EDUCTUM: Journal Research
Vol. 4, No. 2, Maret 2025, pp. 43~51

Digital Transformation in Biology Teaching and Learning among secondary schools in Anambra State, Nigeria

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ABSTRAK

Transformasi digital semakin memengaruhi pendidikan biologi dengan mendukung pembelajaran interaktif dan berpusat pada siswa. Studi ini meneliti pemanfaatan teknologi digital dalam pengajaran biologi, kontribusinya terhadap keterlibatan siswa, dan hambatan yang memengaruhi penerapannya. Desain survei deskriptif kuantitatif digunakan dengan melibatkan 97 responden, yang terdiri dari 17 guru biologi dan 80 siswa. Data dikumpulkan menggunakan kuesioner yang telah divalidasi dan dianalisis melalui statistik deskriptif dan ANOVA Satu Arah. Hasil penelitian menunjukkan bahwa perangkat lunak pemodelan molekuler 3D dan visualisasi anatomi adalah alat digital yang paling sering digunakan (Rata-rata = 3,44), sedangkan laboratorium virtual (Rata-rata = 1,62) dan Sistem Manajemen Pembelajaran (Rata-rata = 1,66) adalah yang paling jarang digunakan. Integrasi digital mendorong keterlibatan dalam pemecahan masalah dunia nyata (Rata-rata = 3,37), pembelajaran yang didukung multimedia (Rata-rata = 3,34), dan pembelajaran mandiri (Rata-rata = 3,32). Hambatan utama meliputi pasokan listrik yang tidak konsisten (Rata-rata = 3,42), pendanaan yang tidak memadai (Rata-rata = 3,34), dan persyaratan kurikulum yang kaku (Rata-rata = 3,30). Perbedaan signifikan ditemukan dalam pemanfaatan alat digital (p = 0,043) dan hambatan adopsi (p = 0,019). Studi ini menyimpulkan bahwa teknologi digital dapat meningkatkan pendidikan biologi jika didukung oleh infrastruktur yang memadai dan komitmen institusional.
Keyword: Transformasi Digital; Pendidikan Biologi; Alat Digital; Keterlibatan Siswa; Kecerdasan Buatan

ABSTRACT

Digital transformation is increasingly influencing biology education by supporting interactive and student-centered learning. This study investigated the utilization of digital technologies in biology teaching, their contribution to student engagement, and the barriers affecting their adoption. A quantitative descriptive survey design was employed involving 97 respondents, consisting of 17 biology teachers and 80 students. Data were collected using a validated questionnaire and analyzed through descriptive statistics and One-Way ANOVA. The findings revealed that 3D molecular modeling and anatomical visualization software were the most frequently utilized digital tools (Mean = 3.44), while virtual laboratories (Mean = 1.62) and Learning Management Systems (Mean = 1.66) were the least utilized. Digital integration promoted engagement in real-world problem solving (Mean = 3.37), multimedia-supported learning (Mean = 3.34), and independent learning (Mean = 3.32). Major barriers included inconsistent electricity supply (Mean = 3.42), inadequate funding (Mean = 3.34), and rigid curriculum requirements (Mean = 3.30). Significant differences were found in digital tool utilization (p = .043) and adoption barriers (p = .019). The study concludes that digital technologies can enhance biology education when supported by adequate infrastructure and institutional commitment.
Keyword: Digital Transformation; Biology Education; Digital Tools; Student Engagement; Artificial Intelligence

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1. INTRODUCTION

Integrating Artificial Intelligence (AI) into education is reshaping the landscape of biological sciences education, offering a transformative paradigm shift in teaching, learning, and the application of biological knowledge. Traditional approaches to teaching complex biological systems, such as genomics, molecular biology, and large-scale ecological mapping, are increasingly inadequate for addressing contemporary educational needs. Biology educators often face substantial challenges in implementing innovative pedagogical strategies due to curriculum constraints and limited instructional flexibility. As noted by Akar (2014), curriculum implementation challenges can place significant burdens on biology teachers, making it difficult to adopt effective teaching approaches. These challenges are particularly evident in developing regions where disparities in physical and digital infrastructure continue to hinder educational advancement. Farhana et al. (2024) further identified teacher readiness and systemic limitations as major obstacles to the successful integration of information and communication technology (ICT) in biology education. In this context, AI emerges as a promising solution capable of addressing both pedagogical and infrastructural gaps.

The successful integration of AI in biology education requires a strong technological foundation. Reliable digital infrastructure, particularly network connectivity, is essential for supporting advanced AI-driven educational tools (Bandaru, 2026). Once such infrastructure is established, AI can significantly enhance existing learning approaches by promoting interactive and personalized learning experiences. Traditional teacher-centered instruction is gradually being transformed through digital innovations. Ruado and Cortez (2024) demonstrated that even simple digital interventions, such as interactive slide presentations, can substantially improve student engagement and learning outcomes in biology. Beyond these basic applications, AI-powered educational technologies can create adaptive learning environments tailored to individual student needs. Game-based learning, for example, has been shown to positively influence motivation, self-efficacy, and academic performance across natural science disciplines (Soriano-Sánchez et al., 2026). Through AI-enhanced gamification, complex biological processes such as cellular mechanisms, molecular pathways, and genetic interactions can become more accessible and engaging for learners.

The future of biology education is also increasingly connected to global socio-scientific challenges. Rahmawati and Turista (2026) emphasized that biology learning should reinforce 21st-century skills to support the achievement of the United Nations Sustainable Development Goals (SDGs). AI facilitates this alignment by enabling the development of personalized and project-based learning tools. For instance, Sumiati et al. (2026) developed a digital Notion-based e-module for teaching plant structures, demonstrating how digital resources can improve students' digital literacy while replacing conventional learning materials. When integrated with AI technologies, such digital modules can adapt to students' learning pace, preferences, and academic needs, thereby enhancing learning effectiveness.

Despite these opportunities, technology alone cannot guarantee educational success. Psychological, emotional, and social factors remain essential components of effective learning environments. Mujallid (2024) highlighted the importance of digital active-learning strategies in blended learning environments for promoting social-emotional learning (SEL) and student engagement. Institutional challenges can also affect the effectiveness of educational innovation. Research by Onwuka et al. (2022) found that workplace conflicts among university staff can negatively influence institutional performance, while Onwuka and Ume (2022) reported that sexual harassment adversely affects female staff productivity. These issues illustrate how organizational and social dynamics can undermine efforts to implement innovative educational practices.

Furthermore, the overall mental well-being of educational communities significantly influences educational outcomes. Structural and political challenges may disrupt social institutions (Chukwu et al., 2018), while unforeseen crises such as pandemics highlight the importance of social support systems. Onyemaechi et al. (2025) emphasized that structured social support serves as a critical mechanism for reducing psychological distress and strengthening community resilience during disruptive periods. Similarly, Agofure et al. (2019) underscored the importance of understanding local perceptions of mental health and reducing stigma, particularly in rural communities. Such considerations are essential for ensuring that AI-enabled biology education remains inclusive, equitable, and responsive to diverse learner needs.

The ongoing digital transformation of biology education represents a shift from passive memorization toward active, immersive, and student-centered learning experiences. While digital technologies and AI-based tools offer substantial opportunities for improving biology education, several challenges remain. Curriculum implementation difficulties, teacher workload, technological readiness, and infrastructure limitations continue to affect the adoption of digital innovations, particularly in developing contexts. Moreover, there remains a limited body of empirical evidence regarding the impact of digital integration on students' engagement with complex biological concepts and the barriers faced by educators during implementation. Consequently, this study seeks to investigate the utilization of digital tools in biology education, examine their influence on student engagement, and identify the challenges encountered by biology educators in adopting digital technologies.

Based on these objectives, the study is guided by the following assumptions: first, there may be differences in the frequency of utilization among various digital tools used in biology education; second, digital integration is expected to influence student engagement in learning complex biological concepts; and third, barriers related to infrastructure, readiness, and institutional support may significantly affect educators' adoption of digital technologies. These assumptions serve as the foundation for examining the role of digital transformation and AI in advancing biology education within contemporary learning environments.

2. RESEARCH METHOD

This study employed a quantitative research approach using a descriptive survey design to investigate the utilization, impact, and barriers associated with digital technology integration in biology education. The design was considered appropriate because it enabled the systematic collection of standardized data regarding the experiences, perceptions, and classroom practices of participants involved in biology teaching and learning.

The study was conducted in educational institutions undergoing digital transformation in biology instruction. The target population consisted of biology educators and students enrolled in biological science programs. A total of 97 respondents participated in the study, comprising 17 biology teachers and 80 biology students. Purposive sampling was used to select participants who had direct experience with digital technologies in biology learning environments, thereby ensuring the relevance of the collected data.

Data were collected using a structured close-ended questionnaire developed in accordance with the study objectives. The instrument contained items measuring the frequency of digital tool utilization, the level of student engagement in independent and collaborative learning activities, and perceived barriers to technology adoption, including infrastructural and institutional challenges. To establish validity, the questionnaire was reviewed by experts in curriculum development and educational measurement. Their feedback was used to refine item wording and ensure alignment with the intended constructs.

A pilot study involving participants outside the main sample was conducted to assess the reliability of the instrument. The collected pilot data were analyzed using Cronbach's Alpha coefficient, which indicated satisfactory internal consistency and confirmed the suitability of the instrument for the main study.

Following validation and reliability testing, the questionnaire was administered both physically and electronically to the selected respondents. The completed responses were compiled, screened, and cleaned prior to analysis. Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS).

Descriptive statistics, including frequency distributions, mean scores, standard deviations, variances, and kurtosis values, were used to answer the research questions and describe patterns of digital technology utilization, student engagement, and perceived barriers. Inferential analysis was conducted using One-Way Analysis of Variance (ANOVA) to test the study hypotheses. All statistical tests were evaluated at a significance level of $\alpha = 0.05$. A p-value less than 0.05 indicated a statistically significant difference or effect, leading to the rejection of the null hypothesis, whereas a p-value greater than 0.05 indicated insufficient evidence to reject the null hypothesis.

3. RESULTS AND DISCUSSION

Table 1. Frequency and Percentage Distribution of Respondents by Primary Role

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Biology Teacher / Educator	17	17.5	17.5	17.5
	Student	80	82.5	82.5	100.0
	Total	97	100.0	100.0	

Table 1 presents the demographic distribution of the 97 survey respondents based on their primary role. The majority of respondents were students, accounting for 82.5% of the sample (80 respondents). In comparison, biology teachers and educators represented only 17.5% of the respondents (17 participants). This distribution indicates that the findings primarily reflect students' perspectives on the use of digital technologies in biology education.

Research Question 1: What specific digital tools are currently utilized in biology education?

Table 2. Mean Distribution of Digital Tools Currently Utilized in Biology Education by Primary Role

Primary Role		Virtual laboratories / simulated experiments	3D molecular modeling / anatomical visualization software.	Artificial Intelligence (AI) tutors / automated feedback platforms.	Digital presentation tools	Learning Management Systems
Biology Teacher / Educator	Mean	2.18	3.53	3.18	3.12	2.12
	N	17	17	17	17	17
	Std. Deviation	1.334	.624	.728	.781	1.269

Primary Role		Virtual laboratories / simulated experiments	3D molecular modeling / anatomical visualization software.	Artificial Intelligence (AI) tutors / automated feedback platforms.	Digital presentation tools	Learning Management Systems
	Variance	1.779	.390	.529	.610	1.610
	Kurtosis	-1.836	.201	-.890	-1.241	-1.735
Student	Mean	1.50	3.43	3.04	3.04	1.56
	N	80	80	80	80	80
	Std. Deviation	1.019	.725	.961	.834	1.017
	Variance	1.038	.526	.923	.695	1.034
	Kurtosis	1.649	-.596	-.288	-1.561	.374
Total	Mean	1.62	3.44	3.06	3.05	1.66
	N	97	97	97	97	97
	Std. Deviation	1.103	.707	.922	.821	1.079
	Variance	1.218	.499	.850	.674	1.164
	Kurtosis	.328	-.494	-.178	-1.511	-.306

Table 2 presents the extent to which various digital tools are utilized in biology education. Among both educators and students, 3D molecular modeling and anatomical visualization software emerged as the most frequently utilized digital tool, with the highest overall mean score of 3.44. Artificial Intelligence (AI) tutors and automated feedback platforms, as well as digital presentation tools, also demonstrated moderate levels of adoption, with mean scores of 3.06 and 3.05, respectively. In contrast, virtual laboratories/simulated experiments and Learning Management Systems (LMS) recorded the lowest levels of utilization, with overall mean scores of 1.62 and 1.66, respectively. These findings suggest that visualization-oriented technologies are more commonly integrated into biology instruction than simulation-based or learning management platforms.

Research Question 2: What is the impact of digital integration on student engagement in complex biological concepts?

Table 3. Mean Distribution of the Impact of Digital Integration on Student Engagement by Primary Role

Primary Role		Digital tools help to maintain the attention of learners during abstraction biology lessons.	Virtual simulations are used to exaggerate student involvement in complex experiments.	The use of multimedia visualization makes the interaction in the classroom in discussing the microscopic process more effective.	When biology concepts incorporate digital elements, learners take the initiative in their independent learning.	Digital integration enables students to engage in real problem solving in biology.
Biology Teacher / Educator	Mean	3.35	1.35	3.71	3.76	3.53
	N	17	17	17	17	17
	Std. Deviation	.786	.996	.470	.437	.624
	Variance	.618	.993	.221	.191	.390
	Kurtosis	4.024	5.440	-1.166	-.149	.201
Student	Mean	2.95	1.30	3.26	3.23	3.34
	N	80	80	80	80	80
	Std. Deviation	1.090	.770	1.003	.993	.980
	Variance	1.187	.592	1.006	.987	.961
	Kurtosis	-.736	5.087	.412	.343	1.092
Total	Mean	3.02	1.31	3.34	3.32	3.37
	N	97	97	97	97	97
	Std. Deviation	1.051	.808	.945	.941	.928
	Variance	1.104	.653	.893	.886	.861
	Kurtosis	-.424	5.023	1.030	.963	1.461

Table 3 examines respondents' perceptions of the impact of digital integration on student engagement in learning complex biological concepts. The highest overall mean score (3.37) was obtained for the statement that digital integration enables students to engage in real-world problem-solving activities in biology. Similarly, multimedia visualization for explaining microscopic processes and the promotion of independent learning received relatively high levels of agreement, with mean scores of 3.34 and 3.32, respectively. These findings indicate that digital technologies can enhance student engagement by facilitating active learning and improving conceptual understanding. Conversely, the statement regarding the use of virtual simulations to increase student involvement in complex experiments recorded the lowest mean score (1.31), suggesting limited implementation or perceived effectiveness of this approach among respondents.

Research Question 3: What barriers do biology educators face when adopting digital technologies in teaching?

Table 4. Mean Distribution of Barriers Faced by Biology Educators in Adopting Digital Technologies

Primary Role		**Inconsistent electricity supply in the school.**	**Poor Internet access / bandwidth in classrooms.**	**Poor digital skills / technical expertise of teachers.**	**Technology-deployment not allowed for due to rigid curriculum requirements and lack of time.**	**Inadequate funding for licensed biology software, hardware maintenance.**
Biology Teacher / Educator	Mean	3.76	2.24	3.47	3.59	3.71
	N	17	17	17	17	17
	Std. Deviation	.752	1.437	.514	.870	.470
	Variance	.566	2.066	.265	.757	.221
	Kurtosis	13.052	-1.961	-2.267	4.576	-1.166
Student	Mean	3.35	1.45	2.96	3.24	3.26
	N	80	80	80	80	80
	Std. Deviation	1.092	.967	.999	1.058	1.003
	Variance	1.192	.934	.999	1.120	1.006
	Kurtosis	.360	2.102	-.208	-.040	.412
Total	Mean	3.42	1.59	3.05	3.30	3.34
	N	97	97	97	97	97
	Std. Deviation	1.049	1.097	.951	1.032	.945
	Variance	1.101	1.203	.904	1.066	.893
	Kurtosis	.949	.557	.248	.265	1.030

Table 4 highlights the major barriers encountered by biology educators in adopting digital technologies for instructional purposes. Inconsistent electricity supply emerged as the most significant challenge, recording the highest overall mean score of 3.42. This was followed closely by inadequate funding for licensed biology software and hardware maintenance (mean = 3.34), as well as rigid curriculum requirements and limited instructional time (mean = 3.30). These findings suggest that infrastructural and financial constraints remain substantial obstacles to effective digital integration in biology education. In contrast, poor internet access and bandwidth limitations were perceived as the least significant barrier, with the lowest overall mean score of 1.59.

Hypothesis 1: There is no significant difference in the frequency of utilization among the various types of digital tools in biology education.

Table 5. ANOVA Results for Differences in the Frequency of Utilization Among Digital Tools

	Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	33.909	1	33.909	4.208	.043
Within Groups	765.452	95	8.057		
Total	799.361	96			

The ANOVA results presented in Table 5 indicate that the null hypothesis is rejected. The calculated significance value ($p = .043$) is lower than the conventional significance level of .05. This finding demonstrates that there is a statistically significant difference in the frequency of utilization among the various digital tools used in biology education. Therefore, the results suggest that some digital tools are utilized more frequently than others, contradicting the assumption that all digital tools are used at similar rates.

Hypothesis 2: Digital integration has no significant impact on student engagement in complex biological concepts.

Table 6. ANOVA Results for the Impact of Digital Integration on Student Engagement

	Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	37.292	1	37.292	3.030	.085
Within Groups	1169.079	95	12.306		

Total	1206.371	96			

The ANOVA results shown in Table 6 indicate that the null hypothesis is not rejected. The calculated significance value (p = .085) exceeds the standard alpha level of .05. This result suggests that there is no statistically significant difference in student engagement outcomes attributable to digital integration. Consequently, the findings imply that digital integration does not have a significant impact on student engagement in complex biological concepts, based on the perceptions of the respondents included in this study.

Hypothesis 3: The identified barriers do not significantly hinder biology educators from adopting digital technologies in teaching.

Table 7. ANOVA Results for the Hindrance of Identified Barriers on Digital Technology Adoption

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	87.784	1	87.784	5.656	.019
Within Groups	1474.546	95	15.522		
Total	1562.330	96			

The ANOVA results presented in Table 7 indicate that the null hypothesis is rejected. The calculated significance value (p = .019) is lower than the accepted significance level of .05. This finding reveals a statistically significant effect of the identified barriers on the adoption of digital technologies in biology education. Therefore, the results suggest that factors such as inadequate infrastructure, limited funding, insufficient technical expertise, and curriculum-related constraints significantly hinder biology educators from effectively adopting digital technologies in their teaching practices.

A. Discussion

The findings related to Research Question 1 revealed that 3D molecular modeling and anatomical visualization software were the most frequently utilized digital tools in biology education, with the highest overall mean score of 3.44. This finding is consistent with the study of Sumiati et al. (2026), who reported that structural digital models and interactive multimedia resources provide effective pedagogical support for understanding abstract biological structures and processes. Similarly, Rahmawati and Turista (2026) found that specialized visualization software integrated with project-based learning significantly enhanced students' ability to identify biological patterns and develop conceptual understanding.

Artificial Intelligence (AI) tutors and automated feedback platforms also demonstrated moderate levels of utilization, with an overall mean score of 3.06. This result aligns with the findings of Farhana et al. (2024), who observed that AI-based educational tools provide immediate feedback, personalized learning pathways, and adaptive support for science learners. In contrast, virtual laboratories and simulated experiments recorded the lowest utilization level, with an overall mean score of 1.62. This limited use may reflect challenges related to infrastructure, technical expertise, or accessibility. Furthermore, the inferential analysis conducted through a One-Way ANOVA yielded a significance value of .043 ($p < .05$), leading to the rejection of the null hypothesis. This result confirms that significant differences exist in the frequency of utilization among digital tools in biology education. The findings suggest that biology instruction currently relies more heavily on visualization-based technologies than on immersive simulation-based learning environments.

Regarding Research Question 2, the findings indicate that digital integration positively supports student engagement in learning complex biological concepts. The highest overall mean score (3.37) was recorded for the statement that digital integration enables students to engage in real-world problem-solving activities. This finding is supported by Soriano-Sánchez et al. (2026), who reported that digitally enriched learning environments encourage student-centered learning and promote deeper engagement with scientific problems. Likewise, the relatively high mean scores for multimedia visualization (3.34) and independent learning initiative (3.32) suggest that digital technologies facilitate conceptual understanding while fostering learner autonomy.

These findings are further supported by Sumiati et al. (2026), who emphasized that digital tools help bridge the gap between abstract biological theories and practical applications. Similarly, Ruado and Cortez (2024) found that interactive digital presentation systems significantly improve cognitive, affective, and behavioral engagement when teaching complex scientific concepts. Conversely, the statement concerning the use of virtual simulations to enhance student involvement recorded the lowest mean score (1.31), indicating limited implementation or perceived effectiveness of simulation-based learning among respondents.

However, despite these positive descriptive findings, the inferential analysis produced a significance value of .085 ($p > .05$). Therefore, the null hypothesis was not rejected. This result suggests that there is no statistically significant difference in perceptions of student engagement between the respondent groups. In other words, although respondents generally viewed digital integration positively, the observed differences were insufficient to demonstrate a statistically significant effect. This finding contrasts with the results reported by Mujallid et al. (2024), who found significant improvements in measurable student engagement through active digital learning strategies compared with traditional instructional approaches.

The findings related to Research Question 3 identified inconsistent electricity supply as the most prominent barrier to digital technology adoption in biology education, with the highest overall mean score of 3.42. Inadequate funding for licensed software and hardware maintenance followed closely with a mean score of 3.34. These findings are consistent with Bandaru (2026), who reported that infrastructural deficiencies, including unreliable electricity, insufficient technological resources, and limited financial support, continue to hinder effective digital education implementation.

Additionally, curriculum rigidity and limited instructional time emerged as substantial challenges, with an overall mean score of 3.30. This finding supports the work of Akar (2014), who observed that biology educators frequently encounter institutional constraints that restrict meaningful technology integration beyond basic classroom applications. To determine whether these barriers significantly influence digital technology adoption, a One-Way ANOVA was conducted. The analysis yielded a significance value of .019 ($p < .05$), resulting in the rejection of the null hypothesis.

The statistical evidence therefore confirms that the identified barriers significantly hinder the adoption of digital technologies in biology education. These findings suggest that infrastructural, financial, and institutional constraints remain major obstacles to effective digital integration. Consequently, addressing issues related to electricity supply, funding availability, curriculum flexibility, and teacher support may be essential for promoting the successful implementation of digital technologies in biology classrooms.

B. Implications of Synergizing Digital Pedagogy and Local Media Paradigms in Modern Biology Education

The findings of this study highlight important implications for the future development of biology education in digitally evolving learning environments. The widespread utilization of 3D molecular modeling and anatomical visualization software demonstrates the value of visualization-based technologies in facilitating the understanding of complex and abstract biological concepts. These tools support meaningful learning experiences by promoting conceptual clarity, independent learning, and engagement in authentic problem-solving activities. Their effectiveness suggests that visual and interactive learning resources should be integrated more systematically into biology curricula.

Despite these benefits, the study revealed a notable disparity between the adoption of visualization tools and the utilization of more advanced digital learning platforms, such as Learning Management Systems (LMS) and virtual laboratories. This gap appears to be influenced by infrastructural and institutional challenges, including inconsistent electricity supply, inadequate funding, and rigid curriculum requirements. These findings suggest that successful digital transformation in biology education requires not only technological availability but also supportive institutional policies and adequate resource allocation.

To address these challenges, educational institutions may consider adopting flexible and locally adaptable digital learning strategies. Mobile-friendly learning applications, offline-accessible educational resources, and low-bandwidth digital platforms could provide practical alternatives in contexts where technological infrastructure remains limited. Such approaches can enhance accessibility while reducing dependence on stable internet connectivity and advanced hardware resources.

Furthermore, collaborative and community-based educational initiatives may offer sustainable solutions for improving digital learning environments. Partnerships among schools, local communities, educational organizations, and government agencies could contribute to the provision of digital resources, teacher training, and technical support. These collaborative efforts may strengthen the capacity of biology educators to integrate digital technologies effectively into classroom practice.

Overall, the findings suggest that the successful integration of digital technologies in biology education requires a balanced approach that combines innovative pedagogical practices with context-sensitive implementation strategies. By addressing infrastructural barriers and promoting adaptable digital learning models, educational institutions can enhance student engagement, improve scientific understanding, and support the development of twenty-first-century learning competencies.

4. CONCLUSION

The findings of this study indicate that the digitalization of biology education remains unevenly implemented and is primarily concentrated on visualization-based technologies rather than interactive experimentation tools. Advanced visualization applications, such as 3D molecular modeling and anatomical visualization software, are widely utilized by both teachers and students, whereas virtual laboratories and simulation-based platforms remain underutilized. This suggests that opportunities for immersive and hands-on digital learning experiences are still limited in many educational settings.

The study further revealed that digital technologies contribute positively to student engagement by supporting real-world problem-solving, independent learning, and the understanding of complex biological concepts, particularly those involving microscopic processes. Although respondents generally expressed positive perceptions regarding the benefits of digital integration, the inferential analysis indicated no statistically significant differences in perceptions of student engagement between the respondent groups.

Despite these benefits, several institutional and infrastructural barriers continue to hinder the effective adoption of digital technologies in biology education. The most significant challenges identified include inconsistent electricity supply, inadequate funding for software licenses and equipment maintenance, and rigid curriculum requirements. These barriers significantly affect the ability of educators to implement and sustain technology-enhanced teaching practices.

Overall, the findings suggest that technological availability alone is insufficient to transform biology education. Effective digital integration requires adequate infrastructure, sustainable funding, institutional support, and flexible educational policies to ensure that digital tools can be utilized to their full pedagogical potential.

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