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Developing and Testing Inquiry-Based E-Modules for Learning Plant Structure and Tissues in Senior High Schools

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Abstract

Plant structure and tissues constitute fundamental topics in senior high school biology; however, students' learning outcomes in this area remain unsatisfactory due to conceptual complexity and limited instructional support. To address this issue, this study aimed to develop and examine the effectiveness of an inquiry-based interactive e-module for learning plant structure and tissues at the senior high school level. The study employed a Research and Development approach using Thiagarajan's 4-D model, which consists of the define, design, develop, and disseminate stages. The dissemination stage was conducted through an experimental method using a pretest–posttest control group design. Data were collected through expert validation sheets, questionnaires, observations, and learning outcome tests, and analyzed using descriptive techniques and an independent samples t-test. The results indicate that the developed inquiry-based e-module is pedagogically feasible and statistically effective in improving students' learning outcomes compared to conventional instruction. The e-module can function both as an independent learning resource and as an instructional support within classroom and online learning environments. This study contributes empirical evidence that integrating inquiry-based pedagogy into digital learning modules enhances conceptual understanding and supports more active and independent learning in biology education.

Keywords: *Keywords; Keywords; Keywords; Keywords; Keywords.*

A. Introduction

Biology education at the senior high school level encompasses a range of foundational concepts essential for students' scientific literacy, one of which is plant structure. This topic plays a central role in shaping students' understanding of plant physiology, growth processes, ecological interactions, and life cycles. A comprehensive grasp of plant structure enables learners to connect microscopic biological components with macroscopic plant functions, thereby supporting higher-order biological reasoning (Kun, 2023; Setiyadi et al., 2020). However, despite its fundamental importance within the biology curriculum, plant structure remains one of the topics that students consistently find difficult to master (Kaspin et al., 2024; Ornstein & Hunkins, 2018).

Plant structure involves multiple organ systems, including roots, stems, leaves, flowers, fruits, and seeds, each composed of specialized cells and tissues with distinct characteristics and functions (Ilic et al., 2007; Preston et al., 2022; Karumanchi et al., 2023). Understanding the organization and function of cells and tissues within each organ is not merely a matter of memorization but requires conceptual integration and visualization (Ilic et al., 2007). Without a solid understanding of these microscopic structures, students struggle to comprehend broader biological processes, such as transport mechanisms, photosynthesis, reproduction, and plant adaptation to environmental conditions (Preston et al., 2022). Consequently, difficulties in learning plant structure can hinder students' overall achievement in biology.

From an educational perspective, plant anatomy is widely recognized as one of the most conceptually demanding topics in secondary-level biology, as it requires students to mentally connect abstract microscopic structures with observable physiological functions (Ilic et al., 2007; Preston et al., 2022). The complexity of cell differentiation, tissue specialization, and organ integration often leads students to rely on surface-level memorization rather than meaningful understanding, particularly when instructional approaches fail to support visualization and conceptual linkage across structural scales. As a result, students may develop fragmented knowledge of plant structure, which limits their ability to transfer anatomical concepts to explain dynamic biological processes and problem-solving contexts (Preston et al., 2022). These learning challenges indicate that difficulties in plant structure comprehension are not incidental but represent a systematic instructional and conceptual issue within biology education.

Empirical evidence from learning evaluations conducted over the past three years (2021–2023) across 10 senior high schools in Banda Aceh highlights the severity of this issue. Assessment results from 145 students revealed persistently low learning outcomes, characterized by a high proportion of incorrect answers and misconceptions related to plant cells and tissues. Incorrect responses accounted for 49% and 52%, misconceptions reached 33% and 31%, while correct answers comprised only 18% and 16% of total responses.

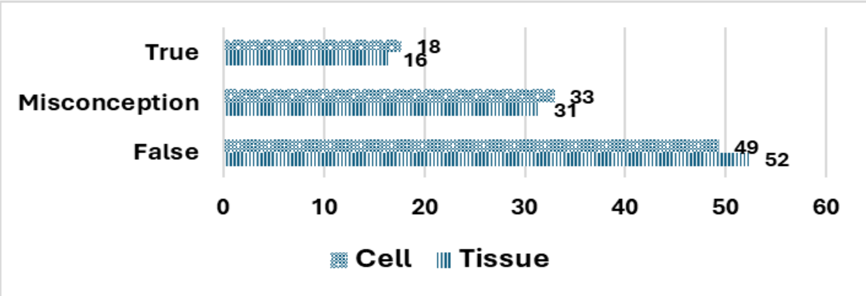

Figure 1. Average percentage of students test results on cells and tissues.

These findings indicate that students' difficulties are not incidental but systemic, reflecting deeper problems in the learning process. Further investigation through a survey conducted in March 2024 involving 50 students and 48 biology teachers from public high schools in Aceh Province corroborated this conclusion. The survey revealed that students experience substantial challenges in understanding plant structure due to the complexity of the material, the extensive use of scientific terminology, a lack of effective visual learning media, limited practicum activities, monotonous teacher-centered instructional methods, and weak connections between the content and students' everyday experiences. These challenges are compounded by the scarcity of adequate learning resources, including textbooks, supplementary materials, and digital learning tools, as well as insufficient learning facilities. Together, these internal and external factors contribute to suboptimal learning outcomes in plant structure education.

In response to these challenges, the development of innovative and technology-enhanced learning resources has become increasingly important. One promising solution is the use of electronic modules (e-modules), which are systematically designed digital learning materials that integrate text, images, animations, videos, and interactive elements. Previous studies have demonstrated that e-modules can effectively support both independent and teacher-guided learning by providing flexible access, rich multimedia content, and structured learning pathways (Asrial et al., 2019; Hardiyanti et al., 2020; N. Lastri et al., 2019; Nurhasnah et al., 2020; Wati et al., 2020). Unlike printed modules, e-modules overcome spatial and temporal constraints, allowing students to learn anytime and anywhere using computers, tablets, or smartphones.

E-modules also offer pedagogical advantages by promoting learner autonomy and motivation. Their self-instructional nature enables students to regulate their own learning pace, while built-in evaluations allow learners and teachers to monitor progress and identify conceptual gaps (Lastri, 2023; Sugihartini & Jayanta, 2017). The integration of multimedia elements reduces the dominance of verbal explanations, making abstract biological concepts more concrete and accessible. Moreover, user-friendly interfaces and interactive features, such as formative tests with automated feedback, enhance students' engagement and understanding (Yanarti et al., 2022; Purwanto et al., 2020). Empirical evidence suggests that well-designed e-modules can significantly improve learning outcomes by fostering motivation and independent learning behaviors (Pramana et al., 2020; Akmal et al., 2024).

Nevertheless, learning resources alone are insufficient without appropriate instructional strategies. Inquiry-based learning, rooted in constructivist theory, has been widely recognized as an effective approach to promote active learning, critical thinking, and deep conceptual understanding. Through inquiry learning, students are encouraged to explore problems, formulate questions, investigate phenomena, and construct knowledge based on evidence and reasoning (Noris et al., 2023). This student-centered approach aligns well with the goals of biology education, as it emphasizes meaningful learning and real-world relevance (Sari et al., 2020). Integrating inquiry-based learning strategies with e-modules creates opportunities to enhance analytical thinking skills and respond to the demands of 21st-century education (Noris et al., 2023).

A growing body of research has explored the development of learning tools to improve student outcomes across scientific disciplines (Brown et al., 2024; Goh et al., 2021; Kerimbayeva et al., 2024; Khotimah et al., 2023; Reen et al., 2024; Reiser et al., 2024; Suryani et al., 2024; van der Leij et al., 2023; Wasendorf et al., 2022; Yazici & Sözbilir, 2022; Yeşilyurt, 2024; Yuliardi et al., 2024). Similarly, numerous studies have focused on the development of e-modules in biology and related fields

(Anggun, 2021; Copriady et al., 2020; Dismarianti et al., 2020; Herawati & Muhtadi, 2018; Hernayati et al., 2021; Husmita et al., 2020; Kimianti & Prasetyo, 2018; Miftakhurrohmah et al., 2023; Noer et al., 2021; Sari et al., 2020; Syahmani et al., 2022). However, despite this extensive literature, research that specifically develops and evaluates e-modules for biology learning on plant structure and development, particularly when systematically integrated with inquiry-based learning strategies at the senior high school level, remains limited.

This gap indicates that existing studies have not sufficiently addressed the combined pedagogical and technological challenges associated with teaching plant structure, especially in contexts where learning resources and facilities are constrained. The novelty of the present study lies in the development and empirical evaluation of an inquiry-based e-module specifically designed for plant structure and development (cells and tissues) learning at the senior high school level. By integrating inquiry learning principles into an interactive e-module tailored to students' learning needs, this study seeks to provide both a practical instructional solution and an empirical contribution to biology education research.

Accordingly, the purpose of this study is to examine the effectiveness of the developed inquiry-based e-module in improving students' learning outcomes on plant structure and development. Through this investigation, the study aims to contribute to the growing body of literature on digital and inquiry-oriented learning in biology education while offering evidence-based insights for educators seeking to enhance learning quality in resource-limited educational contexts.

B. Method

This study employed a quantitative approach using a Research and Development (R&D) methodology based on the Four-D (4-D) development model proposed by Thiagarajan et al. (1974), which consists of the define, design, develop, and disseminate stages. This model was selected because it provides a systematic framework for developing, validating, and testing instructional materials, including digital learning modules. The development process began with the define stage, which aimed to identify and specify learning requirements related to plant structure and development at the senior high school level. This stage involved an initial and final analysis of learning conditions, analysis of students' characteristics such as prior knowledge and learning abilities, material analysis to organize plant structure content systematically, task analysis to align learning activities with curriculum demands, and the formulation of learning objectives based on the senior high school biology curriculum.

The design stage focused on preparing the structure and format of the e-module and the associated research instruments. During this stage, appropriate digital media were selected, and the module format was designed to align with inquiry-based learning principles and the defined learning objectives. An initial draft of the e-module was then developed, consisting of learning objectives, structured material explanations, example problems, formative assessments, summaries, enrichment questions, and answer keys.

The develop stage involved producing the e-module through expert validation and field trials. Validation was conducted to assess the content accuracy, media quality, construction, and presentation format, ensuring that the module met pedagogical and technical standards. Revisions were made based on feedback from material experts, media experts, teachers, and students before the module was tested in classroom settings. The disseminate stage was conducted through an experimental implementation using a pretest–posttest control group design (Gall et al., 2003) to examine the effectiveness of the developed e-module.

Table 1. Pretest–Posttest Control Group Design.

Sample	Class	Pretest	Treatment	Posttest
Random	A (Experiment)	O	X1	O
Random	B (Control)	O	X2	O

Where: X1 = Implementation of Inquiry Learning using e-Module
X2 = Implementation of Conventional Learning
O = Conceptual understanding test

The experiment was carried out at a state senior high school in Banda Aceh, Indonesia, involving 80 students who were randomly assigned to two groups. Forty students were placed in the experimental group, which received inquiry-based learning supported by the developed e-module, while the remaining forty students formed the control group and received conventional, non-digital instruction. In the experimental group, the e-module was implemented online using the heyzine.com platform. Both groups completed a pretest before the intervention and a posttest after the instructional period to measure conceptual understanding of plant cells and tissues.

Data were collected using both test and non-test instruments. The primary test instrument consisted of 90 multiple-choice items designed to assess students' learning outcomes through pretest and posttest administration. Non-test instruments included interviews, questionnaires, and observation sheets, which were used to obtain qualitative data related to module feasibility and learning implementation. All instruments were validated by experts prior to use. Quantitative data were obtained from validation scores provided by experts, teachers, and students using a four-point Likert scale, as well as from students' pretest and posttest scores.

Table 2. Score Conversion on Four-point Scale.

Scale	Interval	Conclusion
4	X ≥ 3.1	Very Feasible
3	3.1 > X ≥ 2.5	Feasible
2	2.5 > X ≥ 1.9	Less Feasible
1	X < 1.9	Not Feasible

Quantitative data were analyzed descriptively to determine the feasibility of the e-module, while learning effectiveness was examined by comparing pretest scores and normalized gain (N-Gain) scores between the experimental and control groups. N-Gain was calculated using the formula proposed by Meltzer (2002), and differences between groups were analyzed using an independent samples t-test. Qualitative data from interviews, questionnaires, and observations were analyzed descriptively to support the refinement of the developed product.

This study adhered to ethical research standards. Permission to conduct the research was obtained from the school authorities, and informed consent was secured from all participants. Students' participation was voluntary, and all data collected were treated confidentially and used solely for research purposes.

C. Results and Discussion

High school students' learning outcomes on plant structure and tissues are still unsatisfactory, with many students struggling to understand the topic. This section presents key findings regarding the development and testing of inquiry-based e-modules for plant structure and tissues in an effort to improve student learning outcomes.

1. Results

The define stage focused on identifying and establishing the learning requirements and comprised five main steps: problem analysis, student analysis, task analysis, concept/material analysis, and the specification of learning objectives. Problem analysis was conducted in five public high schools in Banda Aceh and Aceh Besar District, Aceh Province, to determine the fundamental issues in teaching plant structure and development, highlighting the need for e-module development. Interviews with subject teachers revealed that these schools follow the 2013 and Independent Curricula, using Student Worksheets and textbooks purchased by students. Common teaching methods include lectures, discussions, and demonstrations (practicum).

Observations revealed that students were not actively engaged in the learning process. Interviews and observations indicated that students' ability to grasp and respond to the subject matter varied, affecting their interest, enthusiasm, and attention during lessons. Consequently, students often appeared distracted or engaged in unrelated activities. Subsequent steps included concept analysis, task analysis, and the specification of learning objectives. The analyzed learning material centered on plant structure and development, specifically cell structure and plant tissues and their functions. Core competencies and basic competencies were also evaluated.

The design stage involved preparing test instruments, selecting appropriate media, choosing suitable formats, and creating initial designs. Instrument preparation aimed to assess students' conceptual understanding of the learning outcomes. The evaluation process included several phases: an initial stage featuring a student response questionnaire, a pretest administered before the intervention, and a posttest conducted after the implementation. The pretest and posttest comprised 90 multiple-choice items covering cognitive dimensions from recall to evaluation. The primary medium for delivering the subject matter was the e-module on plant structure and development, with student worksheets as supplementary material.

The e-module format was developed to align with the needs identified during the design stage. The e-module followed the format proposed by Prastowo, (2012), ensuring a structure suitable for the intended objectives. Table 3 presents the outline of the e-module.

Table 3. Outline of the e-Module

No.	Introduction Section	Contents	Final Section
1.	Cover	Material Title	Evaluation
2.	Foreword	Material Description	Bibliography
3.	Table of Contents	Practice Questions	
4.	Competency Standards	Student worksheet	
5.	Basic Competencies	Summary	
6.	Learning Objectives		

The resulting e-module design represents the initial product of the development process. The content section includes material descriptions, worksheets, practice questions, and summaries, all structured to encourage active student participation. The final section comprises an evaluation component and a bibliography. The develop stage involved expert validation, instrument trials, and e-module trials. Instrument validation was conducted to ensure that the research tools were valid and suitable for assessing the e-module. The components evaluated included the alignment of statements with the instrument grid, the appropriateness of content, and suitability for learning. Data from the assessment of the research instruments are presented in Tables 4 and 5.

Table 4. Analysis of Research Instrument Validation Results

No.	Assessment Aspect	Average Score	Criteria
1.	Statements in accordance with the instrument grid	3.00	Feasible to use with revision
2.	Content/Material Appropriateness	4.00	
3.	Suitability for Learning	4.00	

The results of the test item analysis, including item validity, difficulty level, discrimination index, and reliability, are presented in Table 5.

Table 5. Validation analysis of the test

No.	Test Component	Test Result Criteria			Conclusion
		Very High	High	Low	
1.	Item Validity	75 items	9 items	6 items	Revise 6 items
2.	Difficulty Index	82 items	4 items	3 items	Revise 3 items
3.	Discrimination Index	78 items	10 items	2 items	Revise 2 items
4.	Reliability	Very high (r = 0.98)			

Based on the assessments conducted by the validators, this research instrument was deemed suitable for use, albeit with revisions. The necessary improvements were made to the relevant sections before implementation. Media validation was conducted to evaluate the feasibility of the e-module from a media perspective. Two media experts completed the assessment sheets to evaluate the overall quality of the media. The media validation focused on four aspects: design, display, programming, and utilization. Subject Matter expert validation was performed to evaluate and determine the validity of the content and material included in the developed e-module. The subject matter assessment covered four areas: introduction, content, summary, and exercises/evaluation. The

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teacher conducted a simulation of e-module usage to provide students with an overview of how the e-module functions. The simulation demonstrated that the e-module can effectively serve as a learning resource for students and a teaching material for teachers.

In addition to expert validation, the test instruments were trialed to assess item validity, difficulty index, determination index, and reliability. The test results showed items with very high and high criteria. Items with low scores were revised to ensure that all test items could be used effectively in evaluations measuring student learning outcomes. Subsequently, the teacher administered the e-modules to students through an online platform.

Trial of e-Module

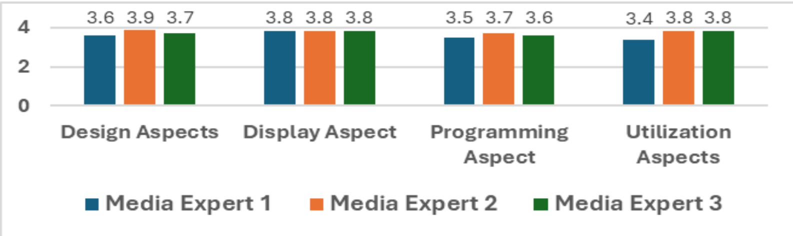

Figure 2 Results of Media Validation from Three Media Experts.

The assessment data from three media experts across all aspects yielded an average score of 3.7 (very feasible). The breakdown of the average scores for each aspect is as follows: the design aspect (ten indicators, M=3.73); the display aspect (nine indicators, M=3.8); the programming aspect (eight indicators, M=3.6); and the utilization aspect (six indicators, M=3.67). These results indicate that the developed e-module was suitable for further testing. The subject matter validation results from three subject matter experts are presented in Figure 3.

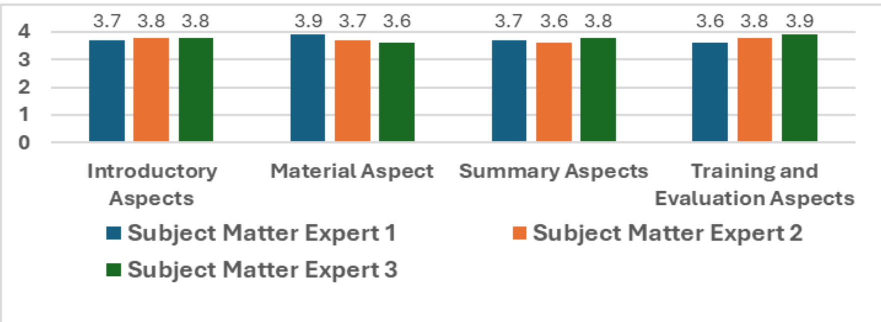

Figure 3. Assessment Results from Three Subject Matter Experts

The assessment data from three subject matter experts across all aspects yielded an average score of 3.74 (very feasible). The breakdown of the average scores for each aspect is as follows: the introduction aspect (five indicators, M=3.77); the content aspect (14 indicators, M=3.73); the summary aspect (three indicators, M=3.70); and the exercise and evaluation aspect (five indicators, M=3.77). Following the validation results from media and material experts, a limited trial was conducted with a small group. The outcomes of this trial provided input for refining the developed products before broader field testing. Data on students' responses from the small group trial are presented in Table 6.

Table 6. Student Response Scores from the Small Group Limited Trial.

No.	Assessment Aspect	Average Score	Criteria
1.	Learning Materials	3.7	Very Feasible
2.	Appearance	3.8	Very Feasible
3.	Programming	3.7	Very Feasible
Average Total Score		3.73	Very Feasible

Table 6 shows the results of the small group limited trial, with a total average score of 3.73 (very feasible). This indicates that the developed e-module was suitable for field testing with larger groups. The results of the large group trial were subsequently used to evaluate and determine the effectiveness of the developed e-module.

Effectiveness Test of e-Module Product

The effectiveness test of the e-module aimed to determine whether its implementation in the learning process could enhance student learning outcomes. To address this question, the effectiveness of the e-module was tested through experimental implementation. The experimental design employed was a pretest-posttest control group design involving 80 students randomly selected from the population of a Public Senior High School in Banda Aceh, Indonesia. Of these, 40 students were assigned to the experimental class and 40 to the control classes. The experimental class was taught using inquiry-based strategies supported by the e-module, while the control class received conventional instruction without the e-module. The e-module was considered effective in improving student learning outcomes if the normalized gain (N-Gain) score showed a significant difference between the experimental and control classes.

Student learning outcomes in the e-module effectiveness test were measured through pretest, posttest, and N-Gain scores. Figure 4 presents these results.

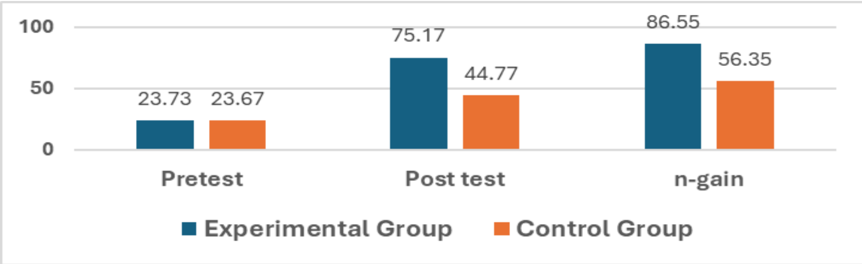

Figure 4. Mean pretest, posttest, and N-Gain scores for the experimental and control groups

Figure 4 shows that the average pretest score of the experimental class participants was 23.73, while the control class participants had an average score of 23.67. The pretest scores for both classes did not show significant differences (Table 7). These results indicate that the initial abilities of students in mastering the subject matter, prior to the application of e-modules, were equivalent in both the experimental and control classes.

Table 7. T-test results for pretest scores between experimental and control classes

Group	Average Pretest	Normality test *)	Homogeneity test **)	t-test***)
Experimental	23.73	Sig. 0.200 (Normal)	Sig. 0.670 (Homogeneous)	Sig.(2-tailed) 0.067 (Not significantly different)
Control	23.67	Sig. 0.148 (Normal)		

Note:
*) = *Kolmogorov-Smirnov Test* (Normal if Sig. ≥ 0.05)
**) = *Levene Test* (Homogenous if Sig. ≥ 0.05)
***) = t-Test (not significantly different if Sig, ≥ 0.025)

After the treatment using the e-module in the learning process, students' understanding of the material increased significantly, as indicated by the average N-Gain scores (86.55 and 56.35 for the experimental and control groups, respectively). The difference in the average N-Gain between the experimental and the control classes was 30.20 and statistically significant (Table 8).

Table 8. T-test results for N-Gain scores between experimental and control classes

Group	**Average N-Gain**	**Normality test *)**	**Homogeneity test **)**	**t-test***)**
Experimental	86.55	Sig. 0.200 (Normal)	Sig. 0.368 (Homogeneous)	Sig.(2-tailed) 0.000 (Highly significant)
Control	56.35	Sig. 0.054 (Normal)		

Note:
*) = *Kolmogorov-Smirnov Test* (Normal, if Sig. ≥ 0.05)
**) = *Levene Test* (Homogenous, if Sig. ≥ 0.05)
***) = t-Test (significant, if Sig. < 0.025)

The t-test results for the N-Gain scores indicate a significant difference between the experimental and control classes. Thus, it can be concluded that the developed e-module is highly effective in improving students' conceptual understanding of the subject matter.

The e-module was developed using the procedures of Thiagarajan's 4-D model with modifications. The 4-D development model consists of four stages: Define, Design, Develop, and Disseminate. The driving factors behind the development of this e-module include results from observations, interviews, needs analysis, supporting research, and relevant theories serving as the foundation for its development. The e-module development process involved the use of various software programs, such as CorelDraw, Adobe Photoshop, Quiz Creator, Flipbook Maker, and Microsoft Office. The resulting e-module product is a digital application with .exe and .swf extensions.

2. Discussion

The findings of this study provide compelling empirical evidence that the inquiry-based e-module developed for learning plant structure and development is both pedagogically feasible and instructionally effective in improving students' conceptual understanding. The consistently high feasibility ratings obtained from media experts, subject matter experts, and student trials indicate that the developed e-module meets essential standards in terms of content accuracy, instructional design, and media quality. These validation outcomes are consistent with previous development-oriented studies demonstrating that carefully designed digital learning tools can achieve high feasibility when they align instructional objectives, learner characteristics, and content structure (Brown et al., 2024; Kerimbayeva et al., 2024; Reiser et al., 2024). However, feasibility alone does not guarantee instructional impact. The more substantive contribution of this study lies in the experimental evidence showing a significant difference in learning gains between students who learned using the inquiry-based e-module and those who experienced conventional instruction, as reflected in the N-Gain analysis.

The observed improvement in learning outcomes can be interpreted through the lens of inquiry-based learning theory, which emphasizes active student engagement in constructing knowledge through questioning, exploration, and reflection. Inquiry-based learning positions students not as passive recipients of information, but as active participants who engage cognitively with learning materials, thereby fostering deeper understanding (Noris et al., 2023; Sari et al., 2020). In the context of plant structure and development, where students are required to integrate abstract concepts related to microscopic cells and tissues with macroscopic plant functions, inquiry-based learning provides an appropriate pedagogical framework. By embedding inquiry activities within the e-module, students are guided to explore relationships between structure and function, test their understanding through formative assessments, and reflect on feedback, all of which support meaningful learning processes.

These findings reinforce and extend previous research on the effectiveness of digital and inquiry-oriented learning tools. Studies across various disciplines have consistently shown that instructional tools developed through systematic design processes can significantly enhance student learning outcomes (Brown et al., 2024; Kerimbayeva et al., 2024; Reen et al., 2024; Suryani et al., 2024; Yeşilyurt, 2024). In biology education specifically, e-modules and multimedia-based instructional materials have been found to facilitate conceptual understanding by providing visual representations and interactive learning experiences that are difficult to achieve through traditional instruction alone (Miftakhurrohmah et al., 2023; Syahmani et al., 2022). The present study contributes to this body of literature by demonstrating that the effectiveness of e-modules is substantially strengthened when digital features are integrated with inquiry-based pedagogical strategies rather than used as stand-alone technological enhancements.

More importantly, the integration of inquiry-oriented pedagogy within digital learning environments reshapes how students cognitively engage with biological content. Inquiry-based e-modules do not merely present information but actively structure learning experiences around questioning, exploration, hypothesis formulation, and evidence-based reasoning. Prior studies have emphasized that such pedagogical integration is essential for transforming digital tools from passive content delivery systems into active learning environments that promote deeper conceptual processing and critical thinking (Sari et al., 2020; Noris et al., 2023). When inquiry principles are embedded into the design of e-modules, students are guided to construct knowledge through systematic investigation rather than memorization, thereby fostering more durable and transferable understanding. This pedagogical dimension distinguishes inquiry-based e-modules from conventional multimedia resources and helps explain the substantial learning gains observed in the present study.

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The topic of plant structure and development presents particular instructional challenges that further highlight the significance of the present findings. Plant cells and tissues involve microscopic structures, specialized terminology, and complex functional relationships that often lead to misconceptions when taught through lecture-based methods. Prior research has documented that multimedia-based e-modules can improve learning outcomes in biology by 30% to 83% compared to traditional instructional approaches (Cahyani et al., 2020; Jafnihirda et al., 2023; Mutmainnah et al., 2021; Nisa et al., 2020). While these studies underscore the general effectiveness of e-modules, they often emphasize technological affordances, such as animations and videos, without sufficiently addressing pedagogical integration. The present study goes beyond this by showing that inquiry-based design principles embedded within the e-module play a critical role in helping students move beyond rote memorization toward conceptual understanding.

A particularly important contribution of this study is its demonstration of how inquiry-based e-modules can support learning independence. The self-instructional nature of the e-module allows students to regulate their learning pace, revisit difficult concepts, and engage in repeated practice without external pressure. This aligns with findings from previous studies indicating that learner autonomy and self-regulated learning are key factors in improving learning outcomes in digital environments (Miftakhurrohmah et al., 2023; Yeşilyurt, 2024). The inclusion of interactive quizzes and immediate feedback mechanisms further strengthens this effect by enabling students to identify misconceptions and correct errors independently, thereby reinforcing conceptual understanding and promoting metacognitive awareness.

From a practical instructional perspective, the findings suggest that inquiry-based e-modules can address several persistent challenges in biology classrooms. Traditional instruction often relies heavily on verbal explanations and static images, which may be insufficient for conveying the dynamic and spatial nature of plant structures. The interactive and multimedia-rich design of the e-module developed in this study offers an alternative that supports diverse learning styles and increases student engagement. This is consistent with earlier studies reporting that interactive digital learning tools enhance student participation and motivation, leading to more effective learning experiences (Reen et al., 2024; Suryani et al., 2024). For teachers, the use of e-modules can reduce instructional workload related to content delivery and assessment, allowing more time to focus on facilitating inquiry processes and addressing students' conceptual difficulties.

Beyond immediate classroom applications, the findings of this study have broader implications for curriculum development and educational innovation. The integration of inquiry-based e-modules into the curriculum supports flexible and adaptive learning models that can accommodate diverse learner needs. Digital modules enable curriculum designers to organize content dynamically, incorporate formative assessments seamlessly, and align instructional activities with competency-based learning objectives. Previous research has highlighted the importance of aligning digital learning tools with curriculum goals to maximize their instructional impact (Reiser et al., 2024; Yeşilyurt, 2024). The present study contributes empirical evidence supporting the inclusion of inquiry-based digital modules as integral components of secondary biology curricula rather than as supplementary resources.

The relevance of these findings extends beyond the local context of this study and contributes to global discussions on educational equity and innovation. Many educational systems, particularly in developing regions, face challenges related to limited laboratory facilities, insufficient instructional materials, and disparities in teacher preparedness for technology integration. Inquiry-based e-modules offer a scalable and adaptable solution that can help mitigate these challenges by providing access to high-quality learning resources without requiring extensive physical infrastructure. Similar arguments have been advanced in prior studies emphasizing the role of digital learning tools in expanding access to quality education and supporting instructional improvement in resource-limited settings (Kerimbayeva et al., 2024; Reiser et al., 2024; Yeşilyurt, 2024). In this sense, the present study contributes to the global discourse on how digital and inquiry-oriented pedagogies can support more inclusive and effective science education.

The global implications of this study are also evident in its alignment with international educational priorities that emphasize the development of 21st-century skills. Inquiry-based digital learning environments encourage students to engage in critical thinking, problem-solving, and self-directed learning, competencies that are increasingly recognized as essential for participation in contemporary knowledge societies. By integrating inquiry-based learning within an e-module format, this study demonstrates how digital tools can be used not only to transmit content, but also to cultivate higher-order cognitive skills that are relevant across educational contexts worldwide (Brown et al., 2024; Reen et al., 2024). These findings underscore the potential of inquiry-based e-modules to contribute to broader educational reforms aimed at enhancing learning quality and relevance in the digital era.

Despite the contributions of this study, several limitations must be acknowledged. The development and implementation of the inquiry-based e-module were constrained by technological infrastructure and access to digital devices, which may limit the generalizability of the findings to contexts with adequate technological support. In addition, the study involved a limited number of schools and participants, and the duration of the implementation was relatively short, restricting conclusions about long-term learning effects and sustainability. The development of high-quality e-modules also requires substantial time, technical expertise, and financial resources, which can pose challenges for large-scale adoption, particularly in under-resourced educational settings. These limitations should be taken into account when interpreting the findings and highlight the need for continued research and refinement of inquiry-based e-module development.

D. Conclusion

This study demonstrates that the inquiry-based interactive e-module developed through a systematic Research and Development approach constitutes an effective learning resource for improving senior high school students' understanding of plant structure and tissue. By integrating inquiry-oriented learning processes with interactive digital features, the e-module addresses persistent conceptual difficulties associated with abstract biological content, particularly at the level of plant cells and tissues. The synthesis of development validation and experimental findings confirms that the e-module is not only technically feasible, but also pedagogically effective when applied in both classroom-based and online learning contexts.

From an academic standpoint, this study contributes to biology education research by reinforcing the importance of pedagogical alignment in digital learning innovation. The findings indicate that the instructional effectiveness of e-modules does not primarily depend on multimedia elements alone, but on the extent to which these elements are embedded within inquiry-based learning structures that actively engage students in exploration, reasoning, and reflection. This contribution strengthens the growing body of evidence that technology-enhanced learning must be guided by sound pedagogical principles to produce meaningful and sustainable learning outcomes.

In practical terms, the inquiry-based e-module offers a flexible instructional alternative that supports independent and self-paced learning while complementing classroom instruction. Its interactive design enables students to revisit complex concepts and receive immediate feedback, while assisting teachers in organizing learning activities and assessments more efficiently. These characteristics make the e-module particularly relevant for educational settings with limited laboratory facilities or learning resources, as well as for schools transitioning toward blended or digitally supported instruction.

Based on the findings and the limitations discussed earlier, future research should focus on extending the implementation of inquiry-based e-modules to broader educational contexts and larger student populations to examine scalability and generalizability. Longitudinal investigations are also needed to explore the sustainability of learning gains over time. In addition, further studies should adapt the inquiry-based e-module design to other biology topics or scientific disciplines and examine strategies for optimizing implementation in contexts with varying levels of technological readiness.

This study affirms that inquiry-based e-modules, when pedagogically designed and contextually implemented, represent a viable and impactful pathway for enhancing conceptual understanding in biology education and for supporting more active, independent, and meaningful student learning in the digital era.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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