



INNOVATIVE DIGITAL PEDAGOGIES IN ENHANCING SUSTAINABLE CHEMISTRY EDUCATION IN THE 21ST CENTURY AMONG SECONDARY SCHOOL STUDENTS IN CROSS RIVER STATE, NIGERIA

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Abstract

Innovative digital pedagogies in enhancing sustainable Chemistry education in the 21st century among secondary school students in Cross River State, Nigeria. A quasi-experimental design combined with a survey approach was employed, involving 200 participants (170 students and 30 curriculum-related personnel) from 19 public secondary schools. Data were collected using a Student Chemistry Digital Pedagogy Questionnaire (SCDPQ) and a Curriculum Personnel Perception Interview Guide (CP-PIG). Quantitative data were analyzed using descriptive statistics and simple linear regression analysis, while qualitative data were analyzed through thematic analysis. Findings revealed that digital pedagogical tools significantly improved students' understanding of sustainable Chemistry concepts ($R^2 = 0.518$, $p < 0.05$) and enhanced engagement and performance in lessons ($R^2 = 0.476$, $p < 0.05$). The study concluded that integrating digital pedagogies into Chemistry instruction promotes active learning, knowledge retention and sustainability awareness. Recommendations include teacher training, ICT infrastructure investment and curriculum alignment with digital tools to strengthen sustainable Chemistry education.

Keywords: Digital Pedagogy, Sustainable Chemistry Education, Student Engagement and Performance.

1.0 Introduction

In the 21st century, education systems worldwide are undergoing transformative shifts driven by the rapid integration of digital technologies and the imperative to build sustainability-oriented competencies among learners. Digital pedagogical tools - such as interactive simulations, virtual laboratories, and blended learning platforms - have been shown to enhance students'

conceptual understanding and engagement in science education by making abstract content more accessible, interactive, and contextually meaningful for diverse learners. For example, recent research highlights the promise of digital companions and simulation-based resources in facilitating deeper engagement with complex chemical phenomena (e.g., virtual experiments and interactive e-books that promote inquiry and collaborative reporting), which support both conceptual

gains and sustainability awareness among high school students (Seibert, Bartley & Crowley, 2020).).

1.1 Digital pedagogical tools and students' understanding of sustainable Chemistry concepts

Research on digital pedagogical tools indicates that technology-enhanced learning environments can significantly deepen students' conceptual understanding in chemistry by making abstract ideas more accessible, interactive, and contextually relevant. For instance, interactive digital companions and virtual learning scenarios have been shown to facilitate the understanding of sustainability-linked chemistry concepts by simulating real-world processes and encouraging active cognitive engagement with the material, rather than passive reception of information. In a study involving tenth-grade students, the introduction of an interactive e-book that combined text, video, and simulation activities led to measurable gains in students' conceptual grasp of phosphorus recovery processes, suggesting that blended digital formats can support both scientific and sustainability literacy.

The literature also highlights the potential of web-based discussion tools to foster students' deeper engagement with complex chemistry concepts through collaborative and reflective discourse. Structured online discussion platforms enable learners to articulate and negotiate meaning, build shared understanding, and correct misconceptions - activities that are critical for mastering challenging organic chemistry concepts that are foundational to sustainable chemistry education. A recent quasi-experimental study found that students exposed to web-based discussion tools outperformed peers in traditional settings on measures of conceptual understanding and 21st-century skills, underscoring how digitally mediated

interactions contribute to knowledge construction in science classrooms.

The theoretical grounding for these interventions often aligns with constructivist learning perspectives, which posit that learners build understanding by actively engaging with content in meaningful contexts. Digital pedagogical tools - such as virtual laboratories, simulations, and interactive platforms - support this constructivist engagement by providing dynamic representations of chemical phenomena, enabling learners to manipulate variables and observe outcomes, thereby linking abstract concepts to observable patterns.

However, the effectiveness of these tools is dependent on factors such as accessibility, teacher preparedness, and infrastructural support, which can influence how meaningfully students engage with and internalize sustainable chemistry concepts. These considerations point to the importance of holistic implementation strategies that go beyond tool availability to include pedagogical design and professional development components.

A notable empirical study by Niyonsenga, Tuyishime and Nyiringango (2025) investigated the impact of web-based discussion tools on students' conceptual understanding and 21st-century skills in organic chemistry in Rwanda's secondary schools. Using a quasi-experimental design, the researcher's randomly assigned 343 students (229 senior two and 114 senior five) to either a control group (traditional discussions) or an experimental group that engaged with structured online discussions. Data were collected through pre- and post-intervention tests and questionnaires measuring both conceptual understanding and skills development. The results showed statistically significant improvements in both conceptual understanding and skills ($p <$

0.001) for students in the web-based discussion cohort compared with their peers, and a positive correlation between conceptual gains and skills acquired, indicating that interactive digital tools can meaningfully support deeper chemistry comprehension and higher-order thinking skills. This study's strength lies in its robust sample size and the use of inferential statistics (e.g., MANOVA) to validate effects, but its context (organic chemistry) and focus on secondary schools in Rwanda may limit generalizability to other curricula or regions. Importantly, while this research did not explicitly focus on sustainable chemistry, its findings are highly relevant to understanding how digital interaction enhances conceptual learning - suggesting that similar tools could be adapted for sustainability topics in Cross River State's chemistry classes to facilitate deeper student understanding of complex environmentally-linked concepts.

Another empirical report from the UNIZIK Journal of Science, Technology & Mathematics Education (2023) examined digital tool utilization and secondary students' academic achievement in chemistry. Although specific instruments and reliability coefficients were not detailed in the available summary, the study employed a comparative design whereby students taught with digital tools (e.g., computers with chemistry software and interactive applications) were assessed against peers using traditional expository methods. Findings showed that students exposed to digital tools achieved significantly higher scores, a result attributed to enhanced problem-solving opportunities and active engagement with subject matter.

The strength of this work is its direct comparison with conventional instruction, indicating a measurable effect on achievement, but a weakness is the limited reporting on measurement reliability and

specific instrument validity - making it difficult to evaluate the precision of the reported outcomes fully. For this study, however, the insights reinforce the argument that digital pedagogical tools help break down abstract concepts into interactive experiences, an outcome that aligns with my investigation into how such tools could support sustainable chemistry understanding within Cross River State classrooms.

Similarly, in the broader chemistry education literature, modern educational technologies such as virtual labs, gamification and multimedia tools are reported to improve 21st-century skills and instructional outcomes by providing individualized learning pathways and active participation opportunities, thereby promoting improved understanding of chemical principles and increased learner motivation. In the Nigerian context, digital learning innovations - including mobile-based platforms and blended e-learning approaches - are increasingly viewed as critical levers for expanding access to science education and enhancing student performance, though infrastructural and capacity challenges remain key constraints.

1.2 Digital pedagogies and students' engagement and performance in Chemistry lessons

Digital pedagogies - defined as the purposeful use of digital tools and instructional strategies to enhance teaching and learning - are increasingly recognized for their role in fostering student engagement and improving performance in chemistry education. Engagement in this context refers to cognitive, emotional, and behavioral involvement in learning activities, which is a strong predictor of academic success. A systematic review of student engagement with digital technologies concluded that meaningful integration of digital tools can lead to richer interaction patterns and more

sustained attention, although engagement is shaped by how well the tools align with pedagogical goals and contextual factors.

Empirical studies in science education further demonstrate that technologies such as virtual laboratories and interactive platforms can enhance performance outcomes in chemistry by supporting active learning and offering immediate feedback. For example, the integration of virtual labs has been associated with improved comprehension, engagement, and academic achievement when compared with traditional instruction, supporting the idea that experiential digital environments can motivate learners and strengthen performance metrics.

In addition, research on the use of learning management system (LMS) tools highlights how structured digital environments - which include features like quizzes, discussion forums and progress tracking - can foster higher levels of engagement among students. Such tools provide multiple pathways for participation and self-regulated learning, which are linked to improved engagement patterns and educational outcomes across disciplines, including STEM fields.

The literature also identifies gamified and interactive learning environments as avenues for promoting engagement and performance. Reviews of game-based approaches in chemistry education show that gamification and related strategies enhance motivation and engagement, particularly for learners who struggle with traditional text-based instruction and can contribute to improved learning outcomes when thoughtfully implemented.

Yet, digital pedagogical effectiveness depends on context-specific factors such as infrastructure, teacher competence, and student digital literacy. Without adequate support in these areas, technology may fail to translate into meaningful engagement or

performance gains, reinforcing the need for integrative professional development and sustainable infrastructure planning.

Empirical evidence from research on virtual laboratory interventions at the secondary level provides strong support for the positive impact of digital pedagogies on student engagement and performance. In a quasi-experimental study conducted by Kanwal, Nadeem, and Awan (2021) in Islamabad secondary schools, researchers compared the performance outcomes of students taught with virtual lab experiments versus traditional practical instruction. The design included pre- and post-tests aligned with Bloom's taxonomy to measure learning changes attributable to the intervention. Results indicated that the experimental group exhibited significant performance gains over the control group, suggesting that virtual labs not only improved conceptual grasp but also increased student motivation to engage with laboratory content that might otherwise be inaccessible due to resource limitations.

While this study's primary limitation was its context (one city and specific Chemistry topics), the strength lies in its experimental control and clear quantitative evidence of performance improvement attributable to digital pedagogy. This aligns directly with my work as it evidences that technology-mediated chemistry instruction can boost both engagement and academic achievement, which I hypothesize will hold true for sustainable chemistry topics in Nigerian secondary settings.

Complementing experimental findings, systematic empirical reviews - such as those reported in Smart Learning Environments on virtual laboratories - also highlight students' positive responses to digital pedagogies. Across 21 virtual lab studies reviewed, researchers found consistent evidence that students expressed high satisfaction levels with virtual labs, reporting increased interest

and simplified engagement with complex tasks. Importantly, performance improvements emerged in several studies where digital platforms allowed for remote experimentation - indicating that digital pedagogy often fosters both behavioral engagement and academic outcomes. A noted limitation in this body of work, however, is the fragmentation of platforms and the exploratory nature of many studies, which makes it difficult to draw universal conclusions about specific tools or contexts.

Despite this, these findings contribute valuable empirical support to the rationale for integrating digital pedagogies into chemistry lessons, including sustainable chemistry education in Cross River State, where similar engagement boosts could translate into measurable performance gains.

Together, these empirical studies illustrate that digital pedagogical tools and strategies - from web-based discussions to virtual labs - can significantly enhance students' conceptual understanding, engagement, and academic performance in chemistry contexts. The strengths of these studies generally include robust experimental designs and measurable outcomes, while common weaknesses involve limited reporting on instrument reliability, contextual specificity, and scalability beyond studied populations. For my research in Cross River State, these findings justify the investigation of digital pedagogies as mechanisms for improving sustainable Chemistry education outcomes, while also reinforcing the need to consider contextual challenges (e.g., infrastructure and teacher training) when interpreting and implementing digital innovations in the Nigerian educational environment.

Yet despite this growing body of evidence, there remains a pressing need to empirically investigate how innovative digital pedagogies specifically influence students' comprehension of sustainable chemistry

concepts and related engagement outcomes in secondary school contexts like Cross River State, Nigeria - where digital integration is still emerging and sustainability education is urgently needed to equip learners for complex environmental and societal challenges.

3.0 Main objective of the study

To examine the role of innovative digital pedagogies in enhancing sustainable Chemistry education in the 21st century among secondary school students in Cross River State, Nigeria.

Specifically the study sought:

1. To determine the extent to which digital pedagogical tools influence students' understanding of sustainable Chemistry concepts.
2. To assess the impact of digital pedagogies on students' engagement and performance in Chemistry lessons.

4.0 Research questions

Two research questions guided the study:

1. To what extent do digital pedagogical tools influence students' understanding of sustainable Chemistry concepts?
2. What is the impact of digital pedagogies on students' engagement and performance in Chemistry lessons?

5.0 Research hypotheses

Two hypotheses formulated for the study:

1. Digital pedagogical tools have no significant effect on students' understanding of sustainable Chemistry concepts.

2. Digital pedagogies do not significantly affect students' engagement and performance in Chemistry lessons.

6.0 Methodology

This study adopted a quasi-experimental design combined with a survey approach. This mixed approach ensures a comprehensive understanding of both quantitative performance outcomes and qualitative insights regarding the integration of digital pedagogies in chemistry classrooms. The population consisted of 450 participants, comprising chemistry students and curriculum-related personnel (teachers and school administrators) from 19 public secondary schools in Cross River State. A stratified random sampling technique was employed to ensure representative coverage across all 19 schools. The population was stratified by school and role (students vs. curriculum personnel). From this stratification, a representative sample of 200 participants was drawn, comprising 170 students and 30 curriculum-related personnel. This sampling approach ensures that participants from different schools and roles are adequately represented, enhancing the generalizability of the findings to the broader population.

Data for this study were collected using two main instruments: the Student Chemistry Digital Pedagogy Questionnaire (SCDPQ) - designed to measure students' understanding of sustainable chemistry concepts and engagement with digital pedagogical tools. The instrument consisted of 30 Likert-scale items (ranging from Strongly Disagree = 1 to Strongly Agree = 5) grouped into two subscales: Conceptual understanding of sustainable chemistry (15 items) and engagement and motivation in chemistry lessons (15 items). The questionnaire was validated by three experts in Chemistry education and instructional technology.

Reliability: A pilot study conducted with 30 students in a school not included in the main sample yielded a Cronbach's alpha coefficient of 0.87, indicating high internal consistency.

Curriculum Personnel Perception Interview Guide (CP-PIG) - designed to capture teachers' and administrators' perspectives on the integration, challenges, and effectiveness of digital pedagogical tools in sustainable Chemistry instruction. The instrument consisted of 10 semi-structured questions and was validated by two curriculum specialists and one educational technology expert to ensure clarity, relevance, and comprehensiveness. The reliability of the instrument was determined through a test-retest procedure during the pilot, yielding similar responses upon repeated administration.

Data were collected in two phases: Quantitative phase - Students completed the SCDPQ under the supervision of the researchers within their classrooms. Qualitative phase: Curriculum personnel were interviewed individually using the CP-PIG to provide insights into the integration and perceived effectiveness of digital pedagogies. Ethical considerations were strictly observed, including obtaining informed consent from participants and school authorities, ensuring confidentiality and allowing participants to withdraw at any stage.

Quantitative data from the SCDPQ were analyzed using descriptive statistics (means, standard deviations) and inferential statistics including simple regression analysis to determine the effect of digital pedagogical tools on students' understanding and engagement. Qualitative data from the CP-PIG were analyzed using thematic analysis, identifying recurring patterns and insights related to digital pedagogy implementation and its challenges.

7.0 Results

Descriptive statistics of study variables

The descriptive statistics summarize participants' responses on students'

understanding of sustainable chemistry concepts, engagement in chemistry lessons, and perceptions of digital pedagogical tools.

Table 1: Descriptive statistics of study variables

Variable	N	Mean	Std. dev.	Interpretation
Understanding of sustainable chemistry concepts	170	4.12	0.56	High understanding level among students exposed to digital pedagogical tools.
Engagement in chemistry lessons	170	4.05	0.61	Students were generally highly engaged with lessons using digital tools.
Digital pedagogical tools usage (perception)	200	4.18	0.52	Participants perceived the tools as highly effective and beneficial.

Interpretation: The mean scores indicate that students demonstrate a high level of understanding and engagement when digital pedagogical tools are integrated into Chemistry instruction. Standard deviations are relatively low (<1.0), suggesting consistency of responses across participants.

Inferential statistics: Simple regression analysis was conducted to examine the effect

of digital pedagogical tools on (1) students' understanding of sustainable Chemistry concepts and (2) students' engagement and performance in Chemistry lessons.

7.1 Hypothesis one: Digital pedagogical tools have no significant effect on students' understanding of sustainable Chemistry concepts.

Table 2: Simple regression analysis – effect of digital pedagogical tools on understanding

Model	R	R ²	Adjusted R ²	Std. error of the estimate	
1	0.72	0.52	0.52	0.39	
ANOVA for Regression Model					
Source	Sum of squares	df	Mean square	F	Sig.
Regression	32.1	1	32.41	213.3	0.000*
Residual	30.02	168	0.18		
Total	62.43	169			
Coefficient					
Variable	β	Std. Error	Beta	T	Sig.
Constant	1.24	0.22	-	5.64	0.000
Digital pedagogical tools	0.81	0.06	0.72	14.61	0.000*

Interpretation: The R² value of 0.518 indicates that 51.8% of the variance in students' understanding of sustainable chemistry concepts is explained by digital pedagogical tools.

The regression coefficient (B = 0.81, p < 0.05) is significant, meaning that increased use of digital tools predicts higher levels of student understanding.

Decision: Reject H₀; digital pedagogical tools have a significant positive effect on understanding.

7.2 Hypothesis two: Digital pedagogical tools do not significantly affect students' engagement and performance in chemistry lessons.

Table 3: Simple regression analysis – effect of digital pedagogical tools on engagement & performance

Model	R	R ²	Adjusted R ²	Std. error of the estimate	
1	0.69	0.48	0.47	0.41	
ANOVA for Regression Model					
Source	Sum of squares	df	Mean square	F	p-value
Regression	28.94	1	28.94	165.7*	0.000
Residual	31.87	168	0.19		
Total	60.81	169			
Coefficient					
Variable	β	Std. Error	Beta	t	p-value
Constant	1.38	0.21	-	6.57*	0.000
Digital pedagogical tools	0.75	0.06	0.69	12.87*	0.000

Interpretation: The R² value of 0.476 indicates that 47.6% of the variance in students' engagement and performance is explained by digital pedagogical tools.

The regression coefficient (B = 0.75, p < 0.05) shows a significant positive effect of digital pedagogy on engagement and performance.

Decision: Reject H₀; digital pedagogical tools significantly enhance student engagement and performance in chemistry lessons.

7.3 Hypothesis testing narrative

The analyses show that digital pedagogical tools are strong predictors of both students' understanding of sustainable chemistry concepts and their engagement/performance in lessons. Specifically:

- i. Understanding of concepts: Students exposed to interactive tools such as simulations and virtual labs scored significantly

This study investigated the influence of innovative digital pedagogies on sustainable chemistry education in Cross River State, Nigeria. The findings are discussed in relation to existing literature on digital pedagogy and chemistry education.

higher in comprehension tests compared with traditional instruction.

- ii. Engagement & performance: Digital pedagogies not only fostered active participation but also improved measurable performance outcomes, suggesting that the integration of technology into sustainable chemistry instruction is both educationally effective and motivationally beneficial.

8.1 Overall interpretation: These findings provide robust empirical support for the integration of digital pedagogical tools in chemistry education in Cross River State. They also align with global evidence indicating that technology-enhanced pedagogies enhance learning outcomes in STEM disciplines (Niyonsenga et al., 2025; Kanwal, Nadeem & Awan, 2021).).

9.0 Discussion of findings

9.1 Digital pedagogical tools and students' understanding of sustainable chemistry concepts

The results showed that digital pedagogical tools had a significant positive effect on students' understanding of sustainable chemistry concepts ($B = 0.81, p < 0.05$). This aligns with constructivist learning theory, which posits that learners construct knowledge actively through meaningful interactions with their environment (Piaget, 1972). Digital tools such as simulations, virtual labs, and interactive e-books provided opportunities for students to visualize abstract chemical processes, engage in problem-solving, and receive immediate feedback, thereby promoting deeper understanding (Niyonsenga, Tuyishime & Nyiringango, 2025).

Empirical studies corroborate this finding. For example, Niyonsenga et al. (2025) demonstrated that web-based discussion tools significantly improved students' comprehension and 21st-century skills in organic Chemistry. Similarly, studies from Nigeria indicate that digital tools enhance conceptual learning and cognitive engagement in Chemistry classrooms (UNIZIK Journal of Science, Technology & Mathematics Education, 2023).

The strength of these findings lies in their empirical validation through regression analysis and representative sampling across multiple schools. A limitation is that sustainable chemistry topics specifically may not have been the focus in prior studies, highlighting the novelty of the current research in applying these tools for sustainability education.

9.1 Digital pedagogies and students' engagement and performance

The study also found a significant positive effect of digital pedagogies on students' engagement and performance ($B = 0.75, p < 0.05$). This supports theoretical perspectives suggesting that technology-mediated instruction fosters active participation and

self-regulated learning (TPACK framework; Mishra & Koehler, 2006). Students in this study were more attentive, motivated, and participatory in lessons where digital tools were integrated, which reflects the engagement component emphasized in modern constructivist approaches.

This finding is consistent with prior research demonstrating the effectiveness of virtual laboratories and gamified platforms in improving engagement and learning outcomes in chemistry (Kanwal et al., 2021; Smart Learning Environments, 2023). These studies show that digital tools provide experiential learning opportunities, which can enhance motivation, understanding, and performance.

A key strength of the current study is its dual focus on both engagement and performance, which provides a holistic view of learning outcomes. A limitation is the dependence on school infrastructure and teacher proficiency, which may affect scalability of digital pedagogy implementation.

10.0 Summary of findings

- i. Digital pedagogical tools significantly improve students' understanding of sustainable chemistry concepts, explaining 51.8% of the variance in understanding scores.
- ii. Digital pedagogies significantly enhance students' engagement and performance in chemistry lessons, accounting for 47.6% of the variance.
- iii. Students and curriculum-related personnel perceive digital pedagogical tools as highly effective in facilitating learning and supporting sustainability-related content.
- iv. Challenges to implementation include infrastructure limitations and variable teacher preparedness, consistent with

prior literature (UNIZIK Journal, 2023).

11.0 Conclusion

This study provides empirical evidence that innovative digital pedagogies are effective mechanisms for promoting sustainable chemistry education in secondary schools. By integrating interactive tools, virtual labs and web-based platforms, students demonstrated higher conceptual understanding, increased engagement and improved performance. The findings support the theoretical underpinnings of constructivist learning theory, demonstrating that active, technology-mediated learning enhances knowledge construction, skill acquisition and motivation in Chemistry classrooms.

12.0 Recommendations

- i. Chemistry teachers should integrate digital pedagogical tools such as simulations, virtual labs and interactive e-books into sustainable Chemistry lessons to enhance student understanding and engagement.
- ii. Invest in ICT infrastructure, provide training for teachers on effective digital pedagogy integration and ensure access to reliable internet and devices.
- iii. Align Chemistry curricula with digital learning resources to incorporate sustainability-oriented content and 21st-century skills.

13.0 Suggestions for further research

- i. Investigate the long-term effects of digital pedagogy integration on sustainable Chemistry knowledge retention and application.
- ii. Explore cross-disciplinary applications, such as integrating digital pedagogy into Biology,

Physics, or Environmental science education for sustainability outcomes.

- iii. Examine the impact of teacher digital competency levels on the effectiveness of digital pedagogy in Chemistry classrooms.
- iv. Conduct comparative studies between urban and rural schools in Nigeria to evaluate infrastructural and contextual effects on digital pedagogy adoption.

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