, observation notes, and documents to gain a complete understanding of the data. The second stage involves generating initial codes related to learning needs, digital experiences, conceptual understanding, implementation barriers, teacher strategies, and student responses. The third stage involves grouping codes into initial themes, such as the need for concept visualization, digital interaction, student engagement, teacher readiness, technology compatibility with content, and conceptual assessment. Braun and Clarke (2021) emphasize that thematic analysis must show a clear relationship between data, codes, themes, and interpretation. Byrne (2022) also explains that reflexive thematic analysis must be conducted gradually, transparently, and in line with the theoretical position of the study.

The results of the analysis will be used to develop a digital technology-based biology learning model. The model will include learning objectives, learning syntax, teacher roles, student activities, types of digital technology, concept reinforcement strategies, formative assessment, and learning reflection. The model design will be validated through expert discussion and biology teacher feedback. The assessed aspects include alignment with learning outcomes, clarity of activity flow, relevance of technology to concept characteristics, ease of classroom implementation, potential to improve conceptual understanding, and feasibility for use in biology learning. Permana et al. (2024) show that research on augmented reality in biology education continues to grow and is closely related to e-learning, mobile learning, and learning performance. Through this procedure, the study is expected to produce a contextual learning model, grounded in field needs, and applicable in a limited way to biology learning at the secondary school level.

3. Results and Discussions

The findings show that the development of a digital technology-based biology learning model was shaped by four main themes: the need for visual representation, active student engagement, teacher facilitation, and contextual constraints in classroom implementation. These themes emerged from semi-structured interviews with biology teachers and students, classroom observations, and documentation of learning materials. The analysis indicates that digital technology was meaningful when it helped students connect abstract biological concepts with visual, interactive, and contextual learning experiences. However, the findings also show that technology did not automatically improve conceptual understanding. Its impact depended on the learning design, teacher guidance, student readiness, and access to digital facilities.

Digital Visualization Helped Students Understand Abstract Biological Concepts

The first major theme concerns the role of digital visualization in helping students understand abstract biology topics. Students reported that concepts such as cell division, genetic inheritance, coordination systems, plant tissues, and ecosystem interactions were difficult to understand when explained only through textbooks or static images. The use of interactive videos, simulations, digital diagrams, and augmented reality-based media helped students observe biological structures and processes more clearly. One student stated, “When I only saw the picture in the book, I memorized the parts, but I did not really understand how they worked. After using the simulation, I could see the process step by step” (S4). This statement shows that students needed more than verbal explanation. They needed visual and process-based representation to construct conceptual meaning.

Classroom observations also showed that students became more active when the teacher displayed dynamic visual media. During the lesson on cell division, students asked more questions after watching a digital animation that showed the phases of mitosis. Several students compared the animation with textbook images and tried to explain the sequence of events using their own words. This indicated that digital visualization supported students' ability to organize biological information in a more structured way. The teacher also noted that students who usually had difficulty explaining processes became more confident after observing the visual representation. As T1 explained, "Some students can answer definitions, but they are confused when asked to explain the process. Digital animation helps them see the order, not just memorize the terms" (T1).

Documentation analysis supported this finding. Student worksheets showed that after using digital media, students were better able to describe relationships between structure and function. For example, in the topic of plant tissues, students not only named xylem and phloem but also explained their functional differences in transporting water and nutrients. This pattern suggests that digital technology helped students move from surface-level knowledge to more relational understanding. The finding also indicates that digital media became meaningful when it was linked to conceptual questions and reflection activities, not merely displayed as visual content.

Student Engagement Increased When Technology Was Integrated with Inquiry-Based Activities

The second theme shows that students became more engaged when digital technology was combined with inquiry-based learning activities. The students did not respond strongly to technology when they only watched videos or read digital modules. Their engagement increased when the teacher asked them to predict, observe, compare, explain, and discuss biological phenomena using digital tools. In one observed session, students used a digital ecosystem simulation to change population variables and observe the effect on food chain balance. The activity encouraged students to test ideas, negotiate explanations with peers, and revise their initial assumptions.

A student explained, "I liked the ecosystem simulation because we could change the number of organisms and see what happened. It made me understand that one change can affect other living things" (S7). This quotation reflects that digital technology supported conceptual understanding when it allowed students to manipulate variables and observe consequences. Another student added, "The lesson felt different because we were not only listening. We had to discuss why the result changed" (S11). These responses show that students valued digital learning when it created opportunities for active participation.

Teacher interviews also confirmed this pattern. T2 explained that digital media became more effective when accompanied by guiding questions. According to T2, "If students only watch a video, they may enjoy it, but they do not always understand the concept. I usually stop the video and ask them to predict what will happen next" (T2). This practice shows that teacher facilitation remained central in digital biology learning. Technology provided learning resources, but teacher questions helped students process information and construct meaning. Observation notes also showed that student engagement was higher when the teacher used digital media as a trigger for discussion rather than as the main source of explanation.

Teacher Facilitation Determined the Quality of Conceptual Understanding

The third theme reveals that the teacher played a key role in transforming digital media into meaningful learning experiences. The use of technology did not reduce the importance of teacher explanation. Instead, it changed the teacher's role from information provider to learning designer, facilitator, and conceptual guide. Teachers selected digital media, arranged learning syntax, prepared questions, guided discussion, corrected misconceptions, and connected digital representations with biological concepts. This role was crucial because students could misinterpret visual information if they did not receive sufficient guidance.

One teacher stated, "Technology is useful, but the teacher must still direct the learning. Students may see the animation, but they may not know which part is important" (T1). This statement highlights the need for pedagogical control in digital learning. Another teacher explained that not all digital resources were suitable for classroom use. “Some videos look attractive, but the explanation is too fast or not aligned with the curriculum. I have to select and modify the material before using it” (T2). This finding shows that digital technology required teacher judgment, content knowledge, and instructional design competence.

Observations showed that conceptual understanding improved when teachers linked digital media with prior knowledge and real-life examples. In a lesson on the human coordination system, the teacher used digital animation to explain nerve impulses, then asked students to relate the process to reflex movements in daily life. Students were able to explain why the hand moves quickly after touching a hot object. This showed that teacher mediation helped students connect abstract processes with familiar experiences. The finding suggests that the digital learning model should include clear teacher roles, guiding questions, scaffolding, and reflection stages.

Digital Learning Faced Constraints Related to Access, Readiness, and Classroom Management

The fourth theme concerns practical constraints in implementing digital technology-based biology learning. The main constraints included uneven student access to devices, unstable internet connection, limited classroom time, and different levels of digital literacy. Some students had difficulty opening digital materials because of weak internet access. Others needed more time to understand how to use simulation tools. One student stated, “Sometimes the internet is slow, so I cannot follow the activity at the same time as my friends” (S3). Another student explained, “I understand the lesson better with simulation, but at first I was confused about which button to use” (S9).

Teachers also reported that digital learning required more preparation time. They had to select media, prepare backup materials, test applications, and design activities that matched learning objectives. T2 stated, “The challenge is preparation. If the media does not work during class, the learning flow can be disturbed” (T2). Observation notes confirmed that technical problems sometimes interrupted the learning process. In one session, several students could not access the digital module at the same time, so the teacher reorganized the activity into group work. This adjustment helped the lesson continue, but it also showed that digital learning needed flexible classroom management.

Despite these constraints, the findings show that teachers and students still perceived digital technology as useful for biology learning. The constraints did not reject the value of technology. Instead, they showed that a digital learning model must include practical design principles, such as offline access, group-based activities, simple user interfaces, teacher guidance, and alternative learning resources. The findings also suggest that schools need to support digital learning through infrastructure, teacher training, and technical assistance.

The Emerging Digital Biology Learning Model

Based on the data analysis, the digital technology-based biology learning model developed in this study consists of five main stages: orientation, visualization, exploration, conceptual construction, and reflection. In the orientation stage, the teacher introduces the learning problem, activates prior knowledge, and explains the learning objective. In the visualization stage, students observe biological concepts through digital media such as animation, simulation, augmented reality, or interactive modules. In the exploration stage, students manipulate variables, answer guiding questions, discuss findings, and compare digital representations with biological explanations. In the conceptual construction stage, students formulate explanations, correct misconceptions, and connect concepts with real-life contexts. In the reflection stage, students summarize what they have learned and complete formative assessments to check conceptual understanding.

This model emerged from the need to avoid technology-centered learning. The findings show that digital tools must support conceptual construction, not replace pedagogical interaction. The model also emphasizes that students need space to observe, question, discuss, and reflect. As T1 stated, “The best result happens when students see the process, discuss it, then explain it again in their own words” (T1). This statement captures the central meaning of the model. Digital biology learning becomes effective when technology, teacher facilitation, student activity, and conceptual reflection work together in one learning sequence.

Discussion

The findings of this study confirm that digital technology can support conceptual understanding in biology when it is integrated into a structured pedagogical model. The first finding shows that digital visualization helps students understand abstract biological concepts. This result aligns with Suprapto et al. (2024), who argue that biology learning, especially plant anatomy, requires visuospatial transformation to help students connect structure and function. The finding also supports Miller and Yoon (2023), who explain that simulations can help students understand complex biological systems through modeling and observation of dynamic relationships. In this study, students did not only remember biological terms. They also began to explain processes, sequences, and relationships among concepts after interacting with digital representations.

This study also supports the constructivist view of learning. Students developed conceptual understanding when they actively interpreted visual information, discussed it with peers, and connected it with prior knowledge. Afnan and Puspitawati (2024) explain that augmented reality can be understood through constructivist theory because students construct knowledge through interaction with digital representations. The present study extends this idea by showing that digital representation alone is not sufficient. Students need inquiry questions, peer discussion, teacher scaffolding, and reflection to transform visual experience into conceptual understanding. Therefore, the contribution of this study lies in emphasizing the pedagogical process behind digital biology learning.

The finding on student engagement is consistent with previous studies on digital technology in biology education. Weng et al. (2020) found that augmented reality improves biology learning by providing concrete visual experiences. Liono et al. (2021) also showed that visual support through augmented reality can help students learn better. However, the current study adds a qualitative explanation of why engagement increased. Students became more engaged because digital tools allowed them to manipulate variables, observe changes, and discuss explanations. This finding suggests that engagement was not caused only by the novelty of technology. It emerged because students were involved in meaningful inquiry activities.

The role of teachers in this study is also important. The findings show that teacher facilitation determined whether digital technology supported or weakened conceptual understanding. This result is consistent with Timotheou et al. (2023), who explain that digital transformation in schools depends on teacher capacity, school readiness, and learning design. It also aligns with Haleem et al. (2022), who state that digital technologies change the educational process by creating more interactive and flexible learning environments. However, this study shows that flexibility must be guided by clear pedagogical decisions. Teachers must select appropriate media, design guiding questions, manage classroom interaction, and correct misconceptions.

The findings also reveal that digital learning faces practical constraints. These include limited devices, unstable internet access, varied student digital literacy, and increased preparation time for teachers. This result supports Hadi et al. (2025), who found that ICT-based biology learning in Indonesia still faces challenges related to teacher readiness, facility availability, and sustainability. It is also consistent with Al-Ansi et al. (2023), who explain that augmented reality and virtual reality implementation in education is influenced by institutional readiness, cost, and technological access. The present study adds that these constraints shape classroom interaction directly. Technical problems can interrupt learning flow, reduce student participation, and require teachers to redesign activities in real time.

The findings differ slightly from studies that emphasize the direct effectiveness of technology on learning outcomes. For example, Vekli and Çalık (2023) found that web-based biology learning environments positively affect academic performance. Majewska and Vereen (2023) also reported that immersive virtual reality can support learning experiences in online biology courses. In contrast, this study shows that technology does not automatically produce conceptual understanding. Students benefited from technology when it was embedded in a learning sequence that included orientation, visualization, exploration, conceptual construction, and reflection. This difference may be caused by the qualitative focus of this study, which examines experience and process rather than only measuring achievement.

The emerging model in this study offers a practical contribution to biology learning. The five-stage model helps teachers use digital technology in a more systematic way. The orientation stage prevents students from using technology without clear learning direction. The visualization stage helps students observe abstract processes. The exploration stage encourages inquiry and collaboration. The conceptual construction stage helps students organize explanations and correct misconceptions. The reflection stage allows teachers to assess conceptual understanding. This model responds to the gap identified by Faria and Miranda (2024), who note that studies on augmented reality in science and biology still need stronger attention to implementation contexts and pedagogical strategies.

Theoretically, this study contributes to the development of digital biology learning by integrating constructivist learning, multimedia learning, visuospatial learning, and experiential learning. The findings show that conceptual understanding develops through interaction among digital representation, teacher mediation, student inquiry, and reflective explanation. This supports Mansour et al. (2025), who argue that embodied learning through augmented reality can strengthen engagement and understanding when students actively participate in learning experiences. In the context of biology education, this means that students need to experience biological concepts through multiple modes, including visual, verbal, interactive, and reflective activities.

Practically, the findings imply that biology teachers need more than access to digital media. They need a model that guides how technology should be selected, sequenced, and evaluated. Teachers should choose digital tools based on concept characteristics, student needs, and classroom conditions. Schools also need to provide infrastructure support, technical assistance, and professional development for teachers. Sattar et al. (2025) show that augmented reality can increase student engagement in secondary biology education when it fits classroom needs and resource conditions. Therefore, digital biology learning should be designed with realistic consideration of school context.

Future research can expand this study in several directions. First, further studies can test the model in different school contexts, such as rural schools, urban schools, and schools with limited digital infrastructure. Second, future research can examine the model through mixed methods to combine qualitative understanding with quantitative measurement of conceptual understanding. Third, future studies can focus on specific biology topics, such as genetics, ecosystem dynamics, plant anatomy, or human physiology. Fourth, researchers can explore teacher professional development models that support the design and implementation of digital biology learning. These directions can strengthen the relevance of the model and support its broader application in biology education.

4. Conclusions

This study concludes that a digital technology-based biology learning model can strengthen students' conceptual understanding when technology supports visualization, inquiry, discussion, and reflection in one structured learning process. The findings show that students understood abstract biological concepts more clearly when teachers used digital visualization, simulations, interactive media, and guided questions to connect structure, function, process, and real-life contexts. The study also found that technology did not automatically improve learning. Teacher facilitation, student engagement, classroom readiness, and access to digital facilities shaped the quality of conceptual understanding. The five-stage model consisting of orientation, visualization, exploration, conceptual construction, and reflection offers a systematic framework for integrating digital technology into biology learning.

Theoretically, this study contributes to constructivist, multimedia, visuospatial, and experiential learning perspectives by showing how digital representation supports concept construction through active student participation and teacher scaffolding. Practically, the findings provide guidance for biology teachers in designing digital learning that is not only visually attractive but also pedagogically meaningful. From a policy perspective, schools need to support digital biology learning through infrastructure, teacher training, technical assistance, and flexible learning resources. Further research should test this model in different school contexts, use mixed-method designs to measure its impact on conceptual understanding, and explore its application to specific biology topics such as genetics, plant anatomy, ecosystem dynamics, and human physiology.

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