Digital Simulations in Science Learning: A Student Perspective on Interactive, Engagement, Conceptual Understanding, and Learning Satisfaction

Wahidin Wahidin[1], Grace Gutierrez[2], Kamisah Osman[3], Supaphorn Akkapin [4], Michael Lip Thye Tan[5]
[1]Department of Biology Education, Faculty of Teacher Training and Education, Universitas Siliwangi, Indonesia
[2]Temple College and Alamo Colleges, Texas, United States of America
[3]Universiti Kebangsaan Malaysia, Malaysia
[4]International College of Rajamangala University of Technology Krungthep, Thailand
[5]Education Research Scientist, Nanyang Technological University, Singapore

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Corresponding Author:
Wahidin Wahidin
Universitas Siliwangi, Indonesia
Email: wahidin@unsil.ac.id

ABSTRACT
Digital-based learning media offers a solution to overcome the limitations of laboratory practice and creates opportunities for more interactive, visual, and contextual learning experiences. Digital simulations in science education represent an innovative form of learning media in the era of technological transformation. However, students' perceptions as users of learning media are closely linked to key indicators used to evaluate its effectiveness. This study aims to analyze students' perceptions of using digital simulation media in relation to learning interactivity, engagement, conceptual understanding, and satisfaction within the context of science education. A quantitative approach was employed using a survey method. Data were collected through online questionnaires from 400 high school and university students in Indonesia, Malaysia, Thailand, Singapore, and the United States of America. The data were then analyzed using Structural Equation Modeling (SEM) with the assistance of AMOS software. The results indicated that all proposed hypotheses were statistically supported. Students' perceptions of digital simulations had a significant positive effect on perceived learning interactivity (H1), learning engagement (H2), conceptual understanding (H3), and learning satisfaction (H4). Positive student perceptions of digital learning media were strongly associated with improvements in the quality of learning interactivity, conceptual understanding, and overall satisfaction. This study makes an important empirical contribution to the development of digital learning media based on student perceptions and provides a foundation for selecting digital-based learning tools that are more responsive, engaging, and effective in the future.

Keywords: Digital Simulations, Interactive Learning, Student Perceptions, Learning Engagement, Conceptual Understanding, Learning Satisfaction, Learning Media.

1. INTRODUCTION

In the era of globalization and rapid technological advancement, mastery of science and technology has become a key determinant of a nation's human resource competitiveness. Science education at the secondary and tertiary levels plays a critical role in equipping students with essential skills such as critical thinking (Ma et al., 2023), problem-solving (Nguyện et al., 2025), and scientific literacy (Fortus et al., 2022). However, science learning continues to face persistent challenges. Many students struggle to grasp abstract concepts such as Newton's laws (Comillo & Mistades, 2025), chemical reactions (Dood & Watts, 2023), or cell mechanisms (Keen & Sevian, 2022) due to learning approaches that remain predominantly conventional and teacher-centered. According to Pacadaljen (2024), these difficulties are further exacerbated by limited laboratory facilities, restricted time for hands-on practice, and a lack of contextualized learning strategies. As a result, students often develop negative perceptions of science education, which are reflected in low learning interest, weak motivation, and poor conceptual understanding.

Digital transformation has permeated nearly all sectors of society and has had a significant impact on the education system (Cantú-Ortiz et al., 2020), particularly in the learning media (Nurdin et al., 2023). The effects of the COVID-19 pandemic have accelerated the shift toward technology-integrated learning media, prompting educational institutions to reassess the effectiveness of traditional teaching methods. This digital shift presents long-term opportunities for the continuous integration of digital learning tools as part of educational innovation. The emergence of various digital platforms, applications, and interactive content has fundamentally transformed the way instructional material is delivered to students. According to González-Zamar et al. (2020); and Mhlongo et al. (2023), digital technologies facilitate more visual, interactive, and flexible learning experiences, which can be tailored to accommodate individual learning styles.

According to Cho & Park (2023), digital simulations are visual and interactive representations of scientific phenomena that allow students to explore science concepts within virtual environments that closely resemble real-world conditions. In the context of limited laboratory facilities, digital simulations offer a safe, cost-effective, and accessible alternative to traditional laboratory experiments (Reyes et al., 2024). Students can simulate a wide range of scientific topics, such as projectile motion, photosynthesis processes, and chemical reactions, by modifying parameters without the need for physical laboratory equipment. Beyond their role as visualization tools, digital simulations enable students to manipulate variables, observe outcomes, and formulate predictions that align with the core principles of scientific inquiry. Kefalis et al. (2025) said that the pedagogical strength of digital simulations lies in their capacity to support exploratory and inquiry-based learning approaches, which are often difficult to implement in conventional classroom settings. Prior studies have demonstrated that digital simulations can significantly enhance conceptual understanding, scientific reasoning, and student engagement in science learning (Banda & Nzabahimana, 2021; Chang et al., 2023; Pang et al., 2025). These findings underscore the transformative potential of simulations in bridging the gap between theoretical knowledge and practical experimentation, especially in resource-constrained educational environments.

Amid the growing enthusiasm for the integration of technology in education, one critical aspect that requires serious attention is students' perception. Donkin & Rasmussen (2021) and Fahruddin et al. (2022) said that the student perception serves as a key indicator in evaluating the effectiveness of learning media. Teachers and educational media developers often make assumptions about the success of a digital learning innovation without fully understanding students' actual experiences. Even when a learning tool is designed with advanced interactive and visual features, its success ultimately depends on how students perceive and engage with it during the learning process. Perceptions reflect students' subjective experiences, including how interested they feel, whether the tool facilitates their understanding of the material, and their overall satisfaction with the learning experience. Positive perceptions are associated with greater cognitive, emotional, and behavioral engagement in learning, whereas negative perceptions can hinder motivation, reduce conceptual understanding, and lower learning satisfaction (El-Sayad et al., 2021; Naibert et al., 2022; M. Singh et al., 2022; Tzafilkou et al., 2021). As such, assessing student perceptions of digital learning media is not only essential but also serves as an early indicator for developing more responsive, adaptive, and learner-centered instructional tools.

One critical yet often overlooked issue in studies of interactive digital learning media is student engagement. Engagement plays a pivotal role in influencing learning outcomes (Xiong, 2025; Xu et al., 2023), particularly within technology-enhanced learning environments. Student engagement extends beyond mere physical presence; it encompasses cognitive (active thinking), affective (interest and emotional involvement), and behavioral (active participation) dimensions (Luo et al., 2022; Wong & Liem, 2022; Xu et al., 2023). In digital learning environments such as interactive simulations, students are expected to actively observe, explore, and reflect on the content presented virtually. When students engage only passively or simply follow instructions without grasping the underlying context, the pedagogical potential of the technology is significantly diminished. Prior research has indicated that a lack of student engagement is a major contributing factor to the failure of technology integration in education (Bond et al., 2020; Wang et al., 2022). Therefore, it is essential for media developers and educators to focus not only on the design and interactive features of digital tools but also on how these tools can holistically stimulate student engagement. Student engagement should not be treated as a secondary outcome of technology use;

rather, it must be positioned as a primary objective to ensure that learning becomes truly meaningful and transformative.

The ultimate goal of the learning process is to achieve deep and enduring conceptual understanding (Higgins et al., 2021; Ruiz-Martín & Bybee, 2022), rather than mere rote memorization. In the context of science education, conceptual comprehension plays a critical role, as students are expected to explain natural phenomena, analyze cause-and-effect relationships, and predict experimental outcomes based on scientific principles they have learned. One of the key challenges in science learning is students' difficulty in connecting abstract concepts to real-world phenomena (Dare et al., 2021; A.-L. Tan et al., 2023). This difficulty is often rooted in the persistence of conventional, teacher-centered instructional approaches. In response to this challenge, digital learning media have emerged as innovative solutions capable of visualizing complex scientific concepts and providing opportunities for students to conduct self-directed experimentation within safe, flexible virtual environments. The use of digital simulations fosters more active and reflective engagement in science learning by allowing learners to manipulate variables, observe outcomes, and build meaning through exploration. These features position digital simulations as powerful pedagogical tools to support inquiry-based and constructivist learning approaches.

Given these various challenges, there is an urgent need to evaluate the effectiveness of digital simulations in science education based on students' direct perceptions as primary users. This study aims to analyze students' perceptions of the use of digital simulations in science learning, specifically examining how these perceptions relate to their views on learning interactivity, engagement, conceptual understanding, and learning satisfaction. The study is expected to make a significant empirical contribution to the growing body of research on digital learning media by centering students' perspectives. Furthermore, the findings may serve as a foundation for the selection and development of digital-based learning tools that are more responsive, engaging, and effective for future educational practices.

2. METHOD

This study employed a quantitative approach using covariance-based Structural Equation Modeling (SEM) (de Rooij et al., 2023), analyzed with the AMOS software. SEM was selected due to its capability to simultaneously examine causal relationships among latent constructs within an integrated model. The primary objective of employing this method is to analyze students' perceptions of the use of digital simulations in science education, particularly their perceptions regarding learning interactivity, engagement, conceptual understanding, and learning satisfaction.

The research sample consisted of 400 participants, ranging from high school to university students, selected through purposive sampling across five countries: Indonesia, Thailand, Malaysia, Singapore, and the United States of America. The inclusion criterion required participants to have prior experience using digital simulation media in the context of interactive science learning. Data were collected via an online questionnaire developed to assess students' perceptions across five key constructs presented in Table 1: (1) Digital simulation (ease of use, comfort, and interest), adapted from Juera (2024); (2) Perceived learning interactivity, adapted from Cole et al. (2021); (3) Perceived student engagement, adapted from Shahzad et al. (2024); (4) Perceived Conceptual Understanding, adapted from Deribigbe et al. (2022); and (5) Perceived Learning Satisfaction, adapted from Cramarenco et al. (2023). Each construct was measured using four statement items on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). The instruments listed in Table 1 were developed based on prior literature and underwent both validity and reliability testing prior to distribution by the researchers. All data collection procedures were conducted ethically with the informed consent of the respondents. Participant identities were kept confidential, and participation was entirely voluntary.

Table 1. Student Perception Questionnaires

Student Perception	Code	Item Statements
Digital simulation in interactive science learning	SD1	Digital simulations make learning science more interesting.
	SD2	I feel comfortable using digital simulations in learning.
	SD3	Digital simulations are easy to use and not confusing.
	SD4	Digital simulations provide a different learning experience compared to conventional methods.
Student perceptions of learning interactivity	LI1	I can directly interact with learning materials through digital simulations.
	LI2	Digital simulations allow me to explore scientific concepts independently.
	LI3	Digital simulations make the learning process more active and participatory.
	LI4	I can conduct experiments and observe the results virtually through simulations.

Student perceptions of engagement	SE1	I am more focused when learning with digital simulations.
	SE2	I feel challenged to understand the material through digital simulations.
	SE3	My learning time feels more productive when using digital simulations.
	SE4	I feel more motivated to learn science using simulations.
Student perceptions of conceptual understanding	CU1	Digital simulations help me understand difficult science concepts.
	CU2	I find it easier to recall concepts after learning through simulations.
	CU3	I can observe cause-and-effect relationships in scientific experiments through simulations.
	CU4	I feel that my understanding has improved after using digital simulations.
Student Perceptions of Learning Satisfaction	LS1	I prefer learning science through digital simulations over traditional lectures.
	LS2	I hope digital simulations are used more frequently in learning.
	LS3	I am satisfied with my learning experience using digital simulations.
	LS4	I would recommend digital simulations to my peers.

The SEM analysis was conducted in two stages: (1) measurement model analysis to assess the validity and reliability of students' perception constructs for each aspect, using the criteria of standardized loading ≥ 0.50, Average Variance Extracted (AVE) ≥ 0.50, and Composite Reliability ≥ 0.70; and (2) structural model analysis to examine the relationships among students' perceptions as hypothesized. Model fit was evaluated using several indices, including Chi-square/df ≤ 3, Comparative Fit Index (CFI) ≥ 0.90, Tucker-Lewis Index (TLI) ≥ 0.90, and Root Mean Square Error of Approximation (RMSEA) ≤ 0.08.

Based on Table 1, four hypotheses were formulated to examine the impact of digital simulations from the perspective of students across various aspects of learning. H1: According to students' perceptions, digital simulations have a positive and significant influence on learning interactivity in interactive science learning. H2: According to students' perceptions, digital simulations have a positive and significant influence on student engagement in interactive science learning. H3: According to students' perceptions, digital simulations have a positive and significant influence on conceptual understanding in interactive science learning. H4: According to students' perceptions, digital simulations have a positive and significant influence on learning satisfaction in interactive science learning.

3. RESULTS AND DISCUSSION

3.1. Results

This study involved 400 participants from five regions: Indonesia, Thailand, Singapore, the United States of America, and Malaysia. The majority of participants were upper secondary and higher education students who had prior experience using digital simulation-based learning media in science education. The results of the construct validity test using Confirmatory Factor Analysis (CFA), as presented in Table 2, indicate that all indicators of the five latent constructs (Perception of Digital Simulation, Perception of Learning Interactivity, Perception of Student Engagement, Perception of Conceptual Understanding, and Perception of Learning Satisfaction) had factor loadings ≥ 0.60, demonstrating good indicator validity.

Table 2. Construct Validity Results

Construct	Indicator	Factor Loading
Perceptions of Digital Simulation	DS1–DS4	0.74 – 0.86
Perceptions of Interactive Learning	LI1–LI4	0.71 – 0.83
Perceptions of Student Engagement	SE1–SE4	0.76 – 0.88
Perceptions of Conceptual Understanding	CU1–CU4	0.73 – 0.85
Perceptions of Learning Satisfaction	LS1–LS4	0.77 – 0.89

The construct reliability test results presented in Table 2 indicate that all latent variables in this research model exhibit a high level of internal consistency. Furthermore, the results show that the values of

Cronbach's Alpha and Composite Reliability (CR) for each construct exceed 0.7, indicating that the items within each construct consistently measure the intended concept. Additionally, the Average Variance Extracted (AVE) values for all constructs are above 0.5, meeting the criteria for convergent validity. This suggests that the proportion of variance explained by the latent constructs for their respective indicators is greater than the measurement error, indicating that the constructs have a strong ability to represent the theoretical concepts being measured.

The structural model was developed based on the relationships among latent variables, and model fit was assessed using the AMOS software. This analysis aimed to determine whether the theoretical model developed aligns with the empirical data collected from the respondents. The results presented in Table 3 indicate that the model used in this study demonstrates a good level of fit with the observed data.

Table 3. Goodness-of-Fit

Fit Index	Value (AMOS Output)	Results
Chi-squar/df	1.746 ≤ 3	Suitable
GFI	0.978 ≥ 0.9	Suitable
AGFI	0.916 ≥ 0.9	Suitable
TLI	0.954 ≥ 0.9	Suitable
CFI	0.939 ≥ 0.9	Suitable
SRMR	0.057 ≤ 0.08	Suitable
RMSEA	0.068 ≤ 0.08	Suitable

Once the structural model was confirmed to have a good fit with the data, the next step involved testing the formulated hypotheses. This testing was conducted by examining the path coefficients and the statistical significance of the relationships among the latent variables within the model. The path coefficient values indicate the direction and strength of the relationships between constructs, while the p-values are used to determine whether these relationships are statistically significant. A hypothesis is considered supported if the p-value is less than 0.05. The results of the hypothesis testing in this study are presented in Table 4.

Table 4. Hypothesis Results

Hypothesis	Path	P-value	Result
H1	DS → LI	0.026	Accepted
H2	DS → SE	0.031	Accepted
H3	DS → CU	0.019	Accepted
H4	DS → LS	0.014	Accepted

The results of the hypothesis testing presented in Table 4 indicate that all relationships among the variables in the structural model have a positive and significant effect. Students' perceptions of using digital simulation-based learning media were found to have a significant impact on learning interactivity (H1), learning engagement (H2), conceptual understanding (H3), and learning satisfaction (H4). These findings reinforce the importance of designing interactive and engaging digital learning media to optimize students' positive perceptions and enhance the overall effectiveness of the learning process.

3.2. Students' Perceptions of Digital Simulation-Based Learning Media in Promoting Learning Interactivity

The results of the structural path analysis using SEM indicate that students' perceptions of using digital simulations have a positive and significant influence on their perceptions of interactivity in interactive science learning. Students perceive digital simulations as easy to use, engaging, and capable of providing an enjoyable learning experience. They tend to feel that they can actively interact with the learning content. This reflects how initial perceptions of technological quality can influence perceptions of the overall learning process. A study by Lahlali et al. (2023) and Pang et al. (2025) demonstrated that the integration of interactive simulations in science learning significantly enhances student interaction and motivation, particularly because students feel they have greater control over their learning process. In this context, a positive perception of simulations not only serves as a supporting factor but also acts as a catalyst that promotes active and exploratory engagement in learning.

According to the Connectivism learning theory, learning occurs within networks that dynamically connect individuals to digital knowledge resources (Almalki et al., 2025; Pandya et al., 2024). In this framework, digital simulations function as interactive nodes that connect students with scientific content, conceptual frameworks, and problem-solving tasks in a dynamic fashion. When students feel empowered to explore and manipulate variables within a simulation, they engage in active and non-linear learning, gaining agency over their virtual experiments. This sense of control enhances their ownership of the learning process. A recent empirical study by Mukhlisa et al. (2024) demonstrates that connectivist learning environments significantly support learner autonomy, network-based knowledge construction, and higher-order reflection in digital contexts. Within this theoretical lens, students' perceptions that digital simulations enable decision-making in virtual experiments not only align with Connectivism's principles but also serve to promote deeper engagement and meaningful learning.

The concepts of Affordance (Dittrich et al., 2022) and Scaffolding (Tawfik et al., 2024) implicitly explain how intuitive simulation design can enhance students' perceptions of interactivity in learning. Affordance refers to interface features in digital media that naturally prompt users to take certain actions, such as clicking, dragging, or modifying variables. When these affordances are well-designed, students feel guided indirectly, without the need for explicit instructions from teachers. Supported by tBanda & Nzabahimana (2021) and Damaševičius & Sidekerskienė (2024), simulations that offer visual feedback and allow guided exploration significantly improve student participation. Strengthened by the literature review of Kefalis et al. (2025), which concluded that digital simulations in STEM education consistently enhance interactivity, particularly when designed to support both independent and collaborative exploration. Students report feeling more engaged when they can directly interact with simulations and receive immediate feedback on their actions. Their perception that simulations encourage exploration, observation, and problem-solving fosters a more proactive approach to understanding scientific concepts. Thus, students' perceptions of digital simulations are not merely related to technical or aesthetic aspects, but rather reflect how they interpret and engage with interactive learning experiences. Overall, the findings of this study underscore the importance of designing digital learning media that are responsive to students' perceptions and expectations, thereby supporting more interactive and meaningful learning processes.

3.3. Students' Perceptions of Digital Simulation-Based Learning Media in Student Engagement

The analysis results indicate that students' perceptions of using digital simulations have a positive and significant impact on their engagement in science learning. Students reported that digital simulations were easy to use, enjoyable, and relevant to the learning context. They also stated that simulations helped them stay more focused, active, and motivated to participate in the learning process. These findings are consistent with the study by Liu et al. (2022) and Ouahi et al. (2022), the use of interactive simulations can enhance students' focus and interest in complex science topics. Positive perceptions of learning through digital simulations foster a sense of comfort and trigger intrinsic interest, ultimately encouraging deeper cognitive, affective, and behavioral engagement.

According to the Theory of Planned Behavior (Hagger et al., 2022), an individual's perception of a particular activity, such as the use of digital learning media, can influence their attitudes, intentions, and actual behavior. In the context of education, students' positive perceptions of the ease of use and perceived usefulness of digital simulations encourage more active engagement in learning activities. Research conducted by Muir et al. (2022) indicates that digital simulations can significantly enhance student engagement by offering visual and interactive tools that support contextual and engaging understanding of the material. In science education, which often involves abstract and complex concepts, fostering student engagement is essential to ensure that learning processes are both effective and meaningful.

Students' perceptions of digital simulations have the potential to make learning materials more concrete, engaging, and enjoyable, thereby increasing their enthusiasm for participating in classroom activities. This aligns with the Engagement Theory (Xu et al., 2023), which outlines three core dimensions of student engagement: cognitive, affective, and behavioral. All of these dimensions can be stimulated by positive perceptions of educational media. In other words, engagement is not solely determined by the content or the teacher's instructional strategies, but also by how students interpret and experience the use of technology in their learning process. Consequently, students' perceptions of the effectiveness and learning experience through digital simulation media serve as a critical driving factor for deeper and more meaningful engagement.

Learning engagement stimulated by positive perceptions of digital learning media has implications for the development of more sustainable learning attitudes. Students who feel engaged are more likely to demonstrate persistence, curiosity, and initiative to learn beyond formal class hours. This is supported by a study by Lee et al. (2021), which found that students who were emotionally and cognitively engaged while using simulations showed increased participation in discussions and exploratory projects. These findings reinforce the assumptions of Self-Determination Theory (Luarn et al., 2023), which emphasizes the importance of fulfilling the needs for competence and engagement in sustaining intrinsic motivation.

3.4. Students' Perceptions of Digital Simulation-Based Learning Media on Conceptual Understanding

The study's findings indicate that students' perceptions of digital simulation-based learning media have a positive and significant effect on their conceptual understanding in interactive science learning. Students who view digital simulations as informative, easy to understand, and enjoyable learning tools tend to report an improvement in their comprehension of complex scientific concepts. This positive perception arises from the advantages of digital simulations in visualizing scientific processes that are difficult to observe directly, such as chemical reactions, particle motion, or energy transformations. Supporting this, Diab et al. (2024) and Ogegbo & Ramnarain (2022) revealed that the use of digital simulations significantly aids students in building connections between theory and practice in science, particularly when students' initial perceptions of the technology are positive and open.

Piaget's and Vygotsky's Constructivist Theories (Afnan & Puspitawati, 2024; Karantalis & Koukopoulos, 2022) provide a crucial conceptual framework for understanding how digital media can support conceptual understanding. From a constructivist perspective, students construct their own understanding through active, exploratory, and meaningful learning experiences. When students use digital simulations independently or with minimal guidance, they take an active role in exploring variables, observing their effects, and reflecting on the processes involved. Students' perception that simulations allow them to experiment and make mistakes without real-world consequences fosters the formation of deeper knowledge. In other words, students' perception of having space for exploration and experimentation within digital simulations serves as a key driver for enhancing conceptual understanding.

Supported by Herrera et al. (2024) indicates that students who hold positive perceptions of the utility of digital simulations achieve higher conceptual understanding scores compared to those with neutral or negative perceptions. Technology-based instructional media can be optimally utilized when students are given the opportunity to assess and experience its benefits within the learning context. When students perceive digital simulations as helpful tools for simplifying complex concepts, they are more motivated to use them to their fullest potential and to engage in more meaningful learning experiences. The conceptual understanding gained through simulations also tends to be more enduring, as it is developed through concrete and reflective learning processes.

Students' perceptions of the clarity, navigability, and visual appeal of digital simulations should be a primary consideration for educators and digital content developers. When students perceive simulations as accurate, intuitive, and easy to navigate, they tend to feel more confident in their own understanding. A recent study published in 2022 demonstrates that increased clarity and user-friendliness of simulation tools corresponded with higher levels of student confidence and satisfaction in simulation-based learning environments (Stead et al., 2022). This finding suggests that design elements that enhance perceived clarity and meaningfulness significantly influence the cognitive effectiveness of simulations in facilitating conceptual understanding.

3.5. Students' Perceptions of Digital Simulation-Based Learning Media on Learning Satisfaction

Analysis results indicate that, from students' perspectives, the use of digital simulation-based learning media has a significant influence on their level of learning satisfaction in science education. Students who perceive digital simulations as engaging, easy to use, and supportive of material comprehension report higher levels of satisfaction. This satisfaction arises not only from the academic outcomes but also from the learning experience itself, which is perceived as more enjoyable and meaningful. Recent research supports this finding. For instance, a study by Alqahtani et al. (2022) and K. H. Tan et al. (2021) found that students' positive perceptions of digital learning environments strongly correlate with higher learning satisfaction. This reinforces the notion that students' perceptions of the features and benefits of digital simulations play a key role in shaping whether or not their learning experience is satisfying.

Based on the Expectation-Confirmation Theory (Rajeh et al., 2021; Ye et al., 2023), a relevant explanation can be provided. This theory states that learning satisfaction arises when students' initial expectations of a learning method are met or exceeded through actual experience. In relation to the findings of this study, when students expect that digital simulations will help them learn in an engaging and effective way, their learning satisfaction tends to increase. Perceptions of the usefulness, ease of use, and relevance of digital simulations play a major role in shaping students' expectations. When digital simulations are perceived as successful in facilitating conceptual understanding, providing opportunities for exploration, and enhancing learning motivation, students are more likely to report high levels of satisfaction with the learning process.

Students' learning satisfaction is directly influenced by their perception of the effectiveness and user-friendliness of the technology employed in the learning process (H. Singh et al., 2024). Well-designed digital simulations in terms of interactivity, visualization, and instructional support can enhance students' positive perceptions and subsequently strengthen their learning satisfaction. Students who feel that simulations help them gain confidence, maintain focus, and foster independence in understanding the material tend to report higher levels of satisfaction. This satisfaction also contributes to a more positive attitude toward science education overall, including a sustained interest in continued learning and exploration. Empirical evidence supports this view: a recent study by Kiegaldie & Shaw (2023) and Gebreheat et al. (2022) confirms that digital simulations significantly improve students' confidence, knowledge acquisition, and satisfaction in STEM education settings. Another study by Casallas-Hernández et al. (2025) on high-fidelity simulation in nursing education revealed strong acceptance, high perceived usefulness, and ease of use among students highlighting the importance of design quality in enhancing satisfaction.

3.6. Implications of Findings for Digital Learning Media

The findings of this study offer important implications for the development and implementation of digital-based learning media. Based on students' perceptions, well-designed digital simulation-based learning media can significantly enhance interactivity, engagement, conceptual understanding, and learning satisfaction. This indicates that digital learning media should not merely serve as visual aids, but function as cognitive bridges that facilitate the construction of scientific knowledge. Therefore, media developers and educators must ensure that the digital learning tools they employ adhere to user-centered design principles, taking into account the students' overall learning experience. The selection of digital learning media should prioritize intuitiveness, accessibility, real-time responsiveness to user actions, and the ability to present instructional content in an exploratory and meaningful way. Involving students in the evaluation process of digital learning media can be a strategic approach to ensure that the content and features developed are aligned with actual needs in the classroom. Students' perceptions serve as a valuable source of data, providing essential guidance that the effectiveness of digital learning tools should not be measured solely by academic outcomes, but must also encompass students' experiences, motivation, and overall engagement in the learning process.

4. CONCLUSION

This study concludes that students' perceptions of the use of digital simulations in science learning significantly influence four key aspects of the learning process: learning interactivity, student engagement, conceptual understanding, and learning satisfaction. All proposed hypotheses (H1–H4) were accepted, indicating a positive and significant effect of students' perceptions on these four variables. Well-designed digital simulations have been proven to create a more interactive and participatory learning environment, enhance students' focus and motivation, deepen their understanding of scientific concepts, and foster a sense of satisfaction with the learning experience. These findings provide empirical evidence that digital simulations possess strong pedagogical potential in the context of interactive science education, particularly when developed with direct attention to students' needs, perceptions, and learning experiences.

The limitation of this study lies in the sample, which was restricted to students with access to and experience using digital simulations. Future research is recommended to explore more diverse populations, such as teachers' perceptions and those of digital media designers. This study makes a theoretical contribution by enriching the literature on constructivist-based digital learning, and a practical contribution to the development of more effective, student-centered technology-based learning media. Furthermore, the findings offer valuable empirical insights for advancing digital learning media rooted in student perceptions, serving as a basis for identifying future digital learning tools that are better aligned with learners' needs, more interactive, and pedagogically effective.

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REFERENCES

Afnan, M. Z., & Puspitawati, R. P. (2024). Exploration of biological concept understanding through augmented reality: A constructivism theory approach. *JPBI (Jurnal Pendidikan Biologi Indonesia)*, *10*(3), 1139–1147. https://doi.org/10.22219/jpbi.v10i3.36896

Almalki, A. D., Alruhaili, H. S., & Tashtoush, M. A. (2025). The effectiveness of an X (Twitter)-platform-based educational model in supporting the learning of gifted students in mathematics by employing connectivism learning theory. *Multidisciplinary Reviews*, *8*(9), 2025263. https://doi.org/10.31893/multirev.2025263

Alqahtani, M. A., Alamri, M. M., Sayaf, A. M., & Al-Rahmi, W. M. (2022). Exploring student satisfaction and acceptance of e-learning technologies in Saudi higher education. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.939336

Banda, H. J., & Nzabahimana, J. (2021). Effect of integrating physics education technology simulations on students' conceptual understanding in physics: A review of literature. *Physical Review Physics Education Research*, *17*(2), 023108. https://doi.org/10.1103/PhysRevPhysEducRes.17.023108

Bond, M., Buntins, K., Bedenlier, S., Zawacki-Richter, O., & Kerres, M. (2020). Mapping research in student engagement and educational technology in higher education: a systematic evidence map. *International Journal of Educational Technology in Higher Education*, *17*(1), 2. https://doi.org/10.1186/s41239-019-0176-8

Cantú-Ortiz, F. J., Galeano Sánchez, N., Garrido, L., Terashima-Marin, H., & Brena, R. F. (2020). An artificial intelligence educational strategy for the digital transformation. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *14*(4), 1195–1209. https://doi.org/10.1007/s12008-020-00702-8

Casallas-Hernández, N., Castillo-Daza, C. A., & González-Guzmán, V. A. (2025). Acceptance and effectiveness of high-fidelity simulation in nursing education: Application of the Technology Acceptance Model (TAM). *Clinical Simulation in Nursing*, *105*, 101765. https://doi.org/10.1016/j.ecns.2025.101765

Chang, C.-Y., Kuo, H.-C., & Du, Z. (2023). The role of digital literacy in augmented, virtual, and mixed reality in popular science education: a review study and an educational framework development. *Virtual Reality*, *27*(3), 2461–2479. https://doi.org/10.1007/s10055-023-00817-9

Cho, Y., & Park, K. S. (2023). Designing Immersive Virtual Reality Simulation for Environmental Science Education. *Electronics*, *12*(2), 315. https://doi.org/10.3390/electronics12020315

Cole, A. W., Lennon, L., & Weber, N. L. (2021). Student perceptions of online active learning practices and online learning climate predict online course engagement. *Interactive Learning Environments*, *29*(5), 866–880. https://doi.org/10.1080/10494820.2019.1619593

Comillo, R. I., & Mistades, V. M. (2025). Impact of Brain-Based Teaching on the Conceptual Understanding of Newton's Laws of Motion. *Jurnal Pendidikan IPA Indonesia*, *14*(2), 216–228. https://doi.org/10.15294/jpii.v14i2.23120

Cramarenco, R. E., Burcă-Voicu, M. I., & Dabija, D.-C. (2023). Student Perceptions of Online Education and Digital Technologies during the COVID-19 Pandemic: A Systematic Review. *Electronics*, *12*(2), 319. https://doi.org/10.3390/electronics12020319

Damaševičius, R., & Sidekerskienė, T. (2024). Virtual Worlds for Learning in Metaverse: A Narrative Review. *Sustainability*, *16*(5), 2032. https://doi.org/10.3390/su16052032

Dare, E. A., Keratithamkul, K., Hiwatig, B. M., & Li, F. (2021). Beyond Content: The Role of STEM Disciplines, Real-World Problems, 21st Century Skills, and STEM Careers within Science Teachers' Conceptions of Integrated STEM Education. *Education Sciences*, *11*(11), 737. https://doi.org/10.3390/educsci11110737

de Rooij, M., Karch, J. D., Fokkema, M., Bakk, Z., Pratiwi, B. C., & Kelderman, H. (2023). SEM-Based Out-of-Sample Predictions. *Structural Equation Modeling: A Multidisciplinary Journal*, *30*(1), 132–148. https://doi.org/10.1080/10705511.2022.2061494

Deribigbe, S. A., Hamdi, W. B., Alzouebi, K., Frick, W., & Companioni, A. A. (2022). Understanding student perceptions of social computing and online tools to enhance learning. *PLOS ONE*, *17*(10), e0276490. https://doi.org/10.1371/journal.pone.0276490

Diab, H., Daher, W., Rayan, B., Issa, N., & Rayan, A. (2024). Transforming Science Education in Elementary Schools: The Power of PhET Simulations in Enhancing Student Learning. *Multimodal Technologies and Interaction*, *8*(11), 105. https://doi.org/10.3390/mti8110105

Dittrich, L., Aagaard, T., & Hjukse, H. (2022). The perceived affordances of simulation-based learning: online student teachers' perspectives. *International Journal of Educational Technology in Higher Education*, *19*(1), 60. https://doi.org/10.1186/s41239-022-00366-2

Donkin, R., & Rasmussen, R. (2021). Student Perception and the Effectiveness of Kahoot!: A Scoping Review in Histology, Anatomy, and Medical Education. *Anatomical Sciences Education*, *14*(5), 572–585. https://doi.org/10.1002/ase.2094

Dood, A. J., & Watts, F. M. (2023). Students' Strategies, Struggles, and Successes with Mechanism Problem Solving in Organic Chemistry: A Scoping Review of the Research Literature. *Journal of Chemical Education*, *100*(1), 53–68. https://doi.org/10.1021/acs.jchemed.2c00572

El-Sayad, G., Md Saad, N. H., & Thurasamy, R. (2021). How higher education students in Egypt perceived online learning engagement and satisfaction during the COVID-19 pandemic. *Journal of Computers in Education*, *8*(4), 527–550. https://doi.org/10.1007/s40692-021-00191-y

Fahruddin, F., Jana, P., Setiawan, J., Rochmat, S., Aman, A., & Yuliantri, R. D. A. (2022). Student Perception of Online Learning Media Platform During the Covid-19 Pandemic. *Journal of Education Technology*, *6*(1), 126–132. https://doi.org/10.23887/jet.v6i1.42738

Fortus, D., Lin, J., Neumann, K., & Sadler, T. D. (2022). The role of affect in science literacy for all. *International Journal of Science Education*, *44*(4), 535–555. https://doi.org/10.1080/09500693.2022.2036384

Gebreheat, G., Whitehorn, L. J., & Paterson, R. E. (2022). Effectiveness of Digital Simulation on Student Nurses' Knowledge and Confidence:An Integrative Literature Review. *Advances in Medical Education and Practice*, *13*, 765–775. https://doi.org/10.2147/AMEP.S366495

González-Zamar, M.-D., Abad-Segura, E., Luque de la Rosa, A., & López-Meneses, E. (2020). Digital Education and Artistic-Visual Learning in Flexible University Environments: Research Analysis. *Education Sciences*, *10*(11), 294. https://doi.org/10.3390/educsci10110294

Hagger, M. S., Cheung, M. W.-L., Ajzen, I., & Hamilton, K. (2022). Perceived behavioral control moderating effects in the theory of planned behavior: A meta-analysis. *Health Psychology*, *41*(2), 155–167. https://doi.org/10.1037/hea0001153

Herrera, L. A., Rodríguez, R. M., & Lopez, C. R. (2024). The Role Of Digital Simulation in Enhancing Conceptual Understanding Of Physics Among University Students. *International Journal of Mathematics and Science Education*, *1*(1), 62–68. https://doi.org/10.62951/ijmse.v1i1.82

Higgins, N., Frankland, S., & Rathner, J. (2021). Self-Regulated Learning in Undergraduate Science. *International Journal of Innovation in Science and Mathematics Education*, *29*(1). https://doi.org/10.30722/IJISME.29.01.005

Juera, L. C. (2024). Digitalizing skills development using simulation-based mobile (SiM) learning application. *Journal of Computers in Education*, *11*(1), 29–50. https://doi.org/10.1007/s40692-022-00246-8

Karantalis, N., & Koukopoulos, D. (2022). Utilizing digital storytelling as a tool for teaching literature through constructivist learning theory. *SN Social Sciences*, *2*(7), 109. https://doi.org/10.1007/s43545-022-00412-w

Keen, C., & Sevian, H. (2022). Qualifying domains of student struggle in undergraduate general chemistry laboratory. *Chemistry Education Research and Practice*, *23*(1), 12–37. https://doi.org/10.1039/D1RP00051A

Kefalis, C., Skordoulis, C., & Drigas, A. (2025). Digital Simulations in STEM Education: Insights from Recent Empirical Studies, a Systematic Review. *Encyclopedia*, *5*(1), 10. https://doi.org/10.3390/encyclopedia5010010

Kiegaldie, D., & Shaw, L. (2023). Virtual reality simulation for nursing education: effectiveness and feasibility. *BMC Nursing*, *22*(1), 488. https://doi.org/10.1186/s12912-023-01639-5

Lahlali, A., Chafiq, N., Radid, M., Moundy, K., & Srour, C. (2023). The Effect of Integrating Interactive Simulations on the Development of Students' Motivation, Engagement, Interaction and School Results. *International Journal of Emerging Technologies in Learning (IJET)*, *18*(12), 193–207. https://doi.org/10.3991/ijet.v18i12.39755

Lee, S. W., Shih, M., Liang, J., & Tseng, Y. (2021). Investigating learners' engagement and science learning outcomes in different designs of participatory simulated games. *British Journal of Educational Technology*, *52*(3), 1197–1214. https://doi.org/10.1111/bjet.13067

Liu, R., Wang, L., Koszalka, T. A., & Wan, K. (2022). Effects of immersive virtual reality classrooms on students' academic achievement, motivation and cognitive load in science lessons. *Journal of Computer Assisted Learning*, *38*(5), 1422–1433. https://doi.org/10.1111/jcal.12688

Luarn, P., Chen, C.-C., & Chiu, Y.-P. (2023). Enhancing intrinsic learning motivation through gamification: a self-determination theory perspective. *The International Journal of Information and Learning Technology*, *40*(5), 413–424. https://doi.org/10.1108/IJILT-07-2022-0145

Luo, N., Li, H., Zhao, L., Wu, Z., & Zhang, J. (2022). Promoting Student Engagement in Online Learning Through Harmonious Classroom Environment. *The Asia-Pacific Education Researcher*, *31*(5), 541–551. https://doi.org/10.1007/s40299-021-00606-5

Ma, X., Zhang, Y., & Luo, X. (2023). Students' and teachers' critical thinking in science education: are they related to each other and with physics achievement? *Research in Science & Technological Education*, *41*(2), 734–758. https://doi.org/10.1080/02635143.2021.1944078

Mhlongo, S., Mbatha, K., Ramatsetse, B., & Dlamini, R. (2023). Challenges, opportunities, and prospects of adopting and using smart digital technologies in learning environments: An iterative review. *Heliyon*, *9*(6), e16348. https://doi.org/10.1016/j.heliyon.2023.e16348

Muir, T., Wang, I., Trimble, A., Mainsbridge, C., & Douglas, T. (2022). Using Interactive Online Pedagogical Approaches to Promote Student Engagement. *Education Sciences*, *12*(6), 415. https://doi.org/10.3390/educsci12060415

Mukhlisa, H., Haenilaha, E. Y., Sunyonoa, S., Maulinaa, D., Nursafitrib, L., Nurfaizalc, N., & Noerhasmalinac, N. (2024). Connectivism and digital age education: Insights, challenges, and future directions. *Kasetsart Journal of Social Sciences*, *45*(3), 803–814. https://doi.org/10.34044/j.kjss.2024.45.3.11

Naibert, N., Vaughan, E. B., Lamberson, K. M., & Barbera, J. (2022). Exploring Student Perceptions of Behavioral, Cognitive, and Emotional Engagement at the Activity Level in General Chemistry. *Journal of Chemical Education*, *99*(3), 1358–1367. https://doi.org/10.1021/acs.jchemed.1c01051

Nguyện, L. C., Hoa, H. Q., & Hien, L. H. P. (2025). Integrating design thinking into STEM education: Enhancing problem-solving skills of high school students. *Eurasia Journal of Mathematics, Science and Technology Education*, *21*(4), 1–11. https://doi.org/10.29333/ejmste/16084

Nurdin, D., Marnita, M., & Ghani, M. F. B. A. (2023). Digital Transformation to Improve Teachers' Learning Management and Students' Science Life Skills. *Jurnal Pendidikan IPA Indonesia*, *12*(3), 329–342. https://doi.org/10.15294/jpii.v12i3.44253

Ogegbo, A. A., & Ramnarain, U. (2022). Teaching and learning Physics using interactive simulation: A guided inquiry practice. *South African Journal of Education*, *42*(1), 1–9. https://doi.org/10.15700/saje.v42n1a1997

Ouahi, M. Ben, Lamri, D., Hassouni, T., & Al Ibrahmi, E. M. (2022). Science Teachers' Views on the Use and Effectiveness of Interactive Simulations in Science Teaching and Learning. *International Journal of Instruction*, *15*(1), 277–292. https://doi.org/10.29333/iji.2022.15116a

Pacadaljen, L. M. (2024). Hurdling obstructions on instructional management of science teachers in schools with challenging laboratory resources. *Environment and Social Psychology*, *9*(10), 1–12. https://doi.org/10.59429/esp.v9i10.3027

Pandya, B., Cho, B., Patterson, L., & Abaker, M. (2024). Impact of Connectivism on Knowledge and Willingness of Students in Higher Education. *Journal of Management Education*, *48*(5), 887–914. https://doi.org/10.1177/10525629241256317

Pang, S., Lv, G., Zhang, Y., & Yang, Y. (2025). Enhancing students' science learning using virtual simulation technologies: a systematic review. *Asia Pacific Journal of Education*, 1–21. https://doi.org/10.1080/02188791.2024.2441676

Rajeh, M. T., Abduljabbar, F. H., Alqahtani, S. M., Waly, F. J., Alnaami, I., Aljurayyan, A., & Alzaman, N. (2021). Students' satisfaction and continued intention toward e-learning: a theory-based study. *Medical Education Online*, *26*(1). https://doi.org/10.1080/10872981.2021.1961348

Reyes, R. L., Isleta, K. P., Regala, J. D., & Bialba, D. M. R. (2024). Enhancing experiential science learning with virtual labs: A narrative account of merits, challenges, and implementation strategies. *Journal of Computer Assisted Learning*, *40*(6), 3167–3186. https://doi.org/10.1111/jcal.13061

Ruiz-Martín, H., & Bybee, R. W. (2022). The cognitive principles of learning underlying the 5E Model of Instruction. *International Journal of STEM Education*, *9*(1), 21. https://doi.org/10.1186/s40594-022-00337-z

Shahzad, M. F., Xu, S., Lim, W. M., Yang, X., & Khan, Q. R. (2024). Artificial intelligence and social media on academic performance and mental well-being: Student perceptions of positive impact in the age of smart learning. *Heliyon*, *10*(8), e29523. https://doi.org/10.1016/j.heliyon.2024.e29523

Singh, H., Singh, V. V., Gupta, A. K., & Kapur, P. K. (2024). Assessing e-learning platforms in higher education with reference to student satisfaction: a PLS-SEM approach. *International Journal of System Assurance Engineering and Management*, *15*(10), 4885–4896. https://doi.org/10.1007/s13198-024-02497-3

Singh, M., James, P. S., Paul, H., & Bolar, K. (2022). Impact of cognitive-behavioral motivation on student engagement. *Heliyon*, *8*(7), e09843. https://doi.org/10.1016/j.heliyon.2022.e09843

Stead, A., Michael, P., & Ondo, K. (2022). Student Navigation Through Computer-Based Simulations: What Predicts Success? *Teaching and Learning in Communication Sciences and Disorders*, *6*(1). https://doi.org/10.30707/TLCSD6.1.1649037808.621089

Tan, A.-L., Ong, Y. S., Ng, Y. S., & Tan, J. H. J. (2023). STEM Problem Solving: Inquiry, Concepts, and Reasoning. *Science & Education*, *32*(2), 381–397. https://doi.org/10.1007/s11191-021-00310-2

Tan, K. H., Chan, P. P., & Mohd Said, N.-E. (2021). Higher Education Students' Online Instruction Perceptions: A Quality Virtual Learning Environment. *Sustainability*, *13*(19), 10840. https://doi.org/10.3390/su131910840

Tawfik, A. A., Payne, L., & Olney, A. M. (2024). Scaffolding Computational Thinking Through Block Coding: A Learner Experience Design Study. *Technology, Knowledge and Learning*, *29*(1), 21–43. https://doi.org/10.1007/s10758-022-09636-4

Tzafilkou, K., Perifanou, M., & Economides, A. A. (2021). Negative emotions, cognitive load, acceptance, and self-perceived learning outcome in emergency remote education during COVID-19. *Education and Information Technologies*, *26*(6), 7497–7521. https://doi.org/10.1007/s10639-021-10604-1

Wang, J., Tigelaar, D. E. H., Luo, J., & Admiraal, W. (2022). Teacher beliefs, classroom process quality, and student engagement in the smart classroom learning environment: A multilevel analysis. *Computers & Education*, *183*, 104501. https://doi.org/10.1016/j.compedu.2022.104501

Wong, Z. Y., & Liem, G. A. D. (2022). Student Engagement: Current State of the Construct, Conceptual Refinement, and Future Research Directions. *Educational Psychology Review*, *34*(1), 107–138. https://doi.org/10.1007/s10648-021-09628-3

Xiong, X. (2025). Influence of teaching styles of higher education teachers on students‘ engagement in learning: The mediating role of learning motivation. *Education for Chemical Engineers*, *51*(April 2025), 87–102. https://doi.org/10.1016/j.ece.2025.02.005

Xu, X., Shi, Z., Bos, N. A., & Wu, H. (2023). Student engagement and learning outcomes: an empirical study applying a four-dimensional framework. *Medical Education Online*, *28*(1). https://doi.org/10.1080/10872981.2023.2268347

Ye, J.-H., Lee, Y.-S., Wang, C.-L., Nong, W., Ye, J.-N., & Sun, Y. (2023). The Continuous Use Intention for the Online Learning of Chinese Vocational Students in the Post-Epidemic Era: The Extended Technology Acceptance Model and Expectation Confirmation Theory. *Sustainability*, *15*(3), 1819. https://doi.org/10.3390/su15031819