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Research Article

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GrowLab: The effect of augmented reality-based learning on secondary school students' critical thinking skills in plant structure instruction

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ABSTRACT

Plant growth is fundamental to understanding biological systems, particularly at the secondary school level. Learning about plant structure is a crucial component of biology education; however, many students find this topic challenging because it is often perceived as abstract. Augmented Reality (AR) technology offers an opportunity to enhance learning experiences by enabling interactive three-dimensional visualizations of plant structures. This study investigates the effect of AR-based GrowLab learning on students' critical thinking skills in the context of plant structure instruction. A quasi-experimental design was employed involving 142 Grade XII secondary school students in Malang. Critical thinking skills were assessed using essay-based test instruments. Data were analyzed using an ANCOVA test with SPSS version 29. The results indicated that AR-based GrowLab learning had a significant effect on students' critical thinking skills in teaching plant structure (sig < 0.05). The study concludes that AR positively affected learning, particularly in understanding plant growth and structure. Furthermore, the findings suggest that augmented reality should be integrated with pedagogical approaches such as problem-based learning (PBL) to maximize its effectiveness in enhancing students' critical thinking skills.

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INTRODUCTION

The structure of plant growth is important for students to learn. Learning about the structure of plant growth introduces students to the world of agriculture and biotechnology (Hubbard, 2024), which is relevant to current global issues. Understanding the material on the structure of plant growth fosters an understanding of the importance of plant conservation and the impact of environmental damage. Students may acquire a more profound comprehension of the biological processes that underlie life on Earth

(Onowugbeda et al., 2024), including respiration, transpiration, and photosynthesis, by comprehending the structure of plants. This understanding provides a basis for further investigation into plant functionality and development under diverse environmental conditions (Fiel'ardh et al., 2023). Moreover, comprehending plant growth structures educates students about the interdependent interaction between plants and their environment (Dauer et al., 2014), as well as the influence of external variables such as light, water, and nutrients on their growth. This offers pupils an expanded understanding of natural dynamics and the processes that underpin the sustainability of life on Earth.

Previous rstudies has demonstrated that augmented reality (AR) has the potential to improve students' cognitive engagement and reasoning abilities in biology education (Faria & Miranda, 2024; Sattar et al., 2025). AR-based applications enable students to visualize imperceptible biological processes, perform investigations, and develop scientific explanations-competencies that are integral to critical thinking skills. Alfiyanti et al., (2025) reported that problem-based learning incorporating augmented reality enhanced students' argumentation skills and problem-solving capabilities. Similarly, Liu et al., (2021) discovered that immersive visualization promotes more profound reasoning when examining biological phenomena. Although several studies demonstrate the role of AR in fostering higher-order thinking, there remains limited evidence explicitly addressing how GrowLab an AR application designed for studying plant growth structures, facilitates the enhancement of critical thinking skills among secondary school students.

Recent research shows that AR can improve learning (Baxter & Hainey, 2024; Hafizi, 2024). However, although many studies discuss AR in education, its application in plant growth structures is still limited. Therefore, this study reveals the effect of AR on plant growth structures, especially in secondary school students. The study of plant growth structure and processes is a crucial component of the secondary school biology curriculum. This topic is frequently seen as abstract and challenging for students to comprehend due to insufficient imagery and a lack of practical experience in the sector. Biology learning is often characterized by low student interest, which negatively affects engagement and achievement (Hidayaty et al., 2022). This adversely affects students' limited intellectual comprehension and enthusiasm for studying biology. Learning about plant growth structures provides scientific insights and enhances skills. We train students to design experiments, solve problems related to plant growth, and collaborate in groups to develop innovative solutions. These skills are crucial for structuring them to face global challenges.

Several studies have shown that Augmented Reality (AR) can help students learn science, especially biology, by making them more interested and helping them understand. For instance, Syawaludin et al., (2019) found that AR helps students better understand abstract ideas, which leads to better learning outcomes. Research suggests that augmented reality (AR) has been extensively employed in biology education, particularly in the context of topics such as viruses, cells, the human skeletal system, and the human digestive system (Indrati & Masing, 2025). Nevertheless, its application in the context of plant growth remains restricted, indicating that there is a key gap that must be addressed. The Problem-Based Learning (PBL) method has also been used a lot to help people think more deeply and solve problems (Tanna et al., 2022). But there aren't many examples of AR and PBL being used together in one learning design, especially when it comes to learning about plant growth in secondary school.

Certain studies primarily concentrate on the utilization of AR as a content visualization instrument (Turhan et al., 2022), neglecting to integrate the technology within a coherent pedagogical framework. In contrast, research on PBL frequently occurs without the aid of visual technology that can enhance students' conceptual comprehension. Conversely, although research exists on the cultivation of 21st century skills via problem-based learning/PBL (Suwastini et al., 2021). On the other hand, investigations into PBL sometimes transpire without the assistance of visual technologies that could augment students' conceptual understanding. Although PBL has demonstrated efficacy in fostering critical thinking, problem-solving, and self-directed learning, the lack of immersive and interactive tools like AR could limit students' capacity to solidify abstract concepts, especially in fields such as science and engineering where visualization is essential.

Additionally, prior research has typically been conducted in the context of general learning or macroscopic and visual subjects (Susilaningsih et al., 2018), such as ecosystems or organ systems. Research has not extensively investigated the application of ARPBL to microscopic and biological topics, such as plant structure and growth. These topics are inherently challenging for students to observe firsthand in the classroom. In reality, this subject is essential for the development of students' fundamental comprehension of plant science. This study investigates the effect of AR-based GrowLab learning on students' critical thinking skills in the context of plant structure instruction so can facilitate meaningful experiences that promote deeper reasoning, problem-solving, and scientific inquiry.

RESEARCH METHODS

This type of research is a quasi-experiment. The objective is to obtain an unbiased assessment of students' critical thinking skills, particularly in the context of biology education related to plant growth. We selected this methodology to assess students' proficiency in critical thinking skills without directly manipulating factors or implementing educational interventions. Before conducting the research, we presented the informed consent to the population who would participate in the study. The informed consent contained the objectives, data collection methods, and guarantees to keep personal data confidential.

The sample in this study was 142 high school students, namely 12th-grade students at a public high school in Malang, East Java, Indonesia. The sample was divided into two groups, namely control (CG) and experimental (EG). The control group consisted of two classes with a total of 72 students, each class having 36 students (CG1: 11 females, 25 males; CG2: 22 females, 14 males). The experimental group consisted of two classes with a total of 70 students, each class having 25 students (EG1: 32 females, 3 males; EG2: 25 females, 10 males). The control group used learning without AR, while the experimental group used AR integrated with PBL. In addition, two media experts and two experts in related fields were also involved in testing the validity of the media that had been developed, namely GrowLab.

Prior to conducting the quasi-experimental study, media development, such as GrowLab, had been conducted and deemed feasible by experts for implementation. GrowLab, a mobile learning medium based on Augmented Reality (AR), was the primary focus of the previous research. This medium is intended to enhance the critical thinking skills of learners by conducting experiments and studies on the growth and development of plants during biology class. By integrating AR technology, students can experience a more interactive and immersive learning environment, which allows them to visualize intricate biological concepts, such as the process of plant growth, in a virtual environment that is more easily comprehensible. The design of a user-friendly interface, intuitive AR programming, and the validation of learning content to ensure that it is in accordance with the current curriculum are all components of this development.

This quasi-experimental study is designed to assess the effect of the GrowLab learning media on improving students' critical thinking skills. The study will involve two groups of students: an experimental group using GrowLab for their learning and a control group following traditional learning methods. Analysis will be conducted on the results of critical thinking assessments and content comprehension to identify significant differences between the two groups. The results of this study are expected to provide empirical information regarding the impact of AR technology on improving students' critical thinking skills in biology education.

To collect data relevant to this study, we used a valid data collection instrument and administered pre- and post-tests to students to measure critical thinking skills. The critical thinking skills test consists of four essay questions based on Greenstein's critical thinking skills rubric (Greenstein, 2012). Data will be analyzed using the statistical program SPSS version 29. The methods used include descriptive analysis and inferential analysis using ANCOVA. This analysis was chosen to test the mean difference between the experimental and control groups while controlling for confounding variables that might influence the results.

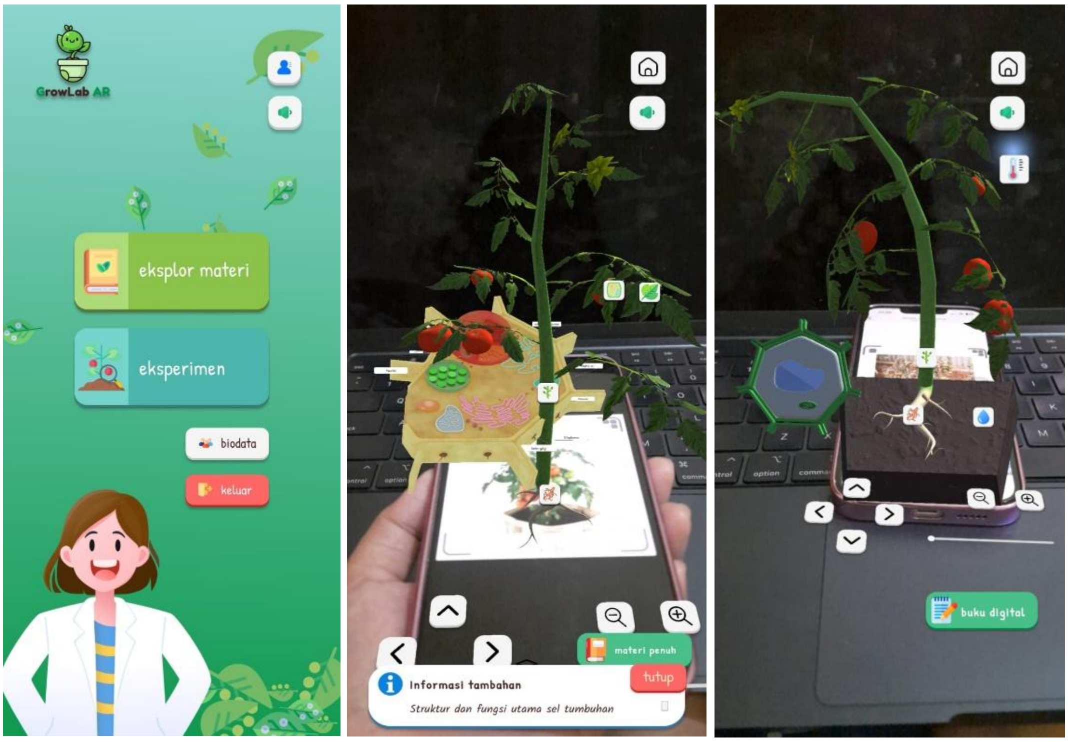
FINDING AND DISCUSSION

In previous research, we completed the development of an Augmented Reality (AR)-based mobile learning media called GrowLab. This media is designed to improve students' critical thinking skills in learning biology, especially regarding plant growth and development. The validity results by media experts showed a score of 98 with a reliability coefficient of 0.96. The material validity results showed a score of 100 with a reliability coefficient of 1. Reliability between scores of 0.81–1.00 is considered highly reliable (Cohen, 2018).

Figure 1a illustrates the main menu, featuring multiple options: "explore material," which presents various theories or instructional resources; "experiments," which enables users to conduct AR-based experimental simulations; "profile," which displays user profile information; and "exit," which terminates the application. Each menu features a distinct set of icons and colors to facilitate navigation for users. Figure 1b illustrates the utilization of the material investigation capability within the GrowLab AR application. Augmented Reality (AR) technology enables the visualization of information regarding the structure and fundamental functions of plant cells as realistic three-dimensional models on a mobile phone display. This image illustrates tomato plants and plant cells, featuring detailed and interactive representations of important organelles. Figure 1c illustrates the experimental characteristics of the GrowLab AR software, which employs augmented reality (AR) to display a three-dimensional model of a tomato plant on a smartphone screen. This mode allows users to examine the principal components of plants, including roots, stems, leaves, flowers, and fruits, in depth.

This enables them to simulate the cultivation of plants. Interactive icons surrounding the plant depict elements such as roots, water, temperature/thermometer, and plant cells. These icons represent the experimental settings, allowing users to modify or examine variables influencing plant growth, such as water availability, climatic conditions, and cellular morphology. The studies in GrowLab AR aim to elucidate the correlation between environmental variables and plant growth through an interactive approach. Augmented reality visualization enables the concrete representation of typically abstract biological processes, hence facilitating a more engaging and contextual learning experience.

Previous studies have shown that augmented reality (AR) can improve understanding of biological subjects. Augmented reality functions effectively as a visual aid, although it remains predominantly a tool rather than an integral component of the educational framework (Al-Ansi et al., 2023). Other studies show that AR helps students understand the relationship between cell structure, tissue, and plant organs more deeply than conventional media (Suprapto et al., 2024). Hernández-Ramos et al. (2021) highlight the importance of incorporating technology into problem-based learning (PBL) for developing 21st-century skills in line with this. Students can employ this knowledge to solve real-world problems in addition to comprehending plant structures visually when AR is integrated with PBL. This study indicates that the use of AR in teaching plant structures can overcome the limitations of traditional media while providing a more concrete, interactive, and meaningful learning experience.



A. B. C.

Figure 1. Display GrowLab
(A. Display in Material Menu; B. Display in Material Menu; C. Display in Experiments Menu)

In order to further illustrate this potential, the descriptive data from the study are presented. The descriptive data results are presented in Table 1. The first assumption test on the study data showed that the data was normally distributed, can we have seen in Table 2. This was shown by the normality test findings, which had a significance value of more than 0.05. The results of the variance homogeneity test also showed that the data between groups were homogeneous, as can be seen in Table 3, which meant that the criteria for variance equality were met.

Table 1. Mean and Standard Deviation Data of EG and CG

Model	Mean	Std. Deviation	N
EG	69.7101	20.17359	70
CG	60.3472	19.93310	72
Total	64.9291	20.52408	142

The data show a difference in the mean between the experimental group (69.71) and the control group (60.35). This difference indicates that the treatment in the experimental group tends to produce better results than the control group, which will be tested using ANCOVA. Previously, the data will be tested for normality and homogeneity.

Table 2. Normality Test Results

	Model	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Pretest Critical Thinking Skills	EG	.098	69	.100	.975	69	.179
	CG	.102	72	.063	.973	72	.124
Posttest Critical Thinking Skills	EG	.104	69	.061	.955	69	.014
	CG	.102	72	.059	.967	72	.057

Table 3. Homogeneity Test Results

		Levene Statistic	df1	df2	Sig.
Pretest Critical Thinking Skills	Based on Mean	.002	1	139	.968
	Based on Median	.000	1	139	.993
	Based on Median and with adjusted df	.000	1	138.963	.993
	Based on the trimmed mean	.001	1	139	.969
Postest Critical Thinking Skills	Based on Mean	.014	1	139	.907
	Based on Median	.011	1	139	.918
	Based on Median and with adjusted df	.011	1	138.965	.918
	Based on the trimmed mean	.017	1	139	.896

Furthermore, the results of the ANCOVA analysis show that there are significant differences between treatment groups after controlling for covariates. This indicates that the treatment given has a significant effect on the dependent variable, while still taking into account the influence of covariates. It suggests that the implementation of AR-based learning in the experimental group positively influenced the enhancement of students' critical thinking skills, irrespective of starting disparities in pretest scores. These results align with Dilviana et al., (2025), who reported that AR enhances PBL processes and facilitates analytical thinking in biology learning. These data validate the efficacy of the administered treatment, corroborating its influence on the students' performance in the posttest. The result of ANCOVA can be seen in Table 4.

Table 4. The Result of ANCOVA Test

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	12486.911[a]	2	6243.455	18.534	<.001
Intercept	31160.238	1	31160.238	92.503	<.001
Pre	9398.142	1	9398.142	27.899	<.001
Model	2954.634	1	2954.634	8.771	.004
Error	46486.380	138	336.858		
Total	653399.000	141			
Corrected Total	58973.291	140			

This study indicates that the use of AR in teaching plant structures can overcome the limitations of traditional media while providing a more concrete, interactive, and meaningful learning experience. This aligns with study findings indicating that augmented reality can assist with complicated and abstract concepts (Mansour et al., 2025; Siki & Leba, 2025). Previous research shows that learning designs integrating AR can improve learning (Farooq et al., 2022; Hafizi, 2024; Liono et al., 2021). AR technology enhances learning by integrating digital elements such as audio, visuals, and animations with the physical environment (Dargan et al., 2023). This enhances student involvement, stimulates their curiosity, and motivates them to learn. AR enables the visual representation of intricate concepts, such as cellular architecture or physical occurrences, in a more engaging and comprehensible format. Previously abstract learning content can now be visualized in three dimensions, enhancing students' comprehension. Moreover, AR enhances the relevance and contextuality of learning by allowing educational materials to be customized to real-world scenarios (Ruangsan, 2025), such as utilizing topographic maps or digitally experiencing historical events.

The technology promotes collaborative learning, wherein students collectively engage in problem-solving or experiential learning activities. This enhances their social and analytical thinking abilities. AR facilitates diverse learning modalities (Ngo & Vo, 2025), allowing students to engage in the methods that are most effective for them. Augmented reality facilitates autonomous learning for students, enabling them to engage with educational resources at their convenience and from any location. This facilitates a more profound comprehension of the content.

CONCLUSION

Based on the results of the study, it was found that GrowLab, as an AR application used in teaching plant growth structures, has an effect on students' critical thinking skills (sig < 0,05). The study's conclusion indicates that students' 21st-century capabilities in biology, particularly regarding plant growth, require significant improvement, notably in critical thinking skills. These skills are essential for conducting comprehensive analyses and resolving issues within the realm of learning science. A learning design incorporating Augmented Reality (AR) technology and the Problem-Based Learning (PBL) methodology is proposed as an effective solution to the issue. Incorporating smartphones into an AR-PBL classroom design enhances interactivity and real-world relevance in education. This assists pupils in cultivating the problem-solving and critical thinking essential for the 21st century.

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