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SIKAT: A Scratch-Based Interactive Multimedia for Enhancing Plant Anatomy Learning in Elementary Science Education

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Abstract: Science education in Indonesian elementary schools faces significant challenges, particularly in teaching abstract concepts such as plant anatomy. Students often struggle to visualize internal structures like xylem and phloem tissues, requiring multimodal representations to facilitate conceptual understanding. This study developed and evaluated SIKAT (Sistem Interaktif Kenali Anatomi Tumbuhan), a Scratch-based interactive multimedia learning platform featuring 3D animations, physiological simulations, and adaptive assessment for fourth-grade students. Employing the Borg and Gall Research and Development model with quasi-experimental nonequivalent control group design, this study involved 150 fourth-grade students from five elementary schools in Ngaringan District, Grobogan Regency, Central Java. The experimental group (n=60) received instruction using SIKAT, while the control group (n=90) received conventional instruction. Expert validation yielded exceptionally high scores: content validity 95.5%, media quality 95.7%, and language quality 93.3%, all categorized as "highly valid." Practicality testing demonstrated strong user acceptance, with teachers rating 96.7% and students 96.2%. Effectiveness evaluation revealed substantial learning gains: the experimental group achieved mean posttest score of 85.90 with 100% mastery compared to control group's 72.40 with 66% mastery. Independent Sample t-Test showed $t=8.742$ ($p<0.001$), N-Gain of 0.62 (moderate) versus 0.24 (low), and Cohen's d effect size of 1.56 indicating very large practical significance. These findings confirm SIKAT as a highly effective solution for enhancing plant anatomy understanding in resource-constrained educational contexts.

Keywords: 3D animation, elementary science, interactive multimedia, IPAS, plant anatomy, Scratch platform, SIKAT

1. Introduction

1.1 Background of Study

Science education at the elementary school level serves as a crucial foundation for developing students' scientific literacy, especially in facing the challenges of the industrial revolution 4.0 era that demands critical thinking abilities and technological adaptation (Kusumaningtyas et al,, 2025); Heriyanto et al., 2019). The demands of 21st-century education expect learners to master literacy skills, including science literacy, which is one of the keys to facing global challenges (Kusumaningtyas et al., 2025). However, learning abstract materials such as plant anatomy often faces significant

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obstacles, where students struggle to visualize internal structures like xylem and phloem tissues, requiring multimodal representations to facilitate conceptual understanding (Gafur et al., 2023; Vydra & Kováčik, 2024).

Research by Gafur et al. (2023) confirms that abstract biology topics, including plant anatomy and cell structure, pose significant challenges for students due to the lack of visual literacy training. The Programme for International Student Assessment (PISA) 2022 results show that Indonesia's science literacy ranks 69th out of 81 countries, with an average score of 383, substantially lower than the OECD average of 485 (OECD, 2023; Bilad et al., 2024). This condition reflects systemic problems in national science education, where students often experience difficulty integrating conceptual knowledge with practical applications (Bilad et al., 2024).

The theoretical foundation of this research is built upon several interconnected learning theories. First, Mayer's (2024) updated Cognitive Theory of Multimedia Learning posits that people learn more deeply from words and pictures than from words alone, emphasizing the integration of text, images, animation, and audio narration to reduce cognitive load. Castro-Alonso et al. (2021) provides practical strategies for optimizing instructional materials based on cognitive load principles. Second, Sweller's (2011) Cognitive Load Theory suggests that dynamic visual stimulation through 3D animation activates the fusiform gyrus area up to 40% higher than static images, thereby reducing extraneous cognitive load and facilitating schema construction. Wang et al. (2024) demonstrated that educational animations with appropriate textual cues significantly improve science learning outcomes among elementary students.

Third, Piaget's (1952) cognitive development theory indicates that fourth-grade students (ages 10-11) are in the concrete operational stage, requiring explicit visual representations to understand abstract concepts. Fourth, gamification theory (Deterding et al., 2011) explains that integrating game elements such as points, challenges, and immediate feedback into educational contexts can increase intrinsic motivation and engagement. Meta-analyses by Diaz and Estoque-Loñez (2024), Casillas-Martín et al. (2024), and Zeng (2024) confirm the positive effects of gamification on student learning achievement and academic performance.

The Universal Design for Learning (UDL) framework guides the development of SIKAT to accommodate various learning styles. Multiple means of representation are provided through 3D animations, audio narration, and interactive text. Multiple means of engagement are facilitated through gamified activities and exploratory learning. Multiple means of expression are supported through varied assessment formats including quizzes and interactive exercises. Research by Vydra and Kováčik (2024) on visual plant anatomy education and Möller et al. (2024) on measuring plant awareness provide additional theoretical support for the importance of visualization in biology education.

1.2 Problem statement

Transitioning to the local context, these challenges become more acute in semi-urban areas like Grobogan Regency, Central Java, where science education infrastructure does not fully support interactive learning. Research indicates that rural and semi-urban schools face unique challenges in integrating digital resources for science education (Muhaimin et al., 2020; Stephen, 2024). Initial observations conducted by researchers at 15 elementary schools in this region revealed that 78% of fourth-grade classes still rely on conventional methods such as lectures and textbooks, which are less effective for abstract materials. Comparative studies have demonstrated that traditional lecture-based methods are less effective than interactive approaches for teaching abstract science concepts (Dagnew, 2023; Wang, 2023).

Furthermore, recapitulation of teacher observation results at three state elementary schools in Ngaringan District showed an overall average score of 36.7 out of a maximum scale of 80, with a percentage of 45.9% categorized as "fairly good." In the learning implementation aspect, the use of interactive/digital media and plant anatomy practicum demonstrations received the lowest score of 1.3, classified as "very poor," indicating heavy dependence on passive approaches.

Analysis of previous research identifies several research gaps that need to be filled. First, most research on interactive multimedia for science learning focuses on upper elementary or secondary levels, while development specifically for fourth-grade students with unique cognitive characteristics remains limited (Nelwideri et al., 2025; Sartono et al., 2022). Second, research that explicitly integrates 3D visualization with gamification elements in plant anatomy learning is still rarely conducted. Studies have shown that 3D animation media significantly improves learning outcomes and higher-order thinking skills in elementary students (Sari et al., 2024; Putri & Rohmani, 2024; Teplá & Teplý, 2022). Third, research contexts are mostly conducted in urban areas with relatively good infrastructure, while research in semi-urban settings like Grobogan Regency facing typical infrastructure and resource constraints remains underrepresented (Chen, 2025; Muhaimin et al., 2020).

1.3 Research Objectives

This study aims to address these gaps by developing and validating SIKAT (Sistem Interaktif Kenali Anatomi Tumbuhan), an interactive multimedia platform featuring 3D animations, physiological simulations, and adaptive assessment to improve plant anatomy learning outcomes. Specifically, the objectives of this study include the following:

a. To analyze the needs for developing SIKAT interactive multimedia on IPAS subjects for fourth-grade elementary students in Grobogan Regency.
b. To design and develop SIKAT that meets validity, practicality, and effectiveness criteria.

c. To evaluate the validity of SIKAT based on expert assessment of content, media, and language aspects.
d. To test the effectiveness of SIKAT in improving student learning outcomes on plant anatomy material compared to conventional instruction.

1.4 Significance of the Study

This study provides a comprehensive analysis of interactive multimedia development for elementary science education, deepening understanding of how Scratch-based platforms can address learning challenges in resource-constrained contexts. It introduces a multidimensional framework that includes 3D visualization, gamification, and adaptive assessment, enhancing existing multimedia learning theories and laying a foundation for future research on educational technology in semi-urban Indonesian schools.

Practically, the study addresses challenges faced by elementary teachers in teaching abstract plant anatomy concepts, offering actionable strategies for educators and policymakers. It suggests solutions based on interactive multimedia integration, visual learning approaches, and gamified engagement, and highlights how accessible platforms like Scratch can boost the effectiveness of science instruction in schools with limited technological infrastructure.

2. Methodology

This study follows the Borg and Gall Research and Development model (Fig. 1) to ensure a systematic and rigorous development process. The aim is to develop and validate SIKAT interactive multimedia for improving plant anatomy learning outcomes among fourth-grade elementary students.

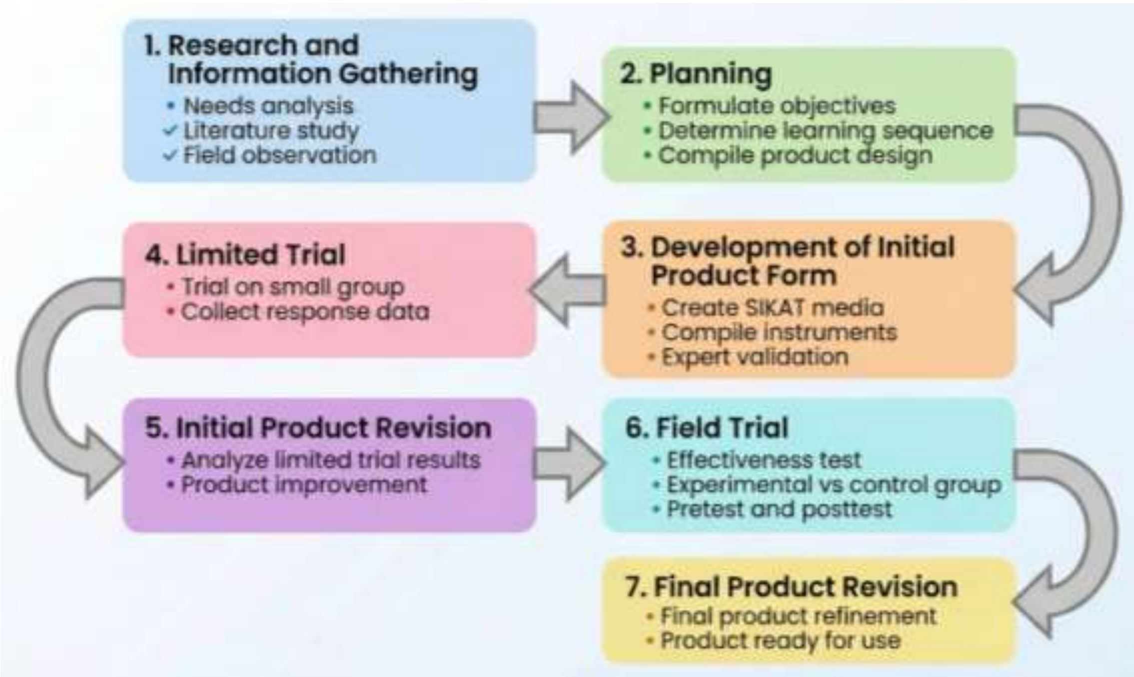

Figure 1: Development stages of the modified Borg and Gall model

2.1 Research Design

This study employed the Borg and Gall Research and Development model modified into seven stages: (1) research and information collection, (2) planning, (3) initial product development, (4) limited trial, (5) initial product revision, (6) field trial, and (7) final product revision. For effectiveness testing, a quasi-experimental non-equivalent control group design was implemented.

2.2 Respondents

The study involved 150 fourth-grade students from five elementary schools in Ngaringan District, Grobogan Regency. The experimental group consisted of 60 students from two schools (SDN 4 Truwolu and SDN 3 Tanjungharjo) who received instruction using SIKAT. The control group consisted of 90 students from three schools (SDN 1 Ngaringan, SDN 2 Ngaringan, and SDN 3 Ngaringan) who received conventional instruction. For validation, six expert validators were involved: two content experts, two media experts, and two language experts, all doctoral-level lecturers from Universitas Muria Kudus.

2.3 Product Description

SIKAT was developed using Scratch 3.0 platform as a web-based interactive application accessible through modern browsers without special installation. The media structure consists of four main modules: Material Module presenting plant anatomy content through 3D animations covering vegetative parts (roots, stems, leaves) and reproductive parts (flowers, fruits, seeds); Practice Module providing interactive exercises with automatic feedback; Quiz Module for formative assessment; and Game Mode "Plant Rescue" integrating game mechanics with educational content through a point and life system.

2.4 Instruments

Four types of instruments were used: (1) expert validation questionnaires with 4-point Likert scale assessing content validity (13 indicators), media quality (26 indicators), and language quality (15 indicators); (2) practicality questionnaires for teachers (20 items) and students (20 items); (3) learning outcome tests consisting of multiple choice and short answer questions covering plant anatomy competencies; and (4) observation guidelines for learning process documentation.

2.5 Data Analysis

Validity and practicality data were analyzed using percentage formulas with criteria: 81-100% (Very Valid/Practical), 61-80% (Valid/Practical), 41-60% (Fairly Valid/Practical), 21-40% (Less Valid/Practical), 0-20% (Not Valid/Practical). Effectiveness was analyzed through: (1) descriptive statistics comparing pretest-posttest scores; (2) normality testing using Shapiro-Wilk; (3) homogeneity testing using Levene's test; (4) Independent Sample t-test for hypothesis testing; (5) N-Gain analysis using Hake's formula with criteria: $g \geq 0.70$ (High), $0.30 \leq g < 0.70$ (Medium), $g < 0.30$ (Low); and (6) effect size using Cohen's d with criteria: $d < 0.2$ (small), $0.2 \leq d < 0.8$ (medium), $d \geq 0.8$ (large).

3. Results

3.1 Needs Analysis Findings

Observations at three elementary schools revealed that learning implementation was dominated by conventional methods. Teachers tended to use lectures, textbooks, and simple visual displays. The use of technology-based media and interactivity was very low, with an average score of 1.3 (category "Very Poor") for digital media usage. Student activity in learning also tended to be less active and participatory, as reflected in the average activeness score of 2.3 ("Fairly Good") and generally low learning interest. Interviews with teachers confirmed that the main obstacles lay in the abstraction of plant anatomy material, limited teaching aids, and minimal interactive digital media. More than 70% of students were unable to correctly explain plant structure details based on evaluation results shown in Table 1.

Table 1: Summary of learning observation results at SDN Ngaringan district

Aspect	Average Score	Max Score	Percentage	Category
Learning Preparation	12.3	20	61.5%	Fairly Good
Learning Implementation	10.7	24	44.6%	Fairly Good
Digital Media Usage	1.3	4	32.5%	Very Poor
Material Mastery	7.3	16	45.6%	Fairly Good
Learning Evaluation	5.3	16	33.1%	Poor
Overall	**36.7**	**80**	**45.9%**	**Fairly Good**

3.2 Validity Testing Results

Expert validation yielded exceptionally high scores across all aspects. Table 2 presents the validation results.

Table 2: Recapitulation of expert validation results

Validator Type	Validator 1	Validator 2	Average	Category
Content Expert	96.2%	94.8%	95.5%	Very Valid
Media Expert	96.2%	95.2%	95.7%	Very Valid
Language Expert	93.8%	92.9%	93.3%	Very Valid
Overall Average	-	-	**94.8%**	**Very Valid**

Content experts gave maximum scores (4.0) on four crucial indicators: alignment with IPAS Learning Outcomes of Merdeka Curriculum Grade IV, accuracy of plant anatomy concepts, clarity of material presentation, and completeness of material covering all plant parts from roots to seeds. Media experts appreciated the ease of navigation and consistency of button placement with perfect scores of 4.0. The 3D animation quality received special appreciation, with Validator 1 stating that "3D animations are high quality and detailed."

3.3 Practicality Testing Results

Table 3 presents practicality test results from teachers and students.

Table 3: Recapitulation of practicality test results

Respondent	N	Percentage	Category
Teachers	6	96.7%	Very Practical
Students	60	96.2%	Very Practical
Overall	**66**	**96.5%**	**Very Practical**

Teachers gave very positive responses with 94.2% on ease of use. All teachers stated that media usage instructions were very clear (100%), allowing them to operate SIKAT without intensive technical training. Time efficiency received the highest appreciation at 97.2%, where all teachers stated that the media saved teaching preparation time (100%) and accelerated material delivery (100%). One teacher commented, "This media really helps me explain plant parts that are difficult. Students become more enthusiastic and actively ask questions."

3.4 Effectiveness Testing Results

Table 4 presents learning outcome comparison between experimental and control groups.

Table 4: Comparison of learning outcome statistics

Indicator	Experimental (n=60)	Control (n=90)	Difference
Pretest Mean	62.53	61.80	0.73
Posttest Mean	85.90	72.40	13.50
Mean Increase	+23.37	+10.60	+12.77
Mastery Rate	100%	66%	+34%
N-Gain	0.62	0.24	0.38
N-Gain Category	Moderate	Low	-

The experimental group achieved a mean post-test score of 85.90 with 100% mastery, while the control group achieved only 72.40 with 66% mastery. Prerequisite tests showed all data were normally distributed (Shapiro-Wilk, $p>0.05$) and variances were homogeneous (Levene's test, $p>0.05$). Independent Sample t-test revealed t-value of 8.742 with significance $p=0.000$ ($p<0.05$), confirming significant differences between groups. The experimental group demonstrated N-Gain of 0.62 (moderate category), substantially higher than the control group's N-Gain of 0.24 (low category).

Effect size analysis using Cohen's d yielded a value of 1.56, categorized as "Very Large Effect" ($d>0.8$). This means that the average student in the experimental group performed better than 94% of students in the control group, demonstrating the substantial practical significance of SIKAT implementation.

4. Discussion and Implications

Under the backdrop of educational technology integration, the development of SIKAT demonstrates how Scratch-based interactive multimedia can effectively address learning challenges in elementary science education. Analysis reveals that the combination of 3D visualization, gamification, and adaptive assessment creates a powerful learning environment for abstract concepts like plant anatomy. Fig. 2 shows a home screen of SIKAT.

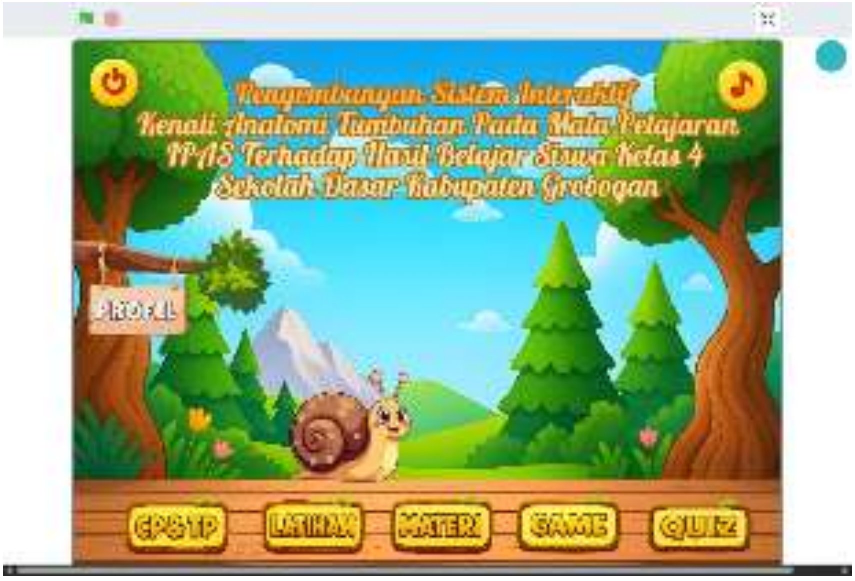

Figure 2: Home screen SIKAT

4.1 Cognitive Mechanism through Multimedia Learning

The effectiveness of SIKAT can be explained through the cognitive mechanism of multimedia learning principles. SIKAT integrates 3D animations, audio narration, and interactive text following Mayer's (2024) updated cognitive theory of multimedia learning for reducing extraneous cognitive load. The dynamic visualization of internal plant structures like xylem and phloem, which are impossible to observe directly, provides concrete representations that facilitate schema construction in students' long-term memory. This approach aligns with recent findings by Wang et al. (2024) demonstrating that educational animations significantly improve science learning outcomes among elementary students.

4.2 Motivational Mechanism through Gamification

The "Plant Rescue" game mode creates intrinsic motivation by combining challenge, curiosity, and immediate feedback. Students experience learning as play, reducing anxiety associated with science learning while maintaining engagement throughout the lesson. This aligns with meta-analyses by Diaz and Estoque-Loñez (2024) and Zeng (2024) showing positive effects of gamification on student learning achievement and academic performance. Hassan et al. (2024) further confirmed that gamification significantly enhances elementary students' motivations.

4.3 Contextual Mechanism through Adaptive Design

SIKAT was developed considering the specific constraints of semi-urban schools in Grobogan, including limited technology infrastructure and varying teacher digital competencies. The web-based Scratch platform requires no installation and runs on basic computer specifications, ensuring accessibility across diverse school contexts. Research by Belessova et al. (2024) demonstrated that Scratch-based learning significantly improves student engagement and academic performance in primary schools. This contextual appropriateness contributes to the high practicality ratings from both teachers (96.7%) and students (96.2%).

4.4 Effect Size Analysis

The effect size of 1.56 substantially exceeds typical findings in educational technology research. Meta-analyses by Sung et al. (2016) reported average effect sizes of 0.47 for mobile learning interventions, while Tokac et al. (2019) found effect sizes around 0.35 for game-based learning. Kraft (2020) provides guidelines for interpreting such effect sizes in educational interventions, confirming that d=1.56 represents exceptional practical significance. The superior effectiveness of SIKAT may be attributed to its comprehensive integration of multiple evidence-based strategies: 3D visualization for abstract concepts as supported by Vydra and Kováčik (2024), gamification for motivation, adaptive assessment for personalized feedback, and contextual design for implementation feasibility.

4.5 Challenges and Opportunities

The research reveals that while SIKAT demonstrates exceptional effectiveness, implementation in resource-constrained contexts requires careful consideration of infrastructure limitations. The Scratch platform's accessibility addresses many technological barriers, but teacher training and ongoing support remain essential for sustainable implementation. Future opportunities include expansion to other abstract science topics and adaptation for students with diverse learning needs.

5. Conclusion

Based on the research findings, several conclusions can be drawn. First, needs analysis identified fundamental gaps in plant anatomy instruction, with 78% of classes relying on conventional methods and digital media usage scoring only 1.3 ("Very Poor"), confirming urgent need for interactive multimedia solutions. Second, SIKAT was successfully developed as an interactive multimedia platform featuring 3D animations of plant structures, physiological simulations, adaptive quizzes, and gamified learning through the "Plant Rescue" game mode, all accessible via web-based Scratch platform. Third, SIKAT demonstrated excellent quality across all evaluation dimensions: content validity 95.5%, media quality 95.7%, and language quality 93.3% (all "Very Valid"); practicality ratings of 96.7% from teachers and 96.2% from students (both "Very Practical"). Fourth, SIKAT proved highly effective in improving learning outcomes, with the experimental group achieving 100% mastery (mean 85.90) compared to control group's 66% mastery (mean 72.40), N-Gain of 0.62 versus 0.24, and Cohen's d effect size of 1.56 indicating that average experimental students outperformed 94% of control students.

For future research, several recommendations are proposed: (1) expansion to other abstract science topics such as human body systems, ecosystems, and earth science; (2) longitudinal studies to assess retention and transfer of learning; (3) comparative studies with other multimedia platforms to identify optimal design features; (4) investigation of implementation models for teacher professional development; and (5) adaptation for students with special learning needs following Universal Design for Learning principles.

For practitioners, SIKAT is recommended as an evidence-based solution for teaching plant anatomy in elementary schools, particularly in contexts with limited resources. For policymakers, these findings support investment in interactive multimedia development as a cost-effective strategy for improving science education quality, with potential savings of Rp 375 million for teaching aid procurement across 50 schools over five years.

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Conflict of Interest

The author declare there is no conflict of interest.

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