

RESEARCH ARTICLE

Development of a Digital Textbook on Plant Transpiration Using Pages for High School Students

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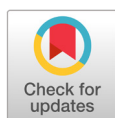
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ABSTRACT

This study develops and evaluates a digital textbook on plant transpiration for high school biology students in Timor-Leste. Using Apple's Pages application, the textbook integrates multimedia elements such as videos, interactive images, and quizzes. The experimental design involved 60 grade XI science students, divided into an experimental group using the digital textbook and a control group using a traditional printed textbook. Learning outcomes were assessed through pre- and post-tests, along with a student satisfaction survey and teacher feedback. Results indicate a statistically significant improvement in academic achievement for students using the digital textbook, with a mean post-test score of 7.30 compared to 6.10 in the control group ($p < 0.05$). Student satisfaction was high, with a mean rating of 4.8 for multimedia content. Teacher feedback highlighted the textbook's interactive features as beneficial for student engagement and comprehension. These findings suggest that digital textbooks effectively enhance learning outcomes and motivation in an educational context for high school biology.

Keywords: Digital textbook, biology education, high school, plant transpiration, Pages



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Introduction

The development of technology and information today, especially digital devices, has influenced children's lives. The current generation of children is considered "digital natives" (Helsper & Eynon, 2009; Prensky, 2012) because they have been familiar with electronic and digital media since birth. Therefore, it is not surprising that children today are categorized as a "digital generation" (Seland & Hyggen, 2021), and their generation has become the leading group of learners in educational practice. This digital generation's preference for fast content delivery and interactive, hands-on learning has led to the increased use of computer technology in content

delivery.

The increasing use of technology in human life has transformed educational materials from traditional paper-based formats to digital books. This digital transition in education has brought opportunities to improve the learning experience and outcomes for students (Balyer & Öz, 2018; Joseph et al., 2024). Studies have shown that digital textbooks (DT) can enhance the learning process through increased interactivity, accessibility, and customization of content (Kim & Yu, 2019; Lee et al., 2022). For example, DT can incorporate multimedia elements, interactive features, and real-time updates, which make the learning process more engaging and effective for students (Vasilenko & Vasilenko, 2021). Furthermore, the mobility and accessibility of digital textbooks accessible on a variety of digital devices offer the advantage of learning anytime and anywhere, significantly expanding the reach and convenience of educational resources (Boone & Higgins, 2003; Kim & Yu, 2019). In contrast, printed textbooks, which contain only text and images, can quickly become outdated as their information may become obsolete before they are printed and distributed (Chavali & Gundala, 2022). Conversely, digital textbooks allow for continuous updates, ensuring that students always have access to the most current information (Holley, 2006; Kim & Jung, 2010; Kim & Yu, 2019).

Digital textbooks play a crucial role in modern education by enhancing learning experiences and outcomes through the integration of technology. They have also been shown to improve digital competencies among future educators. For instance, the introduction of digital textbooks in high school biology education has shown promising results in enhancing student engagement and learning outcomes. Research by Sataroh and Febrianti (2024) demonstrated that digital biology books, specifically on the antioxidant activity of red dragon fruit extract, received high evaluations from both experts and students, indicating their suitability as learning resources. Similarly, Ifrim (2024) confirmed that digital textbooks used in ICT classrooms contributed to higher student engagement and improved academic performance, highlighting the potential of digital resources to supplement the educational experience. Another study by Firmansyah and Munawwaroh (2023) on flipbook-based learning media for the circulatory system also received high validation scores and positive student feedback. This indicates that interactive digital formats, like flipbooks, can simplify complex subjects, making them more accessible to students. Collectively, these studies indicate that the biology learning process for high school students can be enhanced through the interactive and multimedia features of digital textbooks that make learning more interesting and effective.

Moreover, digital textbooks have been shown to positively impact student satisfaction and engagement in various educational contexts. Studies reveal that high school students' satisfaction and engagement are affected by the use of digital textbooks. Digital learning platforms—such as digital textbooks—also show potential in improving student motivation and engagement by offering opportunities for individual and interactive learning. For example, a study by Huang (2024) showed a strong statistically significant positive association between digital platform usage and motivation, indicating that digital platforms effectively increase student motivation in high schools. Similarly, Robja (2024) found that digital textbooks in foreign language teaching improved student performance and engagement by fostering personalized and autonomous learning. Ifrim's experimental study supports these findings, showing increased student interest and motivation, which led to better school performance (2024). However, challenges remain, particularly in rural areas, where students report reduced engagement and increased stress due to technical difficulties and limited interaction

with teachers and peers (Ramamoorthy et al., 2024). Despite these challenges, Saranya and Manivannan (2024) found a strong connection between student satisfaction with online learning and academic achievement, suggesting that higher satisfaction with digital learning leads to improved academic performance. Digital textbooks can improve the quality of high school learning and student engagement, but technical and interactional challenges must be addressed to maximize their effectiveness.

In the case of Timor-Leste, a developing country in Southeast Asia, the integration of digital technologies in education faces various challenges. These include limited digital infrastructure, a lack of teacher training in technology integration, and a scarcity of digital learning materials tailored to the local context (Honda et al., 2024; SEAMEO, 2023). In addition, most teachers in Timor-Leste are used to traditional rote teaching methods, and science education primarily relies on theoretical instruction without experimental approaches (Almeida et al., 2014). As a result, students often struggle to understand abstract concepts. To address these issues, Timor-Leste has made policy efforts to integrate ICT into education, as outlined in the Education Sector Plan for 2020–2024, which focuses on teacher training, expanding digital learning opportunities, and improving infrastructure in secondary schools, especially in rural areas (World Bank, n.d.).

In recent years, the Government of Timor-Leste has invested in internet infrastructure and educational technologies, including computing devices and educational software, to improve access to education for students and teachers (SEAMEO, 2023). The National Teacher Training Institute (INFORDEPE) has also collaborated with national and international partners to develop technology-based learning media training programs that equip national trainers with digital literacy skills. These initiatives align with the goals of the XI Constitutional Government (2023–2028), which emphasizes the use of ICT to support educational reforms and ensure quality learning by modernizing practices and providing access to digital resources (GoTL, 2024).

The Ministry of Education, Youth, and Sport has worked with stakeholders like UNICEF to support digital education initiatives such as the ‘Eskola Ba Uma’ or ‘School Goes Home’ program. This initiative includes TV programs, radio broadcasts, e-books, and the Learning Passport platform, which provides students and teachers in Timor-Leste with access to digital learning content across various subjects, including science (UNICEF, 2020). However, the e-books available on this platform lack interactive features, animations, and experimental components—especially in science content.

To address this gap, creating a digital textbook on plant transpiration using the Pages application could significantly enhance digital learning resources in Timor-Leste. Transpiration involves the loss of water vapor from stomata and is influenced by environmental and physiological factors like light, humidity, and temperature (Taiz et al., 2015). Students often hold misconceptions about transpiration, such as the belief that leaves absorb water or that plants retain all absorbed water, even after traditional lessons. Digital platforms offer simulations, animations, and interactive experiments that help students better visualize and understand transpiration (Barker, 1998). Incorporating this topic into a digital textbook supports new teaching strategies such as interactive and collaborative learning, aligning with modern educational practices.

In Timor-Leste, secondary school biology is taught across Grades 10 to 12. This study focuses on Grade 11, which emphasizes the physiological and structural functions of plant and animal systems. According to the national curriculum,

Grade 11 biology includes three main units: Dinâmicas Biológicas e Produção Vegetal (Biological Dynamics and Plant Production), Dinâmicas Biológicas e Produção Animal (Biological Dynamics and Animal Production), and Biodiversidade, Evolução e Classificação (Biodiversity, Evolution, and Classification). Plant transpiration is addressed in Unit 4, which covers plant organ structure, water and nutrient transport, stomatal regulation, photosynthesis, and plant hormones. However, most schools in Timor-Leste lack laboratory facilities and materials, limiting opportunities for students to conduct direct experiments.

To overcome these barriers, the digital textbook developed in this study incorporates experimental videos and simulations using locally accessible materials. Although most demonstrations avoid specialized tools, one activity includes a microscope-based observation of stomata to support deeper conceptual understanding. This approach ensures that even students in resource-limited environments can meaningfully engage with the curriculum content.

Pages is a user-friendly word processing and page layout application developed by Apple that allows for the creation of interactive and multimedia-rich documents, including digital textbooks (Apple. Inc.). By integrating interactive visualizations, simulations, and multimedia elements, a digital textbook on plant transpiration can enhance students' understanding of this complex scientific concept.

Therefore, the research aims to develop and evaluate the effectiveness of a digital textbook on plant transpiration using the Pages application for high school students. This study focuses on two research questions: How can a digital textbook on plant Transpiration for high school students be developed using pages, and is the digital textbook for high school students created using pages effective for students' learning in achievement and satisfaction?

Method

Participants and Procedure

The study was conducted at a senior high school in Dili City, the capital of Timor-Leste. Sixty students from grade 11 were randomly divided into two groups: the experimental group ($n = 30$) and the control group ($n = 30$). The control group used the traditional printed textbook, while the experimental group used the digital textbook developed using Pages, which provided a computer for each student and allowed them to use their mobile devices to interact with the digital textbook. The intervention was led by an experienced biology teacher, Teacher Macha, who is enthusiastic about using technology in teaching.

Data Collection and Analysis

The data collected in this study included pre-test and post-test scores, student satisfaction survey responses, and feedback from the teacher. To evaluate students' conceptual understanding of plant transpiration, a 10-item academic achievement test was used as both a pre-test and a post-test. The questions were developed based on the content covered in the digital textbook and aligned with the Grade 11 biology curriculum in Timor-Leste. Each item was designed to match specific learning objectives and corresponded with a section of the digital textbook, which featured interactive videos, animations, and practical simulations. The structure of the academic achievement assessment tool is presented in Table 1.

Table 1. Structure of the academic achievement assessment tool

No.	Content Area (Based on Digital Textbook Sections)	Learning Objective	Question Structure	No. of Items
1	What is Transpiration?	Define transpiration and explain its function	Multiple Choice	1
2	Pathway of Water Movement	Identify and sequence the path of water from the root to the stomata	Multiple Choice	1
3	Site of Water Evaporation	Recognize the part of the leaf where water vapor exits	Multiple Choice	1
4	Function of Stomata in Gas Exchange	Identify structures involved in gas exchange for respiration and photosynthesis	Multiple Choice	1
5	Stomatal Anatomy and Labeling	Label the stomatal structure and describe the role of guard cells	Visual Identification	1
6	Mechanism of Stomatal Opening	Explain what controls stomatal opening and closing	Multiple Choice	1
7	Interpreting the Graph of Water Movement	Analyze transpiration and absorption trends from visual data	Graph Interpretation	1
8	Water Movement Mechanism	Explain how water moves through the plant (e.g., osmosis, transpiration pull)	Multiple Choice	1
9	Effect of Light Intensity	Analyze how light influences transpiration and stomatal behavior	Multiple Choice	1
10	Effect of Wind on Transpiration	Assess how wind affects transpiration rate and water vapor diffusion	Multiple Choice	1
Total				10 Items

To validate the academic achievement test, a team of experts, consisting of biology lecturers and high school biology teachers, assessed the tool. The test questions were considered for the content, construction, language, and alignment with the subject matter. For content validity, the percentage of agreement for each question was calculated. The table below presents the validity results for each of the 10 questions in the test.

Table 2. Academic achievement instrument validation result

Number of questions	Percentage of agreement	Interpretation
Q1	93 %	Valid
Q2	89 %	Valid
Q3	96 %	Valid
Q4	96 %	Valid
Q5	95 %	Valid
Q6	88 %	Valid
Q7	90 %	Valid
Q8	95 %	Valid
Q9	92 %	Valid
Q10	91 %	Valid

The reliability of academic achievement and survey instruments (Kimberlin & Winterstein, 2008) was applied to the 60 students who did not participate in the study. Cronbach's alpha was utilized to determine the internal consistency of the academic achievement and survey instruments. The Cronbach's alpha coefficient for both instruments is provided in the Table 3 below:

Table 3. Reliability test of instruments

Instrument	Number of Items	Cronbach's Alpha	Interpretation
Academic Achievement Test	10	.867	Good
Student Satisfaction Test	10	.921	Excellent

The data collected were analyzed using SPSS software. Descriptive statistics and independent t-tests were used to determine the effectiveness of the digital textbook in improving learning outcomes and student satisfaction.

Development Process of the Digital Textbook

The study employed a Research and Development approach, utilizing the ADDIE model procedures, which consist of five phases (Arkün & Akkoyunlu, 2008; Zulkifli et al., 2018; Trust & Pektas, 2018) with the following steps:

Analysis Phase

Analysis involves identifying needs and context. In this stage, the researcher analyzed the national curriculum and identified the topic of plant transpiration. Students learn this content as a particular subunit of the biological dynamics and plant production unit, which appears in the third semester of eleventh grade. The student textbook contains two interesting hands-on activities related to plant transpiration. However, students have never gotten the opportunity to experiment because the tools and materials needed in this practicum require a laboratory, and most schools do not have laboratory facilities. Also, most teachers do not have experience in teaching with practical activities.

Design Phase

In this phase, the researcher planned the content, objectives, and multimedia integration. The content aligns with Timor-Leste's national curriculum. The primary objective is to develop a DT that can provide an interactive and engaging learning experience for students. The DT is divided into the following sections: Introduction to plant transpiration, Stomata, Factors affecting plant transpiration, and Assessment. The media integration includes animations, videos, interactive images, a gallery, hyperlinks, and interactive quizzes to enhance students' understanding.

Development Phase

The development phase involves creating the DT based on the design plan. In this stage, the researcher used the Pages software to develop the DT. The application supports the integration of multimedia elements and ensures easy conversion into other formats like PDF or Word for accessibility on various devices.

The researcher developed four hands-on activity videos for students that enable them to use simple materials found in their local context; they could conduct and observe plant transpiration experiments to deepen their understanding of the concept. To make the DT interactive and engaging, the researcher incorporated multimedia elements such as a simulation video produced by Home Revice (2016) to illustrate the process of plant transpiration, including pictures of stomata captured during the video production process and each picture hyperlink to the sources in the website. Also, integrated interactive applications like Padlet and Google Drive serve as interactive communication tools among teachers, students, and peers, as well as quizzes for assessments in the DT to enable students to self-evaluate their learning progress.

The developed DT was reviewed by experts in biology. Incorporating their feedback, the researcher meticulously refined the content and multimedia features to optimize the DT's alignment with learning objectives and maintain good educational quality standards.

Implementation Phase

In this stage, the DT was distributed to teachers and students and implemented in a real classroom setting with 11th-grade students. During the implementation, the instructor received orientation on how to navigate and facilitate the DT in the classroom. Students accessed the textbook using school-provided computers and personal mobile devices, engaging with interactive elements such as ThingLink images, instructional videos, Padlet discussions, and embedded quizzes.

The digital textbook on plant transpiration was delivered through a 180-minute (3-hour) program, aligned with the national curriculum's unit *Dinâmicas Biológicas e Produção Vegetal* (Biological Dynamics and Plant Production). Table 4 presents the subtopics covered and their estimated time allocation, based on the lesson plan.

Table 4. Subtopics and time allocation for the digital textbook on plant transpiration

Subtopic	Time Allocation (Minutes)
Introduction to Transpiration	20
Transpiration Process	60
Stomata	30
Factors Affecting Transpiration	40
Review and Assessment	30
Total Duration	180

Time allocations, as shown in Table 4, were distributed based on the textbook's structure. More time was dedicated to sections that incorporated video animations, hands-on experiments, ThingLink interactive images, and gallery-based visual analysis. For example, the Transpiration Process section received 60 minutes due to the complexity of its concepts and inclusion of guided experiments and video animation. Factors Affecting Transpiration and Stomata also received extended time due to student-centered experiments and interactive visuals. In contrast, the Introduction and Review phases were shorter, focusing on orientation and assessment.

Evaluation Phase

The final phase involved evaluating the effectiveness of the digital textbook. The researcher collected data through student satisfaction surveys and pre- and post-tests to assess the impact on student learning outcomes.

Results

The Developed Digital Textbook

The digital textbook on "Plant Transpiration" is an interactive learning resource designed to enhance student engagement and understanding. The DT is structured into four main sections: Introduction of Transpiration Process, How Transpiration Takes Place, Stomata, and Factors Affecting Transpiration Rate. Each section integrates videos, interactive images, reading materials, and collaborative tools to promote active learning. The following are figures 1 to 4 depicting the sections of the DT.



Fig. 1. Overview of the digital textbook on plant transpiration

The digital textbook begins with the book cover and table of contents (Fig. 1-A&B), followed by the introduction section (Fig. 1-C), which features a video designed to spark students' curiosity with general questions about the topic. To guide their exploration, Google Docs-based reading materials help students find answers, while the Padlet app provides an interactive platform for discussion and collaboration between students and teachers. Additionally, an interactive image created using Thinglink (Fig. 1-D) illustrates the stages of transpiration and is linked to YouTube videos explaining water movement through different plant parts, such as the roots, stems, and leaves.

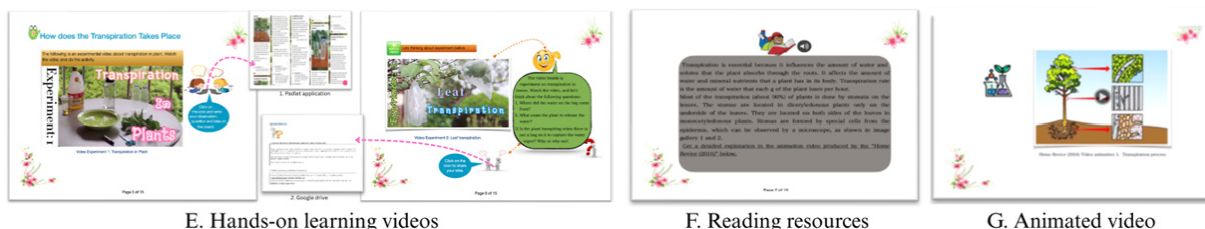


Fig. 2. Multimedia resources for learning plant transpiration

In the section on how transpiration takes place (Fig. 2-E), two experimental videos, produced using CapCut, demonstrate the transpiration process, with each video featuring Padlet discussions and Google Docs activities, allowing students to share observations, experimental results (such as photos), and insights. Hyperlinked key terms in the reading materials (Fig. 2-F) provide students with additional resources for deeper understanding, while the animated video (Fig. 2-G) visually explains the entire transpiration process, from water absorption in the roots to evaporation in the leaves.

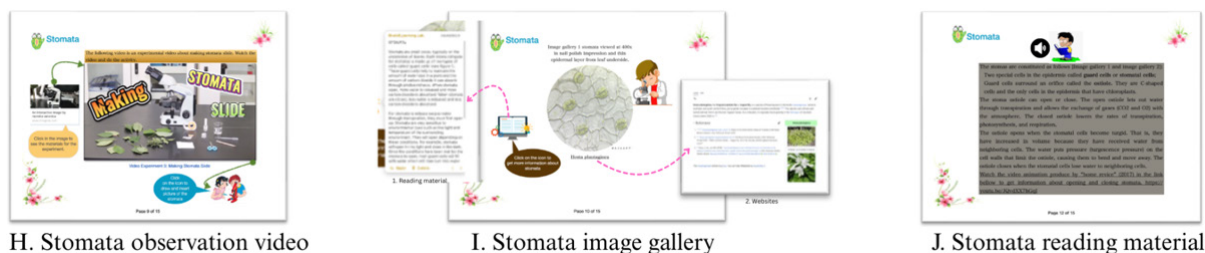


Fig. 3. Exploring stomata and their role in transpiration

The stomata section (Fig. 3-H) includes a video on stomata observation, helping students visualize stomata on different plant leaves. Interactive images display the materials and tools used in the experiment, while a Padlet discussion board allows students to share their findings with peers and teachers. A gallery of stomata observations (Fig. 3-I) linked to educational websites helps students learn more about the plant species used in the experiment. Additionally, a reading passage on stomata (Fig. 3-J) is complemented by audio narration, making the content accessible to diverse learning styles. To further reinforce understanding, a YouTube video on the stomatal opening and closing mechanism is provided.

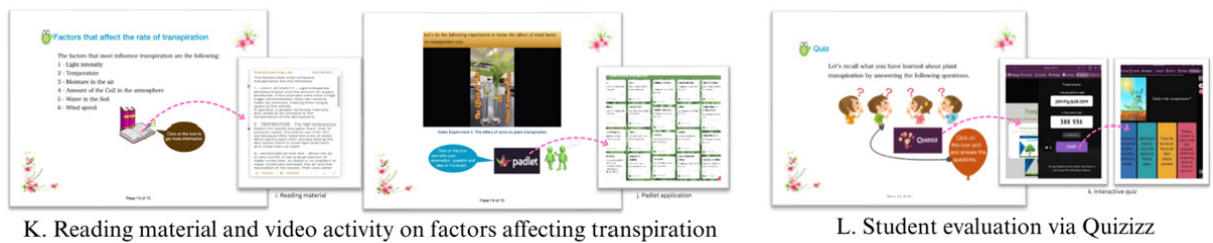


Fig. 4. Factors affecting transpiration and evaluation activities

The factors affecting the transpiration rate section (Fig. 4-K) features an experimental video demonstrating how environmental factors such as light, humidity, temperature, and wind influence transpiration. Students can discuss their findings, share experimental results, and ask questions using the Padlet app. Supporting reading materials are also provided through Google Docs to reinforce key concepts. The textbook includes an interactive quiz (Fig. 4-L) developed using the Quizizz application to assess students' learning. This allows students to test their understanding and receive instant feedback.

Academic Achievements

The pre- and post-academic achievement test results for the experimental and control groups are presented in Table 5. Descriptive statistics were used to summarize the mean (M) and standard deviation (SD) for both groups, while an independent samples t-test was conducted to compare their performance. Before receiving treatment, the experimental group had a mean score of $M=4.77$, $SD=1.524$, while the control group scored $M=4.27$, $SD=1.437$. The difference between the two groups at the pre-test stage was not statistically significant ($t=1.307, p=0.196$). After the treatment, post-test results revealed a statistically significant difference between the groups. The experimental group, which was taught using digital textbooks (DT), achieved a mean score of $M=7.30$, $SD=1.685$, compared to $M=6.10$, $SD=1.517$ for the control group, which used printed books ($t=2.900, p=0.005$). These findings, supported by the descriptive statistics and the results of the independent samples t-test, indicate that the experimental group experienced a greater improvement in academic achievement compared to the control group. This higher average increase suggests that DT is an effective teaching method for improving learning outcomes on plant transpiration content.

Table 5. The pre- and post-academic achievement

Test	Group	N	M	SD	t	p
Pre-test	Experiment	30	4.77	1.524	1.307	.196
	Control	30	4.27	1.437		
Post-test	Experiment	30	7.30	1.685	2.900	.005
	Control	30	6.10	1.517		

Note: M=Mean score, SD= Standard deviation, N= 60 participants in total

Learning Satisfaction

The students' satisfaction questionnaire, developed by Kim & Kwon (2018), was administered to 30 students in the experimental group and utilized a five-point Likert scale ranging from (strongly disagree=1) to (strongly agree=5). The summary of results is presented in Table 6, showing that the students generally expressed high satisfaction with the digital textbooks. Satisfaction with multimedia elements (pictures, videos, etc.) was rated the highest (M=4.80), while the frequency and duration of interaction with the digital textbook were rated the lowest (M=3.93). This shift has positive implications for students, as the findings indicate that students showed positive attitudes toward digital books, particularly regarding their engaging and interactive features.

Table 6. Questionnaire results on students' satisfaction with digital textbooks

Questionnaire content	Mean score/5
I was satisfied with learning activities using the digital textbook	4.33
I would like to continue to use the digital textbook in my future learning	4.40
Multimedia materials (picture, video, quiz, etc.) in a digital textbook help me learn	4.80
Communication with a digital textbook helps me learn	4.47
I was satisfied with the amount of time or frequency of communication with a digital textbook	3.93
I have enough feedback on my learning	4.13
It was easy and convenient to use the digital textbook	4.27
It was easy and convenient to find the contents presented on the screen of the digital textbook	4.27
It was easy and convenient to find the materials I wanted in the digital textbook	4.13
It was easy and convenient to find the content that I wanted in the digital textbook	4.33

Discussions

The development of digital textbooks (DT) in biology has been explored through various research methodologies and contexts, emphasizing their potential to improve educational outcomes across different subjects and educational levels. The integration of DT in biology education aims to address the challenges posed by the abstract nature of biological concepts and the vast amount of material that can overwhelm students.

The DT developed for this study demonstrated significant effectiveness in improving student academic achievement. In the experimental group, the pre-test mean score of 4.77 increased to 7.3 in the post-test, a statistically significant improvement compared to the control group, whose scores increased from 4.27 to 6.0. The study results indicated that the use of DT had a significant positive impact on student learning outcomes compared to the use of traditional printed textbooks. The impact of DT on student learning achievement is multifaceted and generally positive, as evidenced by various studies across different educational contexts.

Digital textbooks have been shown to enhance student engagement, academic performance, motivation, academic interest, and learning achievement across a variety of disciplines (Firmansyah & Munawwaroh, 2023; Hadir, 2023; Holley, 2006; Im, 2024; Kim & Jung, 2010; Kim & Yu, 2019; Lee et al., 2022; Lim et al., 2022; Rockinson - Szapkiw et al., 2013; Zhadan et al., 2024). The use of interactivity, multimedia, and other digital features is among the key advantages of DT. The current study incorporated multiple interactive multimedia elements, such as video, simulation, interactive images, embedded hyperlinks, and interactive applications like quizzes and Padlet, to enhance students' academic achievement, targeting students in Timor-Leste, potentially contributing to increase student interest and understanding of education content which can improved learning outcomes (Kim & Yu, 2019; Wulandari et al., 2024). However, some studies indicate that the level of use of DT features by instructors is low, and there is no significant difference in student grades between digital and paper formats, suggesting that the potential of digital textbooks is not fully realized (Roberts et al., 2021). On the other hand, DT has been shown to enhance affective and social competencies, such as self-efficacy and collaboration, in students, suggesting broader educational benefits beyond academic performance (Im, 2024).

Furthermore, the development of digital textbooks in vocational education, such as interactive digital books for mathematics and bilingual physics learning media, has been validated as effective and feasible, with high scores from both experts and users (Fauziyah et al., 2023). Similarly, the study by Pigai & Yulianto, (2024) found that flipbook learning media in science education has demonstrated effectiveness, with significant improvements in student learning outcomes, particularly in understanding plant body parts and their functions. Moreover, the development of digital learning media for drama text material and biology e-books has shown improvements in student skills and learning outcomes, further supporting the practicality and effectiveness of digital textbooks in diverse educational settings (Hadir, 2023). Overall, while digital textbooks generally enhance learning achievement, their effectiveness can vary based on factors such as subject area, student demographics, and the extent of their integration into the curriculum. Also, these studies underscore the significant role digital textbooks can play in making biology education more accessible, engaging, and effective for students.

Student satisfaction with DT is influenced by a variety of factors, as highlighted across multiple studies. The survey results from 30 students in the experimental group revealed a generally positive attitude towards using DT. The survey results indicate that students were highly satisfied with learning activities using DT, strongly agreeing that multimedia elements such as pictures, videos, quizzes, and animation significantly enhanced their learning. These findings align with previous studies that have reported positive student attitudes and satisfaction with DT, mainly due to their engaging and interactive features (Lee et al., 2014; Lim et al., 2022). For instance, Brnic et al. (2024) and Mashfufah et al. (2019) found that visualizations and interactive elements, such as animations and videos, are the most appreciated features that enhance understanding and engagement with the material. These multimedia components can make complex concepts more accessible. Additionally, DT is also equipped with assessments using Quizizz. This application is fun because it uses elements such as music, memes, avatars, and gamification to make students enthusiastic about learning. This finding aligns with previous research that DT includes interactive assessments, such as quizzes and exercises, provides immediate feedback, and helps reinforce learning (Moreira & Lara Freire, 2024).

Furthermore, students valued the convenience and accessibility of the digital textbook, as it allowed them to easily access and navigate the learning materials. However, students expressed slightly lower satisfaction with the frequency and duration of interaction with the digital textbook, with observations revealing a desire for extended lesson hours due to their enjoyment of DT activities. Thus, while overall satisfaction with the digital textbook was high, several areas for improvement were identified, including increasing the duration of interaction and further enhancing the multimedia features to better engage students.

Teachers commonly consider DT an effective tool for increasing student engagement and motivation, although its effectiveness depends on several factors. In this study, the instructor described DT as an innovative learning medium transforming the classroom experience. The teacher acknowledged that incorporating DT and associated interactive features, such as videos, simulations, and quizzes, helped capture students' attention and foster active engagement during lessons. This finding is consistent with previous studies highlighting that embedded multimedia tools and interactive elements are effective in making lessons more enjoyable and effective as they help students understand and retain information better (Rahmi et al., 2019).

However, the instructor also noted that there were some challenges, including the need for support infrastructure and professional development for teachers on DT integration to ensure a smooth and successful implementation of DT in the classroom. This is congruent with findings from related studies that have recognized critical challenges to the effective integration of DT in the classroom, including a lack of digital devices, and internet connectivity, which are essential for the proper implementation of DT (Ahmad et al., 2024; Baharudin et al., 2024). The digital divide further exacerbates these issues, as not all students have equal access to technology, leading to disparities in learning opportunities (Tang & Fan, 2024). The shift to digital textbooks requires a redefinition of teacher roles, as educators must balance traditional teaching methods with new digital tools, often without sufficient support or guidance from educational institutions (Park, 2023; Lee, 2023). Overcoming these obstacles requires robust teacher training programs, infrastructure development, as well as policies, ensuring that all students and teachers can benefit from the potential advantages of digital textbooks (Baharudin et al., 2024; Tang & Fan, 2024).

Conclusions and Implications

This study examines the efficacy of digital textbooks as an innovative and effective learning tool for high school biology education, with a particular focus on the topic of plant transpiration. The findings indicate a statistically significant improvement in students' academic achievement when using digital textbooks compared to traditional printed books. Students in the experimental group demonstrated higher post-test scores, highlighting the effectiveness of interactive multimedia elements in promoting deeper understanding and engagement. Student feedback further revealed that digital textbooks facilitated active participation and interactive learning, integrating seamlessly into the educational process.

Beyond student academic performance, teachers' feedback underscored the benefits of digital textbooks in fostering active learning and engagement. However, successful large-scale implementation requires addressing challenges such

as limited digital infrastructure and inadequate teacher training. As digital technology continues to play an increasingly central role in science education, this research provides valuable insights into the integration of technology-enhanced learning materials within national science curricula.

The study identifies several key educational implications regarding the use of digital textbooks (DT) in biology education and beyond. First, the significant improvement in student academic achievement suggests that incorporating DT into the curriculum can serve as an effective strategy for enhancing learning outcomes. The interactive, multimedia-rich nature of DT provides students with engaging learning experiences, improving their comprehension of complex biological concepts and increasing motivation.

Second, students' positive attitudes and high levels of satisfaction with DT indicate their potential to foster a more interactive, student-centered learning environment. Features such as videos, simulations, quizzes, and gamified assessments enhance engagement and knowledge retention. Educators should consider integrating these elements into their teaching strategies to optimize student learning experiences.

Despite these benefits, the study also highlights challenges associated with DT implementation. The effectiveness of DT varies based on factors such as subject area, student demographics, and the extent of integration into the curriculum. Additionally, instructor engagement plays a critical role in determining the impact of DT. To maximize the benefits, professional development programs should be established to equip teachers with the necessary skills to effectively incorporate digital resources into their instructional practices.

Furthermore, infrastructure challenges—including limited access to digital devices and internet connectivity—remain significant barriers to equitable DT implementation. Addressing these issues requires investment in technological infrastructure and the development of policies that ensure equal access to digital learning resources for all students. Bridging the digital divide is essential to preventing disparities in educational opportunities.

Finally, this study highlights that DT contributes not only to academic performance but also to the development of social and affective competencies, such as collaboration and self-efficacy. As a result, educators and policymakers should recognize the broader educational benefits of DT and work toward its effective implementation to enhance student engagement, motivation, and overall learning experiences.

Furthermore, although this study was conducted within the context of Timor-Leste, its findings have relevance for educational settings globally, particularly in developing and resource-constrained countries. Many regions face similar challenges related to limited digital infrastructure, insufficient teacher training, and access to quality digital learning materials. The successful development and use of a digital textbook integrating multimedia elements demonstrates a scalable model that can be adapted to other contexts facing similar barriers. By utilizing affordable, accessible technologies like the Pages application and emphasizing localized content, other countries can enhance science education, promote digital literacy, and improve learning outcomes. Therefore, the results of this study contribute not only to the advancement of biology education in Timor-Leste but also offer practical insights for global efforts to integrate digital tools into education effectively and equitably.

Conflicts of Interest

The authors declared no conflicts of interest.

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