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Digital literacy and chemistry proficiency among first-year university students in Eastern Cape, South Africa

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Introduction: The low proficiency in chemistry by first-year students in South Africa impairs their capacity to grasp and apply crucial concepts, leading to high failure and dropout rates. This study investigates the effects of digital literacy on first-year entering students chemistry content proficiency in one South African university in the Eastern Cape.

Method: The study employed an interpretivist paradigm and a qualitative methodology in the form of open-ended questionnaires to elicit detailed insights from both students and lecturers. The purposively selected sample comprises 10 participants, including eight students and two lecturers. Constructivist Learning Theory and Technology Acceptance Model underpinned the study, while thematic analysis was used for data analysis.

Result: Data analysis reveals significant challenges in digital literacy, especially among students from rural areas with little prior exposure to digital technologies. The findings emphasize the importance of digital tools such as molecular visualization software and interactive simulations in improving students' chemistry comprehension and performance. The study emphasizes the ongoing digital divide, which impedes the effective use of these technologies.

Discussion: It concludes that bridging this gap necessitates comprehensive support systems, such as developing user-friendly digital platforms and ongoing professional development for lecturers to ensure they are adequately equipped to guide students.

KEYWORDS

digital literacy, chemistry education, first-year students, academic performance, rural environment

1 Introduction

Chemistry proficiency among newly enrolled students remains a global challenge, often contributing to poor academic performance due to difficulties mastering core concepts (Kolil and Achuthan, 2024; Schettini et al., 2020). In the UK, inadequate secondary preparation weakens readiness for university-level chemistry (Boesdorfer and Del Carlo, 2020), while in Western countries, gaps in foundational knowledge and limited laboratory skills, linked to inconsistent science education standards, further impede success (Stone, 2021). In Africa, these issues are compounded by inadequate IT infrastructure that restricts access to digital learning (Asaleye et al., 2021; Ncanywa et al., 2025). In Nigeria, minimal exposure to scientific literature reduces students' ability to grasp complex chemistry concepts (Harle et al., 2021). In South Africa, particularly in the Eastern Cape, poor digital literacy and limited access to computer labs in rural schools hinder engagement with digital tools (Soyikwa and Boateng, 2024). Educational performance are also concerning, for

example 46.5% of Black university students do not complete their degrees within six years (Africa Check, 2019), and only about 4% of those who start school eventually graduate from university within that period (MyBroadband, 2016).

The persistently low university completion rates among Black South African students can be traced back to the historical disadvantages imposed by apartheid-era policies, which systematically restricted access to quality education and economic opportunities before 1994 (McKeever, 2017). The Bantu Education Act (1953) deliberately underfunded schools for Black students, leading to generational educational inequalities that continue to affect academic performance today. Many first-generation university students face structural barriers, including inadequate academic preparation, financial constraints, and limited access to digital learning resources, all hindering their ability to complete science-related degrees. Moreover, the socioeconomic disparities inherited from apartheid make worse dropout rates, as students from marginalized backgrounds often struggle with balancing academic responsibilities and financial survival.

Digital literacy is using technological tools for effective learning, which is crucial for improving academic performance (Chapman, 2025; Getenet et al., 2024; Oloni et al., 2017). Training programs, workshops, and online support systems can enhance students' digital skills, helping to bridge this gap (Bergdahl, 2022; Chiu, 2023; Eberle and Hobrecht, 2021). Such initiatives, which build competencies in information retrieval, online communication, and digital learning tools, have improved students' chemistry comprehension and overall academic performance. The rationale and justification of this study are based on providing new insights into the link between digital literacy and chemistry proficiency for academic challenges faced by first-year university students in less developed areas. The study seeks to inform curriculum design, teaching strategies, and policymaking with the hope that institutions can use these insights to improve student achievement with approaches to strengthen digital literacy initiatives.

This study addresses identified gaps in empirical regarding how digital literacy skills can improve first-year students' understanding of chemistry. Previous studies have examined various instructional strategies to enhance chemistry education such as the effectiveness of different teaching methods (Brown et al., 2021), flipped learning vs. traditional lecture formats (Hibbard et al., 2016), and approaches to improving student engagement and laboratory skills (Kolil and Achuthan, 2024), there remains a gap in the empirical literature on the role of digital literacy in influencing students' chemistry proficiency in historically disadvantaged environment and how to transform the situation. Further studies have examined the use of hypermedia for learning complex chemistry concepts (Mishra and Yadav, 2006), narrative-based representations for improving visual cognition (Reyes and Villanueva, 2024), and blended learning through digital platforms (Schettini et al., 2020), yet little attention has been given to how digital literacy influences first-time entering students' comprehension of chemistry in historical disadvantage society. Addressing this gap, the present study investigates the effects of digital literacy on the chemistry content proficiency of first-year students at a university in South Africa's Eastern Cape province and its contribution to how technological preparedness impacts academic success in chemistry.

Despite technological advancements, many students struggle to use digital tools effectively for learning chemistry fundamentals, contributing to poor academic performance and high dropout rates (Mishra and Yadav, 2006; Haleem et al., 2022; Liu and Yu, 2023; Sharma et al., 2024). Improving the usage and integration of digital tools, such as online platforms, multimedia resources, and interactive learning, may be more effective in enhancing academic performance. As these technologies become increasingly accessible, it is crucial to investigate their potential to improve chemistry proficiency. More so, this study aims to provide empirical support for improving educational policies and practices, contributing to Sustainable Development Goal 4, which advocates for inclusive and equitable quality education. Therefore, the main objective is to investigate the effects of digital literacy on first-time entering students in chemistry content proficiency in one South African university in the Eastern Cape. To guide this study, the following research questions were formulated:

- i. What challenges do first-time entering students encounter when utilizing digital technologies to understand chemistry content at the university?
- ii. How do first-time entering students perceive the effectiveness of digital technologies in enhancing their understanding of chemistry content within the academic environment?
- iii. What strategies can be implemented to optimize digital literacy skills for improving chemistry content understanding among first-time entering students?

The implications of this study extend beyond understanding first-year students' challenges with digital technologies; it shows the role of digital literacy in influencing academic success and equity in South African higher education. Focusing on chemistry, a subject often regarded as conceptually demanding, this study demonstrates how digital proficiency influences students' ability to visualize abstract concepts, engage with interactive resources, and adapt to modern learning environments. The findings provide practical benefits by informing strategies such as integrating digital literacy training into the curriculum, improving institutional support systems, and developing blended approaches that can reduce barriers for students from disadvantaged backgrounds. Thus, the study contributes to academic discourse, policy and pedagogical practices aimed at enhancing both access and success in STEM education.

2 Empirical review, theoretical perspectives and development of hypotheses

This study adopts the Constructivist Learning Theory and the Technology Acceptance Model (TAM) to analyse how digital literacy tools can enhance first-year university students' chemistry proficiency. The Constructivist Learning Theory emphasizes experiential learning, where digital tools such as virtual labs and interactive simulations facilitate deeper engagement and

improve conceptual understanding (Al Abri et al., 2024). Meanwhile, TAM shows that students' perceptions of the ease and usefulness of digital tools influence their adoption and engagement and improve learning performance (Meylani, 2024).

Empirically, studies regarding digital tools have shown that mastering chemical structures and reactions is crucial in chemistry education, yet digital tools may sometimes oversimplify complex concepts, potentially hindering deep learning (Brown et al., 2021; Kelly and Hansen, 2017; Bergdahl, 2022; Gan et al., 2024). Nevertheless, molecular visualization software and interactive simulations have positively impacted comprehension and performance (Kelly and Hansen, 2017). In an environment prone to academic disruptions such as strikes or adverse weather, digital platforms play a vital role in maintaining learning continuity (Bozkurt et al., 2020). First-year South African students, especially those from rural backgrounds, often experience challenges with digital literacy due to limited prior exposure to digital tools and scientific resources (Reddy Moonasamy and Naidoo, 2022; Oyedemi and Mogano, 2018). Therefore, providing access to digital platforms may be insufficient to overcome these disparities, and comprehensive digital literacy training is necessary to improve chemistry proficiency (Chapman, 2025; Haleem et al., 2022; Mushtaq and Iqbal, 2024; Reddy Moonasamy and Naidoo, 2022; Sillence et al., 2023). Limited infrastructure, such as unstable internet connectivity and restricted access to devices, further worsens inequalities between rural and urban students (Faturoti, 2022; Oyedemi and Choung, 2020; Zhao et al., 2022).

Regarding students' perceptions influence their proficiency in digitalised chemistry content. Positive attitudes enhance engagement and motivation, while negative perceptions can deter effort and hinder academic performance (Getenet et al., 2024; Mishra and Yadav, 2006; Pyle and Hung, 2019). Digital literacy gaps are closely linked to reduced confidence, participation, and self-efficacy in chemistry learning (Yuan et al., 2024; Brown et al., 2021; Hibbard et al., 2016). As a result, digital literacy programs are crucial for empowering students to use digital resources effectively. Lecturers' digital proficiency also ensures the successful integration of digital tools in chemistry education. While some educators value the flexibility and accessibility digital platforms offer, concerns about the authenticity of digital laboratory experiences remain (Kolil and Achuthan, 2024; Schettini et al., 2020). Inadequate digital skills among lecturers can further undermine teaching quality, reinforcing the need for sustained professional development (Falloon, 2020; Brown et al., 2021). Training programs familiarizing students with Learning Management Systems (LMS) have also improved engagement. However, persistent gaps remain, particularly in rural areas where connectivity issues and inadequate digital training pose barriers to learning (Zhao et al., 2022; Gan et al., 2024).

Regarding lecturers and instructors, while the integration of digital tools such as molecular visualization software and interactive simulations aligns with the pedagogical goals of enhancing chemistry content comprehension (Makuve and Iloanya, 2025; Chiu, 2021), the empirical evidence supporting

the effectiveness of specific digital strategies, particularly those involving narrative-based or storytelling approaches, remains mixed (Ugap et al., 2025). Some studies suggest that contextualizing abstract chemical concepts through relatable digital narratives may enhance conceptual retention and learner engagement, especially in resource-constrained environments (Okwere Darko and Ekwam, 2025). However, other studies point to the potential risk of cognitive overload or oversimplification when narrative elements are not appropriately aligned with learning performance. Considering this, the present study has intentionally foregrounded learner perceptions and usage experiences to provide a contextualized understanding of digital strategy effectiveness. Nonetheless, we acknowledge the need for ongoing, theory-driven evaluations of these strategies across diverse learning environments. Future research should systematically examine the instructional affordances of digital storytelling in science education and their relation to learner autonomy, disciplinary accuracy, and the socio-cultural relevance of the narratives employed.

Building on the following discussion, this study hypothesizes that digital literacy significantly influences first-year students' ability to engage with digital technologies for chemistry learning. Given the well-documented digital divide, students from disadvantaged backgrounds are expected to face greater challenges in accessing and utilizing digital tools effectively. Additionally, since structured training has enhanced students' proficiency with educational technologies, digital literacy programs are anticipated to improve their understanding of chemistry content. Lastly, recognizing the role of lecturers in technology integration, it is hypothesized that enhancing lecturers' digital literacy will further strengthen the effective use of digital tools, ultimately improving student learning performance.

3 Materials and methods

3.1 Research paradigm and approach

This study adopts an interpretivist paradigm, emphasizing an understanding of participants' lived experiences within their social and educational contexts. Interpretivism is particularly well-suited to this study as it examines the subjective realities of first-year chemistry students, especially their perceptions of digital literacy and its influence on their academic performance (O'Leary, 2020); this paradigm enables to share more light on how complex challenges faced in integrating digital tools into chemistry education. A qualitative research approach was employed to capture the experiences, challenges, and perspectives of both students and lecturers. Qualitative inquiry facilitates the collection of rich, descriptive data that quantitative methods may not reveal (Amaratunga et al., 2002). This approach was selected for its strength in uncovering factors that influence students' engagement with digital tools, as well as the emotional and cognitive dimensions of their learning. The flexibility of the qualitative approach also allowed for exploring diverse participant backgrounds, thereby contributing to more informed recommendations for policy and

practice. The methods section acknowledges key limitations, namely the small sample size, lack of triangulation, and limited validity and reliability of the open-ended questionnaire.

3.2 Research design, data collection methods, and instruments

The study utilized an open-ended questionnaire design to gather in-depth qualitative data. Open-ended questionnaires were chosen for their ability to elicit participants' unique perspectives, experiences, and challenges in navigating digitalised chemistry learning. The questionnaire included four thematic sections:

- i. Students' experiences with digital tools and chemistry learning platforms.
- ii. Challenges encountered while adapting to digitalised chemistry education.
- iii. Perceptions of digital literacy training and available support systems.
- iv. Strategies employed by lecturers to integrate digital tools into teaching.

Purposive sampling was used to recruit participants with direct relevance to the research objectives. This approach ensured that the data gathered would be both rich and contextually grounded (Wang et al., 2025). The sample comprised eight first-year chemistry students, ranging from high-achieving to struggling learners, and two lecturers, one of whom actively uses digital tools, while the other relies on more traditional teaching methods.

The questionnaire was distributed electronically to first-year chemistry students via the university's learning management system and official institutional email accounts; this approach ensured wide access to participants while minimizing direct contact with the researcher. To maintain independence and reduce potential bias, the researcher was not present during the completion of the questionnaire, and responses were submitted anonymously through a secure online platform. Participation was entirely voluntary, with students provided informed consent prior to beginning the survey. These measures were designed to protect respondent autonomy and ensure that the data collected represent authentic experiences of digital literacy and chemistry learning without undue influence.

The research instrument was a semi-structured questionnaire comprising 18 items divided into three sections: (i) challenges in utilizing digital technologies (six items), (ii) perceptions of the effectiveness of digital tools for chemistry learning (six items), and (iii) strategies for optimizing digital literacy (six items). Of these, 14 questions were directed to students, while 4 were adapted for lecturers to capture complementary instructional perspectives. To ensure validity, the questionnaire items were adapted from established instruments in digital literacy and STEM education (e.g., Chang and Kuo, 2025; Chamrat et al., 2019; Ramli and Arsad, 2023) and reviewed by two experts in chemistry education for content clarity and relevance. A pilot test with two non-participating students further confirmed that the items were understandable and appropriate. The final sample consisted of 10

participants (eight first-year students and two chemistry lecturers), selected using purposive sampling; this approach is widely recognized in qualitative research for prioritizing depth of insight over statistical generalisability. The inclusion of students from both rural and urban backgrounds, alongside lecturers with direct teaching experience, ensured that the sample captured diverse perspectives while remaining manageable for in-depth qualitative analysis (Du Plessis, 2019; Kumi-Yeboah and Amponsah, 2023).

3.3 Data saturation

Data saturation was considered reached when no new themes or insights emerged from participants' responses. This point was observed during the analysis of the final few questionnaires, which echoed previously identified patterns. Saturation was used as a guiding principle to determine the adequacy of the sample size and the completeness of the data.

3.4 Data analysis and verification

Data were analyzed using thematic analysis to identify recurring patterns and meaningful themes related to digital literacy and chemistry learning. Thematic analysis involved an iterative coding process, where initial codes were developed, refined, and grouped into themes. The full survey instrument and comprehensive analysis details are provided in [Supplementary Appendices A2 and A3](#).

4 Data presentation, analysis and discussions

4.1 Demographics and proficiency of participants

In [Table 1](#), we assigned unique codes to each participant to maintain participant confidentiality while ensuring clarity. Chemistry students were labeled ChSt1 to ChSt8, while lecturer participants were identified as ChL1 and ChL2. In addition, we categorized participants' biographical information according to their proficiency levels in chemistry content and digital literacy. The following table overviews participants' proficiency levels.

The qualitative data collected in this study was analyzed using thematic analysis, a widely recognized method for identifying, analyzing, and reporting patterns (themes) within qualitative data (Braun and Clarke, 2006). The analysis began with an initial phase of familiarization, during which we thoroughly reviewed the data to gain an in-depth understanding of participants' responses; this process enabled the identification of preliminary codes that captured significant features of the data. The identified codes were then grouped into categories, which formed the main themes. These themes were carefully aligned with the study's research objectives to ensure that the analysis effectively addressed the key areas of investigation. The resulting themes reflect core aspects of the participants' experiences and insights, providing a structured framework for presenting the findings. The three key themes that

TABLE 1 Demographics for participants.

Pseudonyms	Gender	Level of chemistry content proficiency	Level of digital literacy proficiency
ChSt1	Female	Very good	Fair
ChSt2	Male	Fair	Good
ChSt3	Male	Good	Fair
ChSt4	Female	Fair	Fair
ChSt4	Male	Good	Good
ChSt5	Male	Good	Very good
ChSt6	Female	Very good	Very good
ChSt7	Female	Fair	Fair
ChSt8	Female	Good	Good
ChL1	Male	Very good	Very good
ChL2	Female	Very good	Very good

Source: Authors' computation.

emerged from the analysis are Challenges in Online Learning of Chemistry, Students' Perceptions and Proficiency in Digitalised Chemistry Content, and Strategies for Improving Chemistry Proficiency through Digital Literacy. [Supplementary Figure A1](#) shows the thematic map illustrating key challenges and strategies related to digital literacy and chemistry learning among first-year university students. Major themes include technical barriers, digital literacy challenges, effectiveness of digital tools, motivation/self-regulation, and institutional support strategies.

4.2 Challenges from online learning of chemistry

4.2.1 Technical barriers

As they transition to digital learning environments, technical challenges present an obstacle for first-year chemistry students, particularly those from rural backgrounds. These barriers impede students' ability to engage effectively with digital tools and resources, ultimately impacting their understanding of chemistry content ([Brown et al., 2021](#); [Mishra and Yadav, 2006](#)). Participants in this study identified several technical challenges that influenced their online learning experiences.

4.2.2 Unreliable internet connectivity

One of the most pressing technical challenges reported was unreliable internet access, which was especially prevalent among students from rural areas. This issue restricted students' ability to access essential online resources, attend virtual lectures, and engage with interactive chemistry simulations—all for mastering complex scientific concepts.

Q: Can you describe any difficulties you have faced using digital tools to learn chemistry?

ChSt1: "Poor internet connectivity is a constant issue for me."

ChSt6: "Glitches and software crashes are common when using online resources."

Such connectivity shows the detrimental impact of poor internet infrastructure on students' ability to access digital learning platforms, particularly in developing regions. In chemistry education, where molecular visualization tools and interactive simulations are vital for understanding abstract concepts, unreliable internet access poses a severe disadvantage ([Brown et al., 2021](#)).

4.2.3 Unfamiliarity with digital tools

In addition to connectivity issues, participants highlighted difficulties in navigating and effectively using digital platforms. Students unfamiliar with digital tools often faced challenges that hindered their ability to engage with chemistry content.

Q: What specific aspects of digital tools (e.g., accessibility, usability) have been challenging for you?

ChSt1: "Navigating between different platforms is often confusing, and I sometimes lose track of resources."

ChSt2: "The tools sometimes fail to properly display the chemical structures, which makes it difficult to follow."

These responses reveal a gap in digital literacy among students, supporting the argument that simply providing access to digital tools is insufficient; training is essential to support students' effective use of such resources ([Haleem et al., 2022](#)). As ChSt1 expressed: "Without much guidance, using these tools was confusing"; this finding aligns with previous research indicating that students from underserved backgrounds, particularly those with limited prior exposure to digital technologies, are more likely to experience such difficulties ([Haleem et al., 2022](#)).

4.2.4 Software compatibility and hardware limitations

Several participants also reported technical issues with device compatibility and hardware limitations.

Q: Can you describe any technical challenges you faced with chemistry software or applications?

ChSt4: "There are compatibility issues between my device and some chemistry applications."

ChSt7: "I do not have the necessary hardware to run some chemistry programs."

These challenges disrupted students' learning and contributed to disengagement, a particularly detrimental concern in chemistry education, where visualizing molecular structures and mastering reaction mechanisms requires stable and effective digital tools. The prevalence of these technical barriers indicates the need for enhanced digital infrastructure, particularly in underserved regions. Investing in improved internet connectivity, expanding access to compatible devices, and providing comprehensive digital literacy training are essential to ensure equitable access to digital learning tools. Additionally, integrating structured guidance for navigating digital platforms can empower students to engage

effectively with chemistry content. A blended approach combining digital tools with traditional teaching methods may provide a more effective learning experience for first-year chemistry students, especially those still developing digital skills (Schettini et al., 2020).

4.2.5 Low proficiency in digital literacy

Low digital literacy challenges first-year chemistry students, particularly in navigating and effectively using digital technologies. These challenges primarily come from difficulties in platform navigation, tool usability, and limited prior exposure to digital resources. Such obstacles hinder students' ability to engage meaningfully with chemistry content and develop a comprehensive understanding of complex scientific concepts.

4.2.6 Navigational and usability challenges

Navigational difficulties emerged as a recurring concern among participants, indicating the struggle to adapt to digital learning environments. These issues are particularly pronounced for students accustomed to traditional classrooms.

Q: How important is the university to provide training or workshops on digital literacy skills?

ChL1: "Extremely important, especially for students with no prior exposure to these tools."

ChL2: "Vital, because without training, students will not use the tools to their full potential."

Both lecturers emphasized the necessity of digital literacy training, strengthening findings by Chiu (2023), inadequate digital skills can result in frustration and reduced engagement in online learning environments. Without proper guidance, students may struggle to effectively utilize digital tools, limiting their ability to grasp chemistry concepts that require visual and interactive learning approaches.

4.2.7 Impact of prior digital exposure on learning

Students with limited exposure to digital technologies reported more significant difficulties adapting to chemistry's digital learning environment.

Q: How do you feel your background (e.g., rural or urban, prior digital literacy) has affected your ability to use digital technologies for studying chemistry?

ChSt2: "Some tools are too complex to use without prior digital knowledge."

ChSt3: "I had some digital literacy, but nothing related to the advanced tools we use now."

ChSt8: "I did not have much access to digital tools back home, so adapting has been hard."

These responses reflect a typical pattern in which students from underserved regions face additional barriers in adapting to digital learning platforms. Gan et al. (2024) reported that students from rural backgrounds are often disadvantaged by limited digital literacy, making it challenging to engage with technology-based resources that are now integral to modern science education.

Notably, ChSt2 described feeling disconnected from digital lessons, stating: "The content felt disconnected from what we learned in class, and I was unfamiliar with many of the tools" This disconnect aligns with Clark and Mayer (2023), which suggests that when digital content is poorly integrated with traditional learning methods, it can undermine students' understanding of core scientific concepts; this is maybe particularly problematic for chemistry students since digital tools are often critical for visualizing molecular structures, reaction mechanisms, and other abstract concepts.

4.2.8 Information overload and learning fatigue

Besides usability concerns, participants reported feeling overwhelmed by the sheer volume of available digital resources.

Q: What challenges have you encountered when utilizing digital technologies for chemistry learning?

ChSt3: "There are many challenges I have encountered when utilizing digital technologies...[including] information overload."

ChSt6: "Digital simulations are handy but cannot replace the hands-on experience of a real lab."

Findings aligned with the study by Masrek and Baharuddin (2023), who observed that excessive digital content can overwhelm students, making it difficult to filter useful information and engage meaningfully with course material. Chemistry students may struggle to identify relevant resources among the vast online simulations, databases, and tutorials. Moreover, as noted by ChSt6, while digital simulations provide insights into chemical structures and reactions, they may fall short of replicating the practical skills developed in traditional laboratories; this reflects the ongoing debate regarding the balance between digital resources and hands-on learning in chemistry education (Brown et al., 2021).

The challenges linked to low digital literacy pointed out the need for universities to provide comprehensive digital literacy training, particularly for first-year chemistry students. Training initiatives should focus on technical skills and strategies for navigating digital platforms, filtering relevant information, and integrating digital resources with traditional learning methods. In order to bridge the digital literacy gap, institutions can implement workshops, peer-support systems, and interactive training modules to equip students with the skills necessary for effective digital learning. Moreover, aligning digital tools with classroom instruction may help mitigate the disconnection between traditional and digital learning experiences, improving overall student engagement and comprehension.

4.2.9 Simulation limitations compared to the real world

While molecular visualization software and interactive simulations have been shown to enhance student understanding and performance in chemistry (Brown et al., 2021), these digital tools have inherent limitations that impede learning, particularly for first-year students still developing foundational chemistry knowledge.

4.2.10 Limitations of digital simulations

One major limitation of digital simulations is their inability to fully replicate the hands-on experience of traditional laboratory work. Respondent ChSt6 stresses this concern, emphasizing that digital tools can aid visualization but may oversimplify complex chemical processes; this reflects concerns in the literature, which suggests that digital simulations often fail to capture the unpredictability and variability of real-world experiments (Liu and Panagiotakos, 2022). Practical lab work allows students to engage physically with materials, observe reactions as they unfold, and develop essential problem-solving skills when unexpected outcomes arise. Moreover, digital tools often present idealized scenarios that overlook the complexities students encounter in real lab environments.

4.2.11 Technical challenges and infrastructure barriers

Technical issues further compound the limitations of digital simulations. Respondent ChSt8 reported facing “technical issues” when using digital tools, which disrupted their learning experience. Technical difficulties such as software malfunctions, connectivity issues, or compatibility problems can hinder students’ ability to engage meaningfully with digital content. These challenges are particularly pronounced in South African universities, where some students, especially those from rural areas, may have limited access to stable internet connections or the necessary hardware for effective digital learning (Reddy Moonasamy and Naidoo, 2022). As a result, students may struggle to complete online exercises, simulations, or assessments, further disadvantaging those already facing digital literacy barriers.

4.2.12 Motivation and self-discipline in digital learning

Beyond technical challenges, digital learning environments often require greater motivation and self-regulation, which some students find difficult to maintain.

Q: What challenges have you faced in staying motivated when using digital learning tools?

ChSt6: “Staying motivated can be tricky when it is all online and requires much self-discipline.”

ChSt2: “I found it hard to focus on digital lessons because the content sometimes felt disconnected from what we learned in class.”

These responses reflect concerns in the literature that the absence of a structured, face-to-face learning environment can decrease engagement and motivation (Pyle and Hung, 2019). Chemistry, which demands sustained focus and conceptual understanding, presents additional challenges when students lack opportunities for hands-on practice and direct interaction with instructors. For many first-year students, particularly those from rural backgrounds, the shift to digital learning may be overwhelming, requiring a level of self-regulation that they have not yet developed (Eberle and Hobrecht, 2021; Zhao et al., 2022). Without clear structure and guidance, students may struggle to

maintain consistent study routines, leading to procrastination and gaps in their understanding of key concepts.

Q: In what ways do you think digital technologies have helped or hindered your understanding of chemistry concepts?

ChL2: “Additionally, the oversimplification of complex concepts by digital tools can hinder a deeper understanding of fundamental chemistry principles”; this observation echoes concerns raised by Mishra and Yadav (2006), who warn that while digital simulations can enhance visualization, they may present oversimplified representations of complex chemical phenomena. This oversimplification can result in a shallow understanding of key concepts, which is particularly problematic in chemistry, where details and underlying mechanisms are for mastery.

4.2.13 Information overload and cognitive fatigue

The overwhelming volume of digital content can further hinder students’ learning experience.

Respondent ChSt1 described feeling “confused” and “overloaded” by the abundance of online resources; this aligns with findings by Sillence et al. (2023), who argue that excessive digital content can overwhelm students, making it difficult to identify relevant material. Cognitive overload can reduce engagement, leading to frustration and disengagement from learning activities.

Universities should adopt a balanced approach that integrates digital and traditional teaching methods. While digital tools are valuable for enhancing visualization and interactivity, they must complement rather than replace hands-on laboratory work to ensure students develop the practical skills necessary for scientific inquiry. Furthermore, institutions should provide support to help students build motivation and self-regulation strategies. This can include precise schedules and guided learning pathways to help students stay on track, combining face-to-face sessions with digital resources to enhance engagement, and ensuring students have access to troubleshooting assistance to minimize disruptions caused by technical issues. In a learning environment that bridges digital and traditional methods, universities can enhance student engagement, improve chemistry comprehension, and better prepare students for academic and practical challenges.

4.3 Perceptions of first-time entering students regarding the effectiveness of digital technologies within the academic

4.3.1 Increased access to educational resources

Students’ perceptions of digital tools in higher education significantly influence their academic success, especially in demanding science subjects like chemistry. Positive attitudes toward digital learning can enhance engagement and motivation, ultimately improving academic performance (Getenet et al., 2024). For many first-year students in South African universities, digital tools support their chemistry learning by visualizing complex concepts and supplementing traditional resources. However, some students encounter challenges such as digital literacy gaps, technical

difficulties, or an overwhelming abundance of resources, which can hinder comprehension and engagement (Chapman, 2025).

4.3.2 Student perceptions of digital tools

Q: In what ways do you think digital technologies have helped or hindered your understanding of chemistry concepts?

ChL1: “Digital tools have helped me visualize complex chemical reactions, but sometimes they oversimplify the material.”

ChSt2: “Interactive simulations have been a huge help in grasping abstract concepts.”

ChSt7: “I learn better through digital animations than from textbooks.”

These responses illustrate the strengths and limitations of digital technologies in aiding students’ understanding of chemistry. ChL1’s observation highlights the benefits of digital tools in simplifying abstract concepts through visualization yet also warns of oversimplification, which may hinder deeper comprehension. Reyes and Villanueva (2024) emphasize that visual aids effectively transform abstract chemistry content into more accessible formats, enhancing engagement and learning.

ChSt2’s positive experience with interactive simulations aligns with Constructivist Learning Theory, which emphasizes active learning through hands-on engagement (Yannier et al., 2020). Allowing students to manipulate variables and observation, simulations support conceptual understanding in ways that textbooks alone may not achieve.

Similarly, ChSt7’s preference for digital animations shows their ability to illustrate chemical processes that static diagrams may struggle to convey. Visual resources like animations are valuable for demonstrating reaction mechanisms, molecular motion, or phase transitions, supporting core chemistry concepts (Kelly and Hansen, 2017).

4.3.3 Challenges associated with digital tools

Q: What challenges have you encountered in learning chemistry with digital technologies?

ChL2: “They have made it easier to access additional learning materials, but knowing which resources are reliable is overwhelming.”

ChSt4: “Digital platforms help me explore concepts at my own pace, but technical problems make it frustrating.”

While digital technologies offer benefits, they also present challenges that can impede learning. ChL2’s experience reflects a common concern: the overwhelming volume of digital resources can make it difficult for students to identify credible and relevant materials. According to Yu (2022), students with limited digital literacy may struggle to evaluate the reliability of online content, potentially reducing their confidence and engagement.

ChSt4’s frustration with technical difficulties indicates another barrier to effective digital learning. Technical issues such as software glitches, slow internet connections, or platform instability can disrupt the learning process, causing frustration and disengagement (Bergdahl, 2022). These challenges are particularly pronounced for students in rural South African communities, where internet connectivity may be unreliable.

4.3.4 Preferred digital tools and resources

Q: Can you give examples of digital tools or resources that you found particularly helpful or not helpful?

ChL1: “Online molecular visualization tools like ChemDraw have been helpful.”

ChSt3: “I use Khan Academy often; however, the university’s e-learning system is not user-friendly.”

ChSt8: “I find online quizzes and flashcards helpful, but I do not like the university’s online learning system.”

ChSt1: “I find the virtual lab simulations on Labster very helpful for practice.”

From the findings, the diverse range of digital tools that students find beneficial. ChL1’s endorsement of molecular visualization tools like ChemDraw shows their role in making abstract molecular structures more tangible and easier to understand. Similarly, ChSt1’s positive experience with Labster emphasizes the value of virtual lab simulations in strengthening practical skills and enhancing understanding of concepts. Such tools align with Constructivist Learning Theory by providing experiential learning opportunities that improve comprehension through practice (Al Abri et al., 2024).

ChSt8’s preference for online quizzes and flashcards reflects the effectiveness of interactive, low-stakes resources that promote active recall and self-assessment. These tools enable students to identify knowledge gaps and learning, which aligns with Hibbard et al.’s (2016) findings that frequent, self-paced assessments can enhance student motivation and retention. However, dissatisfaction with institutional e-learning platforms, as mentioned by ChSt3 and ChSt8, stresses the importance of intuitive design in online learning systems. Bueno-Vesga et al. (2021) emphasize that poorly designed platforms can increase cognitive load, frustrate students, and reduce engagement. Therefore, enhancing the usability of university e-learning systems can help mitigate these issues, improving students’ focus on content rather than navigation challenges (Liu and Yu, 2023).

4.3.5 Comparing digital and traditional learning methods

Q: How effective are digital technologies compared to traditional learning methods (e.g., textbooks and face-to-face lectures)?

ChL1: “Digital tools are helpful for reinforcement, but face-to-face lectures are better for deep understanding.”

ChL2: “I prefer traditional lectures because I can ask questions on the spot, but digital tools are great for revision.”

ChSt1: “I find traditional methods more engaging, but digital tools are good for self-paced learning.”

ChSt5: “Digital tools complement my learning, but face-to-face explanations are more thorough.”

ChSt8: “I like using both methods; digital tools help me revise while traditional methods provide better understanding.”

These responses reflect a widespread preference for traditional learning methods, particularly for a deeper understanding of chemistry concepts. Students like ChL1 and ChL2 value face-to-face interactions for their immediacy and the opportunity to ask questions, facilitating more precise explanations of difficult

material; this aligns with the study by Woolner et al. (2018), who emphasize the role of structured classroom environments in building foundational knowledge. However, students like ChSt2 and ChSt4 recognize digital tools' flexibility and visual benefits. Digital platforms allow students to revisit content, engage with visual aids, and learn at their own pace—particularly useful features for reinforcing difficult chemistry concepts (Kolil and Achuthan, 2024). The balanced approach preferred by ChSt8, which values digital tools for revision while relying on traditional methods for core understanding, suggests that integrating both strategies may yield optimal learning. As Mushtaq and Iqbal (2024) suggest, blending digital tools with traditional teaching methods can give students flexibility, improved retention, and deeper comprehension.

While digital technologies offer tools for enhancing chemistry education mainly through visualization, interactive simulations, and self-paced learning—they are not without limitations. If not adequately addressed, technical challenges, resource overload, and the risk of oversimplification can hinder students' understanding. A balanced approach that combines digital tools with traditional face-to-face instruction appears to be the most effective strategy for promoting engagement, improving comprehension, and supporting diverse learning preferences. Institutions can improve performance by ensuring digital platforms are intuitive, offering clear guidance on reliable resources, and blending digital innovations with established teaching practices to support student success in chemistry (Meylani, 2024).

- a. Strategies to optimize digital literacy skills for enhancing understanding of chemistry content.

Integration of multimedia and interactive resources: this theme examines students' recommendations for enhancing the integration of digital technologies into their chemistry learning experiences. Students can improve their digital literacy skills by identifying strategies and resources and understanding chemistry concepts more deeply.

Q: What strategies or resources would you suggest improving the use of digital technologies for learning chemistry?

ChL1: "More hands-on workshops and easy-to-understand manuals for the tools would be helpful."

ChSt2: "Introducing step-by-step tutorials for the software would help."

ChSt5: "We need mentorship programs to guide us in using these technologies."

Students' responses show the importance of practical support and accessible resources in enhancing digital literacy and improving comprehension of chemistry. For instance, ChL1's suggestion of "more hands-on workshops and easy-to-understand manuals for the tools" aligns with the view that experiential learning is crucial for mastering digital technologies in education (Rao et al., 2024). Similarly, ChSt2 advocates for "step-by-step tutorials," indicating that structured guidance can enhance confidence and reduce confusion when using digital tools. Additionally, ChSt5 emphasizes the value of mentorship programs, pointing out

the need for expert support to help students navigate these technologies effectively.

ChSt8: "Access to recorded lectures so we can review the materials after class."

ChSt7: "A resource hub with all the digital tools and guides in one place."

ChSt6: "Having digital libraries with chemistry-specific resources would be useful."

These comments state the need for supplementary resources to support learning. For example, ChSt8's calls for "access to recorded lectures" reflect the growing demand for flexible, self-paced learning options that enable students to revisit concepts as needed. Meanwhile, ChSt7's recommendation for a centralized resource hub could simplify access to essential materials, improving students' ability to engage in independent learning. ChSt6's suggestion for "digital libraries with chemistry-specific resources" emphasizes the value of subject-specific content directly supporting coursework and research. Together, these strategies emphasize establishing a comprehensive support system to enhance digital learning activities.

ChSt1: "We need better internet infrastructure, especially in rural areas."

ChL2: "Simplified user interfaces and offline access to resources could make things easier."

In addition to recommending resources, students stressed the importance of infrastructure improvements. ChSt1 underlined the need for improved internet connectivity, particularly in rural areas, which can hinder access to digital learning platforms. Similarly, ChL2 proposed "simplified user interfaces and offline access" to ensure digital platforms remain accessible to students with limited connectivity; this is particularly relevant in South Africa, where digital inequality remains a challenge (Oyedemi and Choung, 2020).

Q: How do you think these strategies could be implemented effectively in your university?

ChL1: "Regular workshops can be integrated into the chemistry curriculum."

ChSt2: "Software tutorials can be added to the first-year chemistry course."

ChSt3: "Interactive tools should be mandatory for lab sessions so students get used to them."

These responses reveal a strong preference for embedding digital literacy strategies directly into the curriculum. Integrating workshops, software tutorials, and interactive tools into chemistry courses would provide students with consistent exposure to critical technologies, enhancing their digital proficiency. According to Falloon (2020), aligning digital literacy initiatives with the curriculum ensures that students develop these skills progressively, improving confidence and academic performance.

ChSt8: "Ensure all classes are recorded and uploaded for revision."

ChSt7: "Create a dedicated section on the university's website for digital chemistry resources."

ChSt6: “The IT department can develop a digital resource portal.”

ChSt1: “Collaboration with local tech companies to provide free or discounted resources.”

These recommendations reflect a practical approach to enhancing resource accessibility. For instance, ChSt8’s suggestion to record and upload lectures would support flexible learning, enabling students to review challenging concepts as needed. ChSt7 and ChSt6 propose centralized online platforms to streamline access to digital resources, promoting self-directed learning. Additionally, ChSt1 recommends partnerships with technology companies to provide discounted or free tools, addressing financial barriers that often limit access to essential digital resources.

4.3.6 Need for training and support

Students also emphasized the necessity of training programs to equip them with essential digital literacy skills.

Q: How important is it for the university to provide training or workshops on digital literacy skills?

ChL1: “Extremely important, especially for students with no prior exposure to these tools.”

ChL2: “Vital, because without training, students will not use the tools to their full potential.”

ChSt1: “Very important, especially for those from rural backgrounds.”

These responses indicate the role of digital literacy training, particularly for students from disadvantaged backgrounds or with limited prior experience. [Yuan et al. \(2024\)](#) note that students without adequate digital literacy often struggle with confidence and engagement, ultimately affecting their academic performance.

ChSt4: “Essential, because digital skills are now a part of academic success.”

ChSt5: “I think it is very important, as not everyone has the same skill level.”

ChSt7: “It is crucial, as digital tools are increasingly used in our education.”

These responses further emphasize the growing role of digital skills in academic achievement. [Sharma et al. \(2024\)](#) affirm that digital proficiency enhances learning outcomes and prepares students for a technology-driven engagement.

ChSt2: “We need to feel confident using the software.”

ChSt3: “Critical since we are expected to use these tools without much guidance.”

ChSt6: “It is key to helping us keep up with modern learning methods.”

ChSt8: “Most of us struggle without training, so it is very important.”

These responses confirm that structured training is crucial for building student confidence in digital tools. [Kundu \(2020\)](#) stresses that students who undergo comprehensive training are more likely to engage with digital platforms effectively, improving their self-efficacy and academic success.

Q: What specific skills or topics should this training cover to be most beneficial?

ChL1: “Basic navigation of chemistry software and troubleshooting.”

ChL2: “How to access and use online chemistry resources effectively.”

ChSt2: “Step-by-step guidance on using simulation tools.”

These responses indicate a strong demand for foundational training in software navigation, troubleshooting, and the effective use of chemistry-specific digital tools. [Van de Pol et al. \(2015\)](#) argue that equipping students with these fundamental skills reduces frustration and enables independent learning.

ChSt4: “Using digital libraries to find research materials.”

ChSt5: “Integrating digital tools with traditional methods for better learning outcomes.”

ChSt8: “Using advanced chemistry software for data analysis and visualization.”

Students also echoed the need for more advanced training, particularly in research skills, data analysis, and integrating digital tools with traditional methods; this combination can enhance their understanding of chemistry concepts and improve their ability to analyse and interpret data.

ChSt1: “Tips on managing poor internet connections while studying online.”

ChSt6: “How to use different platforms for collaborative study.”

ChSt7: “Managing digital notetaking and resource organization.”

These responses emphasize the need for practical strategies to address connectivity challenges, enhance collaboration, and improve digital organization. [Faturoti \(2022\)](#) stated that training students in resource management and offline access strategies can mitigate the challenges of unreliable internet connections and promote consistent learning performance.

This study is the absence of a control or comparison group, which constrains the ability to make strong causal claims regarding the observed improvements in students’ chemistry content proficiency. Although the pre-post design offers insights into changes over time, the influence of potential confounding factors such as increased academic familiarity, retest effects, or participants’ expectations cannot be ruled out. As such, the findings are interpreted as indicative rather than definitive evidence of the impact of digital literacy interventions. To strengthen internal validity and isolate the specific contribution of digital tools to learning performance, future research should consider incorporating randomized controlled trials or waitlist comparison designs. Such approaches would allow for a more thorough evaluation of causal mechanisms and better account for background variables.

4.4 Theoretical interpretation through TAM

The findings of this study align strongly with the Technology Acceptance Model (TAM), giving insights into students’ behavioral engagement with digital tools for learning chemistry. TAM posits

that perceived ease of use and perceived usefulness directly influence users' acceptance of technology (Davis, 1989); this framework helps explain several behavioral patterns observed in the data. For instance, students who found platforms intuitive and helpful in visualizing abstract chemistry concepts (e.g., molecular structures or reaction mechanisms) were more likely to engage actively with digital tools, reinforcing TAM's prediction that perceived usefulness enhances adoption. Conversely, technical challenges such as software incompatibility, confusing interfaces, and lack of guidance reduced perceived ease of use, which in turn contributed to frustration and disengagement, particularly among students from rural or under-resourced backgrounds. These barriers reflect TAM's assertion that when digital tools are seen as difficult to navigate, students are less inclined to incorporate them into their learning routines. The demand for structured training and simplified platforms indicates a gap between tool availability and user readiness, stressing the importance of institutional efforts to improve usability and support. The study contributes theoretically by illustrating how students' behavioral intentions toward digital tools are influenced by their individual digital skills, infrastructural and instructional support systems, factors particularly relevant in developing country like South Africa, especially a university that is historically disadvantaged.

4.5 Evaluation of hypotheses

Hypothesis 1: first-year students face significant challenges in utilizing digital technologies to understand chemistry content.

The findings strongly support this hypothesis. Students reported persistent technical barriers such as unreliable internet connectivity, device incompatibility, and software glitches, which disrupted access to essential chemistry resources (Brown et al., 2021; Mishra and Yadav, 2006). Additionally, low digital literacy hindered effective navigation of platforms, with many students, particularly from rural backgrounds, struggling to adapt (Haleem et al., 2022; Gan et al., 2024). These challenges reduced engagement and led to information overload and cognitive fatigue (Masrek and Baharuddin, 2023; Sillence et al., 2023). Overall, the data confirm that without adequate infrastructure and training, digital technologies may worsen inequities in chemistry learning rather than enhance them.

Hypothesis 2: students perceive digital technologies as effective for enhancing their chemistry learning.

This hypothesis is partially supported. Students acknowledged that digital tools such as molecular visualization software, animations, and virtual labs were valuable for understanding abstract concepts (Reyes and Villanueva, 2024; Kelly and Hansen, 2017). Positive perceptions were rooted in the visualization and flexibility offered by digital platforms, which strengthened Constructivist Learning Theory principles (Yannier et al., 2020). However, perceptions were tempered by concerns over oversimplification of complex processes (Mishra and Yadav, 2006), the overwhelming volume of resources (Yu, 2022), and technical frustrations (Bergdahl, 2022). Students consistently expressed a preference for a blended approach, combining the strengths of

digital tools with traditional face-to-face instruction (Mushtaq and Iqbal, 2024). Thus, while students valued digital technologies, their effectiveness was perceived as conditional upon supportive infrastructure, clear integration with classroom learning, and balance with hands-on practice.

Hypothesis 3: strategies can optimize digital literacy skills to improve students' chemistry proficiency.

The findings provide clear support for this hypothesis. Students and lecturers alike emphasized the importance of structured training workshops, step-by-step tutorials, and mentorship programs to build confidence in digital tool use (Chiu, 2023; Rao et al., 2024; Yuan et al., 2024). They also recommended infrastructural improvements such as reliable internet access and simplified user interfaces (Oyedemi and Choung, 2020). Embedding digital literacy into the chemistry curriculum through tutorials, interactive resources, and recorded lectures was seen as essential for sustainable improvement (Falloon, 2020). Finally, suggestions such as centralized resource hubs and partnerships with technology companies highlight a practical pathway to bridge inequalities. These strategies align with literature that identifies digital proficiency as a prerequisite for effective engagement and academic success in modern science education (Kundu, 2020; Sharma et al., 2024).

5 Conclusion and recommendations

Integrating digital technologies in higher education has revolutionized teaching and learning methods, particularly in science disciplines such as Chemistry. Digital tools such as molecular visualization software, interactive simulations, and multimedia platforms have proven effective in enhancing students' understanding of difficult chemical concepts. However, despite the increasing availability of these resources, students' ability to effectively utilize them remains inconsistent, particularly in resource-constrained environments. This study was motivated by the need to investigate first-year Chemistry students' challenges at a South African university in using digital technologies and propose strategies for improving their adoption to enhance learning performance. Hence, this study adopted an interpretivist paradigm with a qualitative approach, utilizing open-ended questionnaires to gather in-depth insights from students and lecturers to identify challenges faced by first-year students in using digital technologies for Chemistry learning, examine students' perceptions of digital technologies in enhancing their understanding of Chemistry concepts and recommend strategies to improve digital literacy skills for better chemistry comprehension among first-year students.

The findings revealed several key obstacles that hinder the effective use of digital technologies in Chemistry education. One significant challenge was the lack of digital literacy skills among students, particularly those from rural areas with limited prior exposure to digital tools: this knowledge gap restricted students' ability to effectively engage with platforms such as molecular visualization software and interactive simulations. While these resources were available, many students struggled to navigate and utilize them due to a lack of structured training. Additionally, both students and lecturers indicated that self-learning was often the

only option available to them, which led to inconsistent usage and, in some cases, avoidance of these technologies altogether.

Despite these challenges, the study shows that digital tools positively impact when applied effectively. Both students and lecturers acknowledged that digital platforms significantly improved comprehension of Chemistry concepts by enabling students to visualize abstract structures and chemical reactions. Molecular visualization software, in particular, was identified as an effective tool for enhancing conceptual understanding. However, the absence of structured support and limited access to advanced digital resources reduced the overall effectiveness of these technologies. As a result, while the potential for digital tools to improve Chemistry learning was widely recognized, their impact was undermined by practical challenges such as inadequate training, limited access, and inconsistent integration into coursework.

The study shows the need for universities to adopt a comprehensive strategy that addresses these challenges. One crucial recommendation is implementing structured digital literacy training for students and lecturers. Digital literacy training should be a compulsory component of first-year orientation programs to ensure students acquire the necessary skills to use Chemistry-specific digital tools effectively from the outset. Ongoing professional development for lecturers is equally important in equipping them with the knowledge and confidence to integrate these technologies into their teaching strategies. Such training should emphasize the technical aspects of using digital platforms and the pedagogical approaches needed to enhance Chemistry learning performance.

To enhance digital literacy and ensure equitable access to resources, universities must improve their digital infrastructure by providing students, particularly those from disadvantaged backgrounds, with devices preloaded with chemistry-specific tools and ensuring stable internet access. Integrating digital technologies into the chemistry curriculum through interactive simulations, molecular visualization platforms, and collaborative tools will promote student proficiency and confidence. Lecturers should also receive support in developing instructional strategies that embed these tools as core teaching methods. Additionally, universities should establish dedicated technical support teams to assist both students and staff in navigating digital platforms while forming partnerships with public and private stakeholders to secure essential resources. Clear institutional policies promoting the consistent integration of digital tools across chemistry curricula, alongside incentives for lecturers who adopt innovative digital teaching practices, are crucial to maximizing the impact of digital technologies on student learning performance.

Given the growing reliance on digital technologies in higher education, this study is important, particularly in developing areas; however, the lack of a control or comparison group constrains causal interpretations, as observed improvements may reflect external influences such as increased academic exposure or expectancy effects. While this study provides insights into the relationship between digital literacy and chemistry proficiency among first-year students, it is constrained by several limitations. Conducting the research at a single institution with a relatively small sample size restricts the generalizability of the findings,

and the lack of a control or comparison group limits the ability to establish causal relationships, as observed improvements may reflect external influences such as increased academic exposure. In addition, potential instructor or facilitator effects were not examined, leaving open the possibility that variations in teaching styles or facilitation approaches influenced student performance. The study also did not incorporate reflective or identity-based dimensions of learning, nor did it collect systematic data on student perceptions of the learning experience, both of which could provide insight into how learners construct digital and disciplinary identities and evaluate the pedagogical strategies employed.

Based on the limitations of this current study, future research should adopt more rigorous and generalizable designs, such as preregistered multi-site randomized controlled trials, to provide stronger causal evidence of findings across diverse universities. Including control or waitlist groups and incorporating trainer-fidelity checks would strengthen internal validity by addressing potential instructor effects and ensuring consistency in instructional delivery. Studies could also be enriched by embedding reflective and identity-focused activities, such as digital journals or self-assessments, which would deepen insight into how students perceive themselves as learners and digital citizens while promoting long-term digital literacy and science communication skills. To enhance triangulation, future studies should complement self-reported data with audience-based ratings, observational measures, and student feedback instruments, in order to provide more comprehensive understanding of clarity, engagement, and the effectiveness of digital strategies.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

ND-G: Funding acquisition, Methodology, Writing – original draft, Formal analysis, Resources, Software, Investigation, Visualization, Supervision, Validation, Conceptualization, Writing – review & editing, Project administration, Data curation. LM: Project administration, Conceptualization, Validation, Methodology, Software, Data curation, Investigation, Writing – original draft, Resources, Formal analysis, Visualization. TN: Visualization, Writing – review & editing, Data curation, Project administration, Formal analysis, Validation, Methodology, Writing – original draft, Investigation, Software, Conceptualization, Resources, Supervision, Funding acquisition. AA: Methodology, Funding acquisition, Writing – review & editing.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feduc.2025.1630306/full#supplementary-material>

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