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RESEARCH ARTICLE

# Effect of An Interactive Digital Textbook for Academic Achievement and Learning Satisfaction in Lower School Biology

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## Abstract

This study developed and evaluated an interactive Digital Textbook (DT) to improve genetics learning among 10th-grade students in Tanzania. Traditional approaches to genetics instruction often present abstract content that limits student engagement and understanding. To address these issues, the DT was created using the Genially platform, incorporating multimedia and interactive features to promote active learning. The development followed the ADDIE model: analysis, design, development, implementation, and evaluation. A true experimental design with 30 secondary school students compared outcomes between an experimental group using the DT and a control group using print-based textbooks. Results revealed that the experimental group achieved significantly higher post-test scores ($M = 7.49$, $SE = .46$) than the control group ($M = 6.05$, $SE = .46$), $F(1, 27) = 4.89$, $p = .036$, $\eta^2 = .153$. In addition, students using the DT reported greater learning satisfaction. Qualitative feedback highlighted the effectiveness of multimedia and interactivity in enhancing understanding of complex genetic concepts. These findings support the integration of interactive digital tools in science education and call for investments in digital infrastructure, teacher training, and the development of high-quality digital content to support broader implementation.

**Keywords:** Biology education, digital textbook, genially platform, academic achievement, learning satisfaction

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## Introduction

### Digital Technology in Education

Advancements in digital technologies, particularly information and communication technology (ICT), have significantly reshaped educational practices worldwide. Among these innovations, digital textbooks (DTs) have transformed the production, distribution, and use of learning materials (Aslam & Saeed, 2022; Byeon, 2022). Emerging in the late 1990s as part of the digital publishing revolution (Woody et al., 2010), DTs gained momentum in schools and universities from the early 2010s (Roberts et al., 2021).

DTs are electronic versions of traditional print textbooks (TPTs), enhanced with interactive features such as multimedia, hyperlinks, embedded assessments, and collaborative functions (Dobler, 2015). Accessible via tablets, smartphones, e-readers, and computers, they contrast with TPTs' static format of paper-based text and images (Cozart et al., 2021). Early DTs largely replicated print versions, but technological advances have since enabled the integration of animations, audio, adaptive assessments, and learning analytics (Chavali & Gundala, 2022). These features allow for more engaging and personalized learning, particularly in complex subjects like genetics, where abstract concepts often challenge students (Falode et al., 2019; Riyanto et al., 2020).

In the context of biology education, particularly in complex and abstract fields such as genetics, DTs offer new pedagogical opportunities. Traditional methods often fail to effectively convey molecular processes, resulting in student disengagement and poor academic outcomes. Interactive DTs provide a promising solution by using visual and interactive content to simplify abstract concepts and facilitate deeper understanding (Falode et al., 2019; Riyanto et al., 2020).

One of the most transformative advantages of digital technology is the delivery of multimedia-rich content. The integration of text, visuals, animations, and simulations enhances comprehension of scientific phenomena, particularly at the molecular or cellular level. Studies show that animated and visual content can significantly improve understanding of genetics, a field traditionally difficult to grasp through text alone (Rahim et al., 2020; Duncan et al., 2009). Furthermore, digital technologies support interactive and adaptive learning. Simulations, virtual laboratories, and gamified assessments provide hands-on experiences, immediate feedback, and opportunities for critical thinking. Evidence indicates that students using such tools outperform peers in assessments, demonstrating the effectiveness of technology-enhanced learning (Barnett-Itzhaki et al., 2023).

Adaptive systems also enable personalized learning pathways, aligning instruction with individual needs. This shift not only sustains motivation but also supports mastery learning. Nonetheless, effective integration of digital tools requires robust infrastructure and teacher training. As Choi (2017) notes, the impact of digital technologies depends on their thoughtful design and pedagogical alignment. Poor preparation or weak content can undermine potential benefits.

Despite these challenges, growing evidence supports the pedagogical value of digital technologies. When carefully designed and implemented, DTs and other digital tools can transform classrooms into dynamic, student-centered spaces. They not only enhance knowledge acquisition but also cultivate scientific reasoning, collaboration, and digital literacy—competencies essential in the modern world. As education systems evolve, integrating digital technologies must remain central to curriculum and instructional design.

## Digital Textbook and Learning Biology

The digital textbook (DT) represents a significant evolution from traditional print textbooks (TPTs), offering an enriched learning experience through the integration of multimedia and interactivity. DTs are defined as electronic versions of textbooks that incorporate features such as embedded videos, animations, hyperlinks, audio narrations, and assessment tools (Dobler, 2015; Chavali & Gundala, 2022). These features enhance accessibility and engagement, allowing students to interact with content in ways that align with contemporary digital habits. Unlike static TPTs, DTs support multimodal learning by catering to diverse sensory inputs, which is particularly advantageous in science education, where visual and experiential understanding is critical.

Biology, and specifically genetics, presents unique challenges in education due to its abstract nature and reliance on complex conceptual models. Traditional approaches often fall short in helping students grasp molecular interactions and dynamic biological processes. Studies have shown that interactive DTs can significantly improve comprehension and retention in biology by visualizing invisible phenomena (Riyanto et al., 2020; Rahim et al., 2020). For instance, animations that depict DNA replication or protein synthesis provide learners with concrete representations of abstract mechanisms, thereby reducing cognitive load and enhancing understanding (Duncan et al., 2009). DTs also support learner autonomy and engagement by enabling students to control their learning pace, revisit complex topics, and engage with interactive assessments. Ahmed & Kwon (2022) demonstrated that a digital biology textbook with integrated quizzes and diagrams improved student motivation and academic performance. Similarly, Falode et al. (2019) reported that students using DTs outperformed those using TPTs in genetics tests, highlighting the effectiveness of interactivity and multimedia integration. Importantly, the benefits of DTs are not confined to performance metrics alone; students also report greater satisfaction and confidence when engaging with interactive digital materials.

Usability is a key factor in the success of DTs. Sulaiman and Mustafa (2020) identified critical usability dimensions, including user interface design, content organization, visual appeal, and accessibility. These factors influence how effectively students can navigate and interact with digital content. Poorly designed DTs can hinder learning by causing confusion or cognitive overload, whereas intuitive and visually coherent designs can facilitate smooth information processing. Fan et al. (2015) emphasized the importance of maintaining a familiar structure and layout, mirroring TPTs to ease the transition and support traditional reading habits while introducing digital enhancements. The scalability and adaptability of DTs make them valuable tools for diverse educational settings. As digital infrastructure continues to expand, DTs offer a cost-effective and sustainable solution for delivering quality science education at scale. Their capacity for continuous updates, real-time feedback, and integration with learning management systems (LMS) further positions DTs as a cornerstone of modern educational ecosystems. Nevertheless, the development of effective DTs requires interdisciplinary collaboration among educators, instructional designers, and software developers to ensure pedagogical alignment and technical robustness.

Overall, the literature suggests that DTs, when thoughtfully designed and contextually adapted, can transform biology education by improving content comprehension, promoting engagement, and supporting differentiated instruction. As educational systems seek to prepare learners for complex scientific and technological challenges, DTs offer a promising avenue to enhance biology teaching and learning through digital innovation.

## Research Objective

Building on the existing body of literature and educational theory, this study aimed to design, develop, and evaluate an interactive digital textbook (DT) specifically tailored for the teaching of genetics. Given the subject's abstract and complex nature, the research sought to explore the potential of interactive DTs to enhance academic achievement and learning satisfaction among lower secondary school students.

The first objective was to document the development process of an interactive DT for genetics using the ADDIE instructional design model, encompassing analysis, design, development, implementation, and evaluation phases. This framework ensured a systematic approach to content creation and usability testing. The second objective was to evaluate the effectiveness of the developed DT by comparing academic achievement outcomes between students using the interactive DT and those relying on TPTs. The study employed a pre-test–post-test experimental design to assess knowledge gains and identify significant differences in performance. The third objective focused on assessing students' perceptions of learning satisfaction when using the interactive DT. Qualitative and quantitative data were collected to understand user experiences and identify which features most contributed to motivation, comprehension, and engagement.

Collectively, these objectives aimed to contribute to the growing discourse on digital innovation in science education by providing empirical evidence on the design and pedagogical value of interactive DTs in genetics instruction.

## Research Methodology

### Research Design and Participants

This study employed a true experimental pre-test–post-test control group design to evaluate the effectiveness of an interactive DT in enhancing student academic achievement and learning satisfaction in genetics education. A total of 30 participants were selected from a population of 184 Form Four (10th-grade) students using a convenience sampling approach, based on accessibility within the school context (Stratton, 2019). Following recruitment, students were randomly assigned to either the experimental group (DT) or the control group (TPTs), with 15 students in each group, thereby ensuring comparability across conditions and supporting internal validity (Hall et al., 2024).

The intervention was implemented over a specified instructional period. Both groups completed a pre-test designed to assess their baseline understanding of genetics concepts. Following the pre-test, the experimental group received instruction using the interactive DT, which incorporated multimedia elements, interactive simulations, and embedded assessments. Meanwhile, the control group received conventional instruction using standard print-based biology textbooks per student. Upon completion of the instructional period, a post-test was administered to both groups to measure academic achievement. In addition to the post-test, a learning satisfaction survey was distributed to all participants. This survey aimed to assess students' perceptions of their learning experiences, specifically comparing the digital and traditional textbook formats. Instruction and facilitation for both groups were delivered by the same qualified biology teacher to ensure consistency in content coverage and instructional quality. In addition, an unstructured interview, as outlined by Braun and Clarke (2006), was conducted with the biology teacher who facilitated the instruction. The purpose was to gather insights into instructional experiences, including perceptions of student engagement, motivation, and challenges associated with the use of the digital twin (DT), in order to triangulate the results.

### Designing and Intervention of the Interactive Digital Textbook

The interactive digital textbook (DT) developed for this study was created using the Genially platform, a web-based tool designed to facilitate the development of engaging, interactive content, even for users with limited technical expertise (Genially, 2025, https://genially.com/features/). Genially was selected due to its robust features, compatibility with a variety of digital devices—including laptops, tablets, and smartphones—and its intuitive, user-friendly interface. These characteristics make it particularly suitable for use in diverse educational contexts, including settings with limited digital infrastructure. Key features that informed the platform's selection included interactive assessment tools, automated feedback and results summaries, web-based accessibility, multimedia integration, and versatile content-sharing capabilities.

To enrich the DT's content and functionality, the researcher integrated additional resources from platforms such as Google, YouTube, and Padlet. The final product consisted of multimodal components including explanatory text, embedded videos, animations, external links, interactive simulations, Padlets for collaborative activities, as well as interactive assessments and learning tasks (Brnic et al., 2024; Kempe & Grönlund, 2019). In addition, the final product maintained a familiar structure and layout, mirroring TPTs to ease the transition while introducing digital content as emphasized by Fan et al. (2015). The textbook content was fully aligned with the national biology curriculum, ensuring curricular relevance and coherence. The design emphasized interactivity, accessibility, and learner engagement to support meaningful and autonomous learning experiences.

The development process followed an instructional design framework based on the ADDIE model (Molenda, 2015), which includes five iterative phases: Analysis, Design, Development, Implementation, and Evaluation [Table 1]. This model has been widely adopted for the systematic development of educational resources and was selected for its adaptability and effectiveness in digital learning environments. The process also drew from DT development principles established by Chung et al. (2018) and Fan et al. (2015), who emphasize the importance of integrating both pedagogical and usability factors in DT design.

**Table 1.** ADDIE instructional model adapted in the development of an interactive digital textbook

| ADDIE Phase | Description | Application in DT Design |
|---|---|---|
| Analysis | Define learning needs, instructional goals, and learner characteristics | Identified difficulties in genetics education, assessed learner digital readiness, and reviewed curriculum requirements |
| Design | Plan instructional content, structure, media, and assessments | Outlined textbook structure, designed multimedia content, storyboarded interactivity, and selected appropriate tools |
| Development | Produce and assemble learning materials | Created and integrated text, video clips, narration, animations, simulations, padlets, quizzes, and links using Genially, YouTube, and Google tools |
| Implementation | Deliver and administer instructional materials | Piloted the DT with students in a real classroom setting, facilitated learning sessions, collected usability feedback |
| Evaluation | Formative and summative evaluation to improve and validate | Piloted the DT with students in a real classroom setting, facilitated learning sessions, collected usability feedback |

Note. ADDIE = Analysis, Design, Development, Implementation, and Evaluation.

In summary, the design of the interactive DT was guided by evidence-based instructional design practices, technological accessibility, and a learner-centered philosophy. By leveraging the Genially platform and integrating multimodal features aligned with pedagogical goals, the DT aimed to offer a scalable, engaging, and effective digital learning resource for genetics education.

## Validation and Reliability of DT and Instruments

To ensure validity, all research instruments—the Academic Achievement Test (AAT), Student Learning Satisfaction (SLS) survey, and the interactive DT—were subjected to expert validation. The AAT, developed in alignment with Bloom's taxonomy and covering genetics content from the national biology syllabus, was reviewed by 10 subject and assessment experts. The SLS survey, adapted from previously validated instruments, was evaluated by 20 experts specializing in biology education and educational technology. In addition, the DT itself was validated by 15 experts for content accuracy, interactivity, language clarity, accessibility, and usability. Content Validity Index (CVI) values were calculated, confirming satisfactory levels across all instruments, as shown below in Table 2.

**Table 2.** Content validity index (CVI) summary of instruments

| Instrument | I-CVI | S-CVI/Ave | S-CVI/UA Ave | S-CVI/Ave/PR | Interpretation |
|---|---|---|---|---|---|
| AAT | 0.80 | 0.96 | 0.08 | 0.96 | Valid |
| SLS Survey | 0.94 | 0.98 | 0.08 | 0.98 | Valid |
| DT | 0.80 | 0.96 | 0.08 | 0.96 | Valid |

Note. I-CVI = Item-level content validity index; S-CVI = Scale-level CVI; UA = Universal agreement; PR = Proportion relevance.

Instrument reliability was assessed using internal consistency reliability via Cronbach's alpha, which evaluates how well a set of items measures a single construct (Lodico et al., 2010; Taber, 2018). A Cronbach's alpha value of 0.70 or higher is generally acceptable, with values above 0.80 considered good and those above 0.90 excellent (Taber, 2018). The reliability of the Academic Achievement Test (AAT) was evaluated using post-test scores from a pilot group of 30 students. The resulting Cronbach's alpha was 0.774, indicating acceptable internal consistency (Table 3). Similarly, the Student Learning Satisfaction (SLS) survey yielded a Cronbach's alpha of 0.87 based on responses from 15 expert validators, suggesting high reliability (Table 3). Both instruments were therefore deemed suitable for use in the main study.

**Table 3.** Cronbach's alpha reliability coefficients

| Instrument | Cronbach's Alpha | Number of Items | Interpretation |
|---|---|---|---|
| AAT | 0.774 | 10 | Acceptable |
| SLS Survey | 0.87 | 10 | High reliable |

## Intervention Procedure

The learning intervention followed a true experimental pre-test–post-test control group design. Both the experimental and control groups (n = 15 each) first completed a pre-test to establish their baseline understanding of genetics. The experimental group received instruction via an interactive DT, with each student assigned one computer. On the other hand, the control group was taught using TPT per student. At the conclusion of the instructional period, both groups completed a post-test to measure academic achievement. Subsequently, a learning satisfaction survey was administered to assess students' perceptions of the instructional approach.

To maintain instructional consistency and internal validity, one qualified biology teacher—experienced in integrating ICT but new to DT—was responsible for teaching both groups. The teacher underwent a three-day orientation on DT use, provided via video and phone calls. Instruction occurred over two sessions, one per group, with group identities concealed from each other to minimize bias. The DT included interactive simulations (e.g., base pairing and DNA construction), multimedia explanations, and collaborative Padlet activities designed to enhance engagement and understanding (Ahmed & Kwon, 2022; Rahim et al., 2020; Fan et al., 2015). Finally, an unstructured interview was conducted with the teacher to gather insights on the instructional experience.

### Analysis of Learning Effect

To evaluate the intervention's effectiveness, quantitative data from the Academic Achievement Test (AAT) and Student Learning Satisfaction (SLS) survey were analyzed using SPSS (version 26). Descriptive statistics included means, standard deviations, and standard errors. For inferential analysis, a one-way ANCOVA was applied to post-test scores, controlling for pre-test scores as a covariate, while an independent samples t-test was conducted to compare the mean learning satisfaction scores (Randolph & Myers, 2013), between the experimental and control groups. All statistical analyses were conducted following confirmation that the data met the necessary assumptions for ANCOVA (Normality, independence of covariates, linearity, homogeneity of regression slopes, and equality of variances for both ANCOVA assumption and t-test procedures were tested and met, ensuring validity and minimizing potential bias. Moreover, the interview responses, were analyzed thematically, as outlined by Braun and Clarke (2006), including identification of patterns in instructional experiences, such as student engagement, motivation, and challenges associated with the DT.

To complement the overall group-level analysis, an item-level analysis was conducted to examine the specific contributions of individual features of the interactive DT in academic achievement (Lee et al., 2023). In this context, the interactive DT features were grouped into simulations, collaborative activities, and immediate feedback and mapped to the assessment items. At the item level, student responses were scored dichotomously (1 = correct, 0 = incorrect). For each item, the number of correct responses within each group (experimental, control) was divided by the total number of students in the group, and the result was expressed as a percentage. The gains were calculated by subtracting the pre-test percentage correct from the post-test percentage correct.

## Results

### Development of the Interactive Digital Textbook

The interactive digital textbook (DT) developed in this study was designed with a focus on usability, interactivity, accessibility, and instructional alignment, all of which are essential to foster student engagement, comprehension, knowledge retention, and diverse learning styles (Bikowski & Casal, 2018; Sulaiman & Mustafa, 2020). These pedagogical qualities were enhanced through the integration of Genially's interactive features and various embedded instructional tools. The DT is divided into four major content blocks (Block A to D), each incorporating specific interactive and multimedia elements:

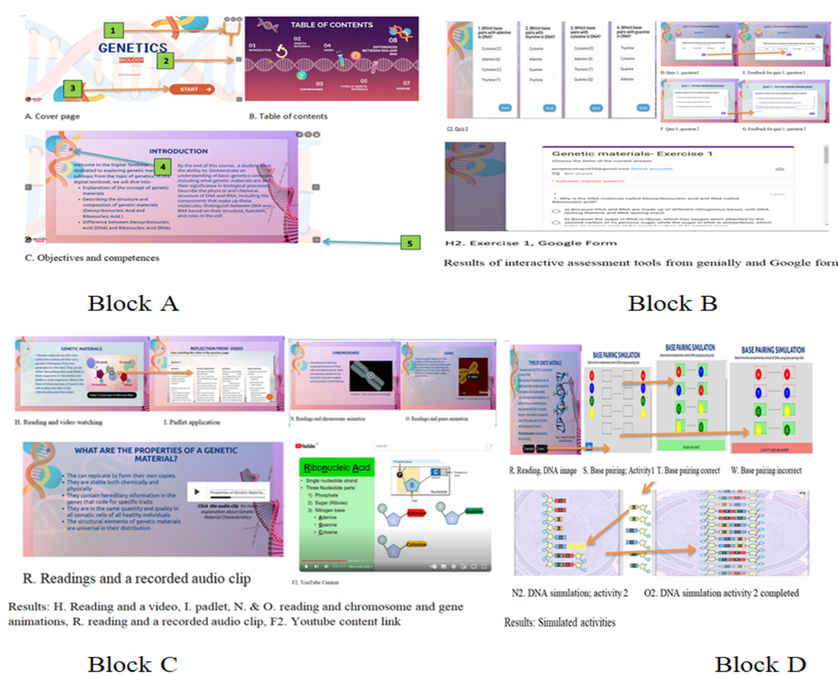
- Block A includes the cover page, which displays the topic title and a "START" button (indicated by arrow 3), serving as the entry point to the learning module. This block also contains the hyperlinked table of contents (arrow 1), allowing students to jump directly to specific sections by clicking on the corresponding page numbers. The final page in Block A outlines the lesson objectives and competencies to guide student learning.

• Block B features interactive assessments developed with Genially and Google Forms. Learners could respond to the questions and receive immediate feedback, enabling self-evaluation and differentiated instruction (Fan et al., 2015). Visual indicators (arrows 2 and 5) and the Genially hamburger button (arrow 4) support seamless navigation.

• Block C provides the instructional content related to genetic materials, including texts, padlet boards, and a variety of multimedia such *as images, animations, video clips, audio narration,* and an external YouTube link for extended learning. These elements were included to address diverse learning preferences and to elaborate on complex topics like the structure and composition of DNA and RNA (Ahmed & Kwon, 2022; Riyanto et al., 2020).

• Block D incorporates simulated activities, such as DNA molecule modeling, base pairing, and double helix construction. These simulations offered students hands-on digital experiences, promoting conceptual understanding through interaction and visualization (Alharbi et al., 2024; Talan, 2020). An image of the DNA molecule and related simulations are also presented in this block to reinforce structural comprehension.

Across the DT, navigation tools and interactive elements were strategically placed to ensure a learner-centered environment. The combination of embedded formative assessments, immediate feedback, and rich multimedia created an immersive and engaging digital experience that aligned with the goals of 21st-century science education. The following figures are the Block A to D showing illustrated features that made up the interactive DT in this study [Figure 1].




Note. A = Cover page, table of contents, objectives, and competencies. B = Interactive assessment tools from Genially and Google Forms. C = Text, video, Padlet, a recorded audio clip, link to YouTube. D = Image, simulated activities.

**Fig. 1.** Representative final product of the interactive digital textbook, their embedded features, showcasing the layout and pedagogical design of the DT

## Learning Effect of the Interactive Digital Textbook

As shown in Table 4, prior to conducting the ANCOVA, assumptions were evaluated in accordance with recommended procedures (Randolph & Myers, 2013). Starting with Skewness and kurtosis values for both pre-test and post-test scores (Skewness: Post-test = -0.26, Pre-test = 0.36) and (Kurtosis: Post – test = -0.34, Pre-test = -0.21) fell within the acceptable range of −1 to +1, indicating approximate normality. Independence of covariates was confirmed, as the independent variable (group) did not significantly affect pre-test scores, $F(1, 28) = 0.013$, $p = 0.909$, $\eta^2 = 0.000$. This negligible effect indicates that pre-test scores were evenly distributed across groups and did not confound the post-test comparisons. Pearson's correlation revealed a significant positive relationship between pre-test and post-test scores, $r(28) = 0.410$, $p = 0.024$ (two-tailed). This moderate correlation supports the inclusion of pre-test scores as a covariate in the ANCOVA model. The assumption of homogeneity of regression slopes was met, as the interaction between group and pre-test scores was not significant, $F(1, 26) = 0.007$, $p = 0.936$. This indicates that the relationship between the covariate (pre-test) and the dependent variable (post-test) was consistent across both groups. Finally, Levene's test confirmed homogeneity of variances in post-test scores, $F(1, 28) = 0.892$, $p = 0.353$, suggesting that the assumption of equal error variances was satisfied. Collectively, these checks confirm that the ANCOVA assumptions were adequately met, validating the use of this approach for comparing post-test outcomes while controlling for baseline performance.

**Table 4.** ANCOVA assumptions for academic achievement results

| Assumption | Test/Statistic | Result | Interpretation |
|---|---|---|---|
| Normality | Skewness & Kurtosis | Skewness: Post-test = -0.26, Pre-test = 0.36 and Kurtosis: Post – test = -0.34, Pre-test = -0.21 | Data approximately normal |
| Covariates Independence | Pre-test effect | $F(1, 28) = 0.013$, $p = 0.909$, $\eta^2 = 0 .000$ | Pre-test evenly distributed across groups |
| Linearity | r | $r(28) = 0 .41$, $p = 0.024$ | Moderate positive association |
| Regression slopes homogeneity | Group × Pre-test | $F(1, 26) = 0.007$, $p = 0.936$ | Regression slopes equivalent across groups |
| Variances homogeneity | Levene's test | $F(1, 28) = 0.892$, $p = 0.353$ | Equal variances across groups |

Note. Normality evaluated using skewness and kurtosis (−1 to +1 = acceptable). DV = dependent variable. r = Pearson correlation

To evaluate the effect of the interactive digital textbook (DT) on academic achievement, descriptive statistics, inferential, and item -level analysis results are presented systematically.

Table 5 shows the pre-test and post-test performance of both groups. At pre-test, the experimental group ($M = 4.80$, $SD = 1.97$) and the control group ($M = 4.87$, $SD = 1.06$) performed almost identically, confirming group equivalence at baseline. At post-test, the experimental group ($M = 7.47$, $SD = 2.33$) outperformed the control group ($M = 6.07$, $SD = 1.49$), suggesting that the DT contributed to meaningful learning gains. Notably, the higher variability in the experimental group ($SD = 2.33$ vs. 1.49; Range = 8 vs. 4) suggests that while most students benefited from the DT, the magnitude of improvement varied across individuals. When adjusting for baseline differences through ANCOVA, the estimated marginal means supported this trend: the experimental group achieved an adjusted post-test score of $M = 7.49$ ($SE = 0.46$, 95% CI [6.54, 8.43]), compared to $M = 6.05$ ($SE = 0.46$, 95% CI [5.11, 6.99]) for the control group. This adjusted comparison confirms that the performance gap remained statistically significant even after accounting for pre-test scores.

**Table 5.** Descriptive (mean, SD, range, EMM)

| Test | Group | N | Mean | SD | Min | Max | EMM |
|---|---|---|---|---|---|---|---|
| Pre - Test | Experimental | 15 | 4.80 | 1.97 | 2 | 8 | |
| | Control | 15 | 4.87 | 1.06 | 3 | 7 | |
| Post-Test | Experimental | 15 | 7.47 | 2.33 | 2 | 10 | [a]7.49 |
| | Control | 15 | 6.07 | 1.49 | 4 | 8 | [a]6.05 |

Note.[a] Covariate evaluated at pre-test = 4.83. N = Total number of observations, SD= Standard Deviation, Min = Minimum, Max = Maximum, EMM = Estimated Marginal Mean.

As shown in Table 6, a one-way ANCOVA was conducted on post-test scores, with pre-test performance as a covariate. The overall model was statistically significant, F (2, 27) = 5.66, p = 0 .009, partial $\eta^2 = 0.296$, explaining approximately 30% of the variance in post-test scores (adjusted $R^2 = 0.243$). The pre-test covariate was significant, F (1, 27) = 6.69, p = 0.015, partial $\eta^2 = 0.20$, indicating that baseline knowledge accounted for nearly 20% of the variance in post-test performance. Importantly, the group effect was also significant, F (1, 27) = 4.89, p = 0.036, partial $\eta^2 =$ 0.15, corresponding to a medium effect (Cohen's d ≈ 0.85). This demonstrates that, after controlling for pre-test scores, students using the DT achieved significantly higher post-test results than those taught with traditional print textbooks

**Table 6.** ANCOVA results for post-test academic achievement, controlling for pre-test scores

| Source | DF | F | *p* value | $\eta^2$ |
|---|---|---|---|---|
| Corrected model | 2 | 5.66 | 0.009 | 0.30 |
| Pre-test | 1 | 6.69 | 0.015 | 0.20 |
| Group (DT vs TPT) | 1 | 4.89 | 0.036 | 0.15 |

Note. $R^2 = 0.296$ (Adj. $R^2 = 0$ .243). DF = Degree of freedom, p = Significance, F = F-statistics, $\eta^2$ = Partial eta squared, R2 (R-squared) = Coefficient of correlation.

Pairwise comparisons with Sidak adjustment confirmed a mean difference of 1.44 points between groups (95% CI [0.10, 2.77], p = 0.036), favoring the experimental group (Table 7).

**Table 7.** Estimated pairwise comparisons of post-test scores

| Comparison | MD (I-J) | SE | *p* value | 95% CI |
|---|---|---|---|---|
| Control vs. Experimental | −1.44* | 0.65 | 0.036 | −2.77, −0.10 |
| Experimental vs. Control | 1.44* | 0.65 | 0.036 | 0.10, 2.77 |

Note. $p < .05$. MD = Mean Difference, SE = Standard error; CI = Confidence interval. Sidak adjustment applied.

In summary, students who learned with the interactive DT demonstrated significantly higher academic achievement than those who used TPTs. The adjusted effect size (partial $\eta^2 = .15$; d ≈ 0.85) indicates a practically meaningful improvement. Together, these findings suggest that the DT not only supported content delivery but also enhanced conceptual understanding in genetics, particularly benefiting students through interactive simulations and collaborative tasks, as highlighted in the subsequent item-level analysis.

## Item-Level Analysis of Academic Achievement

To complement the overall group-level results, an item-level analysis was conducted to determine the contribution of the DT features grouped into simulations, collaborative activities, and immediate feedback to students' learning outcomes (Lee et al., 2023) as shown in Table 8. Th descriptive gains in percentage DT linkage feature mapped to item were compared across groups as shown in Table 8. Simulation-linked items (Q1, Q8, Q10) yielded substantial gains in the experimental group (+33%, +53%, and +60%, respectively), whereas the control group showed more modest or negative changes (−13%, +40%, and +40%). Collaborative activity items (Q2, Q3, Q5) also produced moderate-to-large improvements in the experimental group (+20% to +27%), while the control group exhibited minimal or no gains. In contrast, items associated with immediate feedback (Q4, Q6, Q7, Q9) produced mixed results. The experimental group showed variable gains ranging from +6% to +53%, but in some cases, the control group outperformed the experimental group (e.g., Q4: +20% vs. +7%).

On average, simulation items improved by +49% in the experimental group compared to +22% in the control group. Collaborative items showed an average improvement of +18% in the experimental group, while the control group improved by only +2%. Immediate feedback items yielded smaller and more inconsistent gains across both groups, suggesting less reliable effects. These finding reveal that the DT had the strongest impact on items linked to interactive simulations and collaborative learning, which significantly enhanced conceptual understanding and peer engagement in the experimental group compared to the control group. Simulations offered dynamic visualizations of abstract scientific concepts, likely promoting deeper cognitive processing and retention. (Alharbi et al., 2024; Talan, 2020) Similarly, collaborative tasks fostered peer interaction and discussion, reinforcing learning through the social construction of knowledge (Riyanto et al., 2020; Rahim et al., 2020). In contrast, tasks involving immediate feedback showed inconsistent effects, with some items favoring the control group. This indicates that although feedback is a valuable instructional tool, its effectiveness depends on thoughtful design and alignment with specific learning objectives to ensure meaningful support for student outcomes (Sommers et al, 2019). Superior performance on simulation and collaboration items underscores the value of interactive and social learning opportunities in digital environments (Riyanto et al., 2020). By contrast, the weaker performance on feedback-only items may reflect a need for more personalized or elaborated feedback mechanisms.

**Table 8.** Item-level analysis of academic achievement by digital textbook features

| Item No. | Linked DT Feature | Exp. Pre- test (%) | Exp. Post -test (%) | Exp. Gain (+) | Ctrl. Pre-test (%) | Ctrl. Post-test (%) | Ctrl. Gain (+) |
|---|---|---|---|---|---|---|---|
| Q1 | Simulation | 60 | 93 | 33 | 60 | [a]47 | 27 |
| Q2 | Collaborative | 60 | 80 | 20 | 60 | 60 | 00 |
| Q3 | Collaborative | 60 | 87 | 27 | 87 | 87 | 00 |
| Q4 | Immediate Feedback | 67 | 60 | 07 | 53 | 73 | 20 |
| Q5 | Collaborative | 47 | 53 | 06 | 47 | 53 | 06 |
| Q6 | Immediate Feedback | 67 | 73 | 06 | 60 | [a]53 | 07 |
| Q7 | Immediate Feedback | 60 | 73 | 13 | 73 | [a]67 | 06 |
| Q8 | Simulation | 27 | 80 | 53 | 13 | 53 | 40 |
| Q9 | Immediate Feedback | 20 | 73 | 53 | 27 | 60 | 33 |
| Q10 | Simulation | 13 | 73 | 60 | 13 | 53 | 40 |

Note. [a] = Negative change. Exp. = Experimental, Ctrl. = Control

### Effect of instructional method on Learning Satisfaction

To evaluate the impact of instructional method on students' learning satisfaction, an independent samples t-test was conducted comparing the experimental group (interactive DT) and the control group (TPT). As shown in Table 9, students in the experimental group reported significantly higher satisfaction (M = 4.42, SD = 0.59) than those in the control group (M = 2.77, SD = 0.69). Prior to the t-test, Levene's test for equality of variances was performed and yielded a non-significant result, F (1, 28) = 0.17, p = .682, suggesting that the assumption of homogeneity of variance was met. The t-test revealed a statistically significant difference in learning satisfaction between groups, t (28) = 7.05, p < .001, with a mean difference of 1.64 and very large effect size (Cohen's d ≈ 2.67), suggesting a substantial impact of the instructional method.

**Table 9.** Estimated student learning satisfaction scores by group

| Group | N | M | MD | SD | t | *p* value |
|---|---|---|---|---|---|---|
| Experimental | 15 | 4.42 | 1.64 | 0.59 | 7.05 | 0.000 |
| Control | 15 | 2.77 | | 0.69 | | |

Note. N=Population, M=Mean, SD= Standard deviation, MD = Mean difference, t = t-statistic, *p* value = significance

### Instructor Opinions on Digital Textbook Use

The instructor's reflections highlighted both challenges and strengths in the experimental class. A major challenge concerned technological barriers, particularly unstable network connections that delayed content loading and caused frustration for both students and the teacher. Despite these obstacles, students remained highly engaged with the digital textbook (DT). The instructor emphasized that specific DT features, most notably videos, simulations, and Padlet-based collaborative tasks strongly motivated students to participate actively and sustain their interest throughout the lessons. This feedback illustrates a tension between technological limitations and pedagogical potential: while infrastructure issues hindered seamless integration of multimedia elements, the overall experience suggests that, with adequate support, digital textbooks can foster meaningful engagement and resilience in learning.

## Discussions

### Development of the Interactive Digital Textbook

The findings of this study support the growing body of literature suggesting that interactive digital textbooks (DTs), particularly those enhanced with multimedia and simulation features, can significantly improve student learning outcomes and engagement in science education. The DT developed in this study was pedagogically grounded in interactivity, usability, accessibility, and alignment with curricular standards. Using Genially's platform, students were able to explore complex genetics concepts through animations, collaborative padlet boards, immediate assessments, and simulations—features that directly align with constructivist approaches to digital learning (Bikowski & Casal, 2018; Sulaiman & Mustafa, 2020).

The structural design of the DT—organized into four interactive content blocks—demonstrated how modular digital environments can scaffold learning. Blocks A through D presented navigable content areas that included lesson objectives, interactive assessments, multimedia resources, and digital simulations. These elements not only supported diverse learning styles but also encouraged active participation and iterative self-assessment. The integration of Padlet and Google Forms facilitated collaborative and reflective learning, while features such as embedded feedback and linked multimedia enhanced personalization and accessibility (Ahmed & Kwon, 2022; Maraza-Quispe et al., 2024; Riyanto et al., 2020).

## Learning Effect of the Interactive Digital Textbook

The findings of this study provide strong evidence for the effectiveness of an interactive DT in supporting student learning in genetics. At baseline, the experimental and control groups performed nearly identically at pre-test, confirming equivalence in prior knowledge before the intervention. This strengthens confidence that subsequent post-test differences can be attributed to the DT rather than pre-existing disparities between groups. By the end of the intervention, students in the experimental group demonstrated significantly higher achievement than their peers in the control group. The raw post-test means revealed a 1.40-point advantage for the DT group, and the ANCOVA-adjusted estimated marginal means confirmed this effect even after statistically controlling for pre-test performance. Pairwise comparisons further supported the robustness of this difference (MD = 1.44, SE = 0.65, $p = 0\ .036$, 95% CI [0.10, 2.77]). Importantly, this effect was not trivial: the group effect corresponded to a medium-to-large effect size ($\eta^2 = .153$, $d \approx 0.85$), while the model as a whole explained nearly 30% of the variance in achievement ($R^2 = 0.296$), with the pre-test score emerging as a significant covariate ($\eta^2 = .198$). These findings are in line with prior studies showing that multimedia-rich and interactive learning environments can enhance student understanding and engagement in science education (Aslam & Saeed, 2022; Kempe & Grönlund, 2019; Talan, 2020). Importantly, these findings underscore the importance of integrating interactive DTs into biology instruction, particularly, in content areas like genetics, which are often abstract and conceptually challenging for students

Instructor opinions offer qualitative insights into the implementation of DTs in real classroom settings, showing limitations not captured by test scores including network instability and occasional device compatibility issues. On the other hand, the instructor emphasized high levels of student motivation and engagement boosted by simulations and collaborative features (padlets) which showed biggest gains in student learning as demonstrated by item – level analysis. In other words, students were particularly drawn to simulations and collaborative features, which allowed them to explore content dynamically (Kempe & Grönlund2019). These reflections echo the broader discourse on digital-based science education, where infrastructure and digital readiness remain critical concerns (Alharbi et al., 2024), but student receptivity to interactive learning tools remains strong.

Taken together, these results suggest that interactive DTs can make a meaningful contribution to learning in conceptually challenging areas of biology such as genetics. The significant performance advantage, coupled with evidence of increased engagement, supports the pedagogical value of integrating digital resources into secondary science instruction.

## Effect of instructional method on Learning Satisfaction

Students who engaged with the DT reported higher satisfaction scores ($M = 4.42$, $SD = 0.59$) compared to those taught with traditional print textbooks ($M = 2.77$, $SD = 0.69$). The large effect size, confirmed by an independent samples t-test ($t(28) = 7.05$, $p < .001$), highlights the value of interactive features in enhancing learners' emotional and cognitive engagement. These results align with existing studies that link multimedia use and student satisfaction in digital environments (Ahmed & Kwon, 2022; Fan et al., 2015). However, it is also possible that satisfaction was influenced by contextual factors, such as one-computer-per-student access, which may have created novelty effects or advantages beyond the textbook design itself.

## Variability in Student Outcomes

The greater variability observed in the experimental group ($SD = 2.33$ vs. $1.49$; Range = 8 vs. 4) suggests that while most learners benefited from the digital textbook (DT), the degree of improvement varied widely. Item-level analysis indicated strong gains from simulations and collaborative activities, highlighting the effectiveness of interactive and social elements (Barnett-Itzhaki et al., 2023). In contrast, items linked to immediate feedback produced mixed results, with some showing less improvement than in the control group. This suggests that DT feedback mechanisms may not consistently yield measurable academic outcomes, particularly when misaligned with assessments or unevenly utilized (Roberts et al., 2021; Sommers et al., 2019).

Instructor observations provided further context. Unstable networks and technical issues limited some students' engagement, while others remained motivated by multimedia features. One instructor noted that unreliable internet disrupted lesson flow and frustrated both students and teachers. Nonetheless, many learners stayed engaged, particularly when using videos, simulations, and collaborative boards. These technical barriers likely contributed to the wider spread of scores by limiting real-time participation.

Overall, findings show that DTs can enhance achievement (Kempe & Grönlund, 2019) but may also widen disparities depending on prior knowledge, digital readiness, and technology access (Rajabalee & Santally, 2021; Sulaiman & Mustafa, 2020; Roberts et al., 2021). Addressing such issues through adaptive supports, reliable infrastructure, and teacher scaffolding will be critical for achieving more consistent benefits.

This study demonstrates that well-designed DTs, particularly those integrating simulations, collaboration, and feedback, can promote deeper understanding and higher satisfaction in biology education. The findings emphasize the importance of investing in infrastructure, teacher training, and high-quality digital resources tailored to complex scientific content.

## Limitations and Future Research

Several limitations temper these findings. First, although the DT improved post-test scores overall, the greater variability in the experimental group complicates interpretation of the mean effect. Second, unequal resource access may have biased results: experimental group students used individual computers, while control group students relied on print textbooks. Third, technological barriers, such as unstable networks and device delays, disrupted implementation and likely disadvantaged some learners. Fourth, the short intervention period limits conclusions about long-term retention. Finally, the small, localized sample reduces generalizability.

Future studies should address these limitations by using larger, more diverse populations and ensuring resource equity across groups. Refining feedback mechanisms to align with assessment formats, extending intervention periods, and adding delayed post-tests could yield more reliable evidence of long-term effects. Examining subgroup differences (e.g., digital literacy, prior knowledge) would also clarify which learners benefit most from DT-based instruction.

In addition, future research could explore emerging tools such as digital twins and virtual reality, which may complement DTs by providing immersive, inquiry-based experiences. To maximize effectiveness, digital learning tools should be developed through iterative, participatory design processes involving both educators and learners. Such co-design ensures that resources are not only technically robust but also pedagogically meaningful and culturally responsive.

## Conclusions and Implications

This study developed and evaluated an interactive digital textbook (DT) grounded in the ADDIE instructional design model, integrating multimedia, interactivity, and collaborative elements to support the teaching of complex genetics concepts. The findings confirm that the DT significantly improved students' academic achievement and learning satisfaction compared to traditional print-based instruction. These results highlight the pedagogical value of DTs in fostering active engagement, improving conceptual understanding, and addressing the limitations of conventional, lecture-driven science education—particularly in subjects requiring visualization, such as genetics.

The educational implications are broad. First, educators should be encouraged and supported to integrate interactive DTs and digital twin-based environments into science instruction. Professional development should focus on enhancing teacher competencies in instructional design, digital content creation, and platform use (for example, Genially, Padlet). Second, curriculum developers and instructional designers should collaborate to ensure the pedagogical alignment and contextual relevance of digital resources. Learning tools must not only deliver content but also offer meaningful interactivity, adaptive feedback, and multimodal access to support diverse learners.

From a policy perspective, stakeholders should prioritize the development of robust digital infrastructure—including high-speed internet, reliable devices, and technical support—to ensure equitable access to technology-enhanced learning. Additionally, addressing the digital divide between students and educators requires systemic strategies that build capacity across all levels of education.

In a rapidly evolving educational landscape driven by metaverse applications, artificial intelligence, and immersive media, digital twin and DT technologies represent a new frontier for 21st-century science learning. Their ability to converge indoor and outdoor learning spaces, support data-driven inquiry, and provide dynamic visualizations positions them as powerful tools for both curricular innovation and equity in science education.

Finally, this study contributes to the growing body of research advocating for digitally-mediated science education and reinforces the need to equip learners with the skills, motivation, and tools to thrive in a digitally connected, knowledge-driven world.

## Conflicts of Interest

The authors declared no conflicts of interes

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