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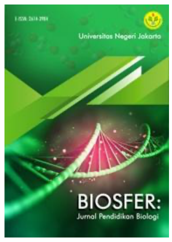

A Meta-analysis: Trends in the use of augmented reality in biology learning (2016-2025)

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ABSTRACT

Augmented reality, which can visualize abstract concept especially in biology education has made these concepts more tangible, engaging, and easier to understand in biology education. This study employs a mixed-method meta-analysis approach (qualitative and quantitative) to examine the trends in the use of augmented reality in biology education from 2016 to 2025. A total of 35 articles were selected from 100 reviewed, based on inclusion criteria guided by the PRISMA protocol. The qualitative analysis was conducted by examining the thematic trends of the articles, while the quantitative analysis was carried out through effect size calculations. Research and Development (37%) and quasi-experiments (34%). The studies were predominantly conducted in the Java region, particularly West Java and East Java, indicating that there is still a technological gap between regions in Indonesia. The most frequently studied variables included concept understanding and learning outcomes (each with 7 articles) and learning motivation (6 articles). Quantitative analysis of 6 articles showed an average effect size of 2.249, which falls into the very high category.

INTRODUCTION

The field of education is currently experiencing rapid development, which is in line with the advancement of science and technology that supports many innovations in learning. The era of the 4.0 industrial revolution is marked by the development of the internet, automation, and the internet of things, thereby forming new habits in all aspects, including in the field of education (Patandung & Panggua, 2022). Advancements in science and technology have created numerous opportunities for innovation and the development of new products, such as learning methods or learning tools (Saputra et al., 2017). One such product emerging from these advancements is digital learning media (Dewi & Harini, 2021). Digital media serves as a tool for delivering content and engaging students' interest in learning. These digital-based examples can take the form of electronic media, such as, e-books, websites, e-modules, flash, interactive multimedia CDs, and others (Sitepu, 2022).

Digital learning media that is currently being developed and implemented is augmented reality. Augmented reality changes the paradigm in learning, especially in understanding abstract biological concepts, making them clearer (Mustaqim, 2016). Augmented reality provides a more interactive learning experience and allows students to "see" and "feel" the material directly (Khanan & Wardhani, 2024). The solutions offered by augmented reality are highly innovative, transforming learning into a more practical and interactive experience. Students can use real-time 3D visual representations with the help of augmented reality (Schmidthaler et al., 2023).

The application of augmented reality in biology education in Indonesia has shown significant progress, but it still faces various challenges. Limited educational facilities, including the lack of augmented reality support devices and inadequate internet access in various regions, are the primary obstacles to its utilization. In addition, the lack of training for educators in operating augmented reality-based technology also reduces its effectiveness in the classroom. Similar challenges were identified in a systematic study that highlighted the main barriers to the implementation of augmented reality in biology education, including limited access, availability of hardware, costs, training, and adaptation to distance learning conditions (Azzahra et al., 2024). Another issue is that many students still struggle to understand abstract biological concepts, such as physiological mechanisms, microscopic structures, and ecosystem interactions. One challenge in learning is the low engagement of students with complex science material; augmented reality can enhance engagement, but will only be effective if designed with interactive learning (Turan & Atila, 2019).

The positive impact of augmented reality on biology learning has been proven by numerous published studies. In their research, Thahir & Kamaruddin (2021) stated that augmented reality-based media can visualize abstract biological concepts for understanding and the structure of an object model, as well as provide an attractive display of application features. In another study conducted by Baihaki et al. (2023), it was stated that the use of augmented reality can help students visually present material, thereby aiding their understanding and sparking their interest in learning difficult topics such as the nervous system. Another study shows that augmented reality applications provide teachers with creative ways to deliver instruction (Rahmawati et al., 2023). Augmented reality fosters a dynamic and engaging learning environment that stimulates critical thinking, collaboration, and creativity among students (Marrahi-Gomez & Belda-Medina, 2022).

Many studies have produced articles on the development and application of augmented reality in biology education, but none have systematically summarized these findings. Meta-analysis can be used to synthesize findings from studies on augmented reality in biology education that share the same theory or hypothesis (Vekli & Çalik, 2023). The meta-analysis approach serves to combine the results of various studies that have similar research questions but are conducted in different contexts, samples, and conditions (Glass, 1981). Meta-analysis has advantages over other literature studies. Meta-analysis can use a systematic and objective quantitative approach in combining research results, thereby reducing subjective bias from researchers (Borenstein et al., 2009). A qualitative meta-analysis approach can answer important questions in education. Through meta-analysis studies, we can see the strengths and weaknesses of each study (Nindrea, 2016). This approach allows researchers to combine the results of various studies that have similar research questions but were conducted in different contexts, samples, and conditions.

The purpose of this study is to assess the trend of augmented reality usage over the last ten years (2016-2025). This study looks at the effectiveness and trends of the variables in the study. Through a meta-analysis approach, this study describes and concludes thoroughly about the effectiveness of the use of augmented reality. The research is expected to provide opportunities for further research by determining variables that have not been studied. The results of this study can also be used as a basis for developing technology-based learning media according to future needs.

METHODS

This study uses a mixed meta-analysis method with a skinative and quantitative approach, data obtained by collecting various articles that research and development of augmented reality in 2016-2025 accredited by SINTA 1-6. Meta-analysis is a technique used to summarize the findings of two or more studies to combine, review, and summarize previous research (Putri & Zulyusri, 2022). The mixed method meta-analysis approach combines qualitative and quantitative analysis to assess the effectiveness of Augmented Reality learning media in learning biology. The qualitative approach is used to identify topics or themes, research variables, research trends, and challenges that arise in the implementation of augmented reality. The quantitative approach is used to measure the effectiveness of the media through the calculation of effect size values from various research results.

This study obtained data from SINTA-accredited journals 1-6 to ensure the quality of the source. Article searches were conducted through Google Scholar, Scopus, DOAJ, and ERIC. The keywords used to search for articles included "augmented reality" and "biology learning." Article sources were restricted from 2016-2025 and selected for inclusion for data accuracy. Articles were then classified into qualitative and quantitative meta-analysis groups. The inclusion criteria for article selection

Table 1.
Criteria of inclusion and exclusion for references

Inclusion Criteria	Exclusion Criteria
SINTA-accredited articles 1-6	Source articles other than SINTA 1-6
Articles published from 2016-2025	Articles published outside 2016-2025
Article available full-text	The article is not available in full-text
Articles on the topic of biology learning with augmented reality	Topic articles other than augmented reality in biology learning
Written in English and Indonesian	Written in languages other than English and Indonesian

The results of the selection are illustrated in Figure 1. Screening of articles using the PRISMA guidelines resulted in 100 articles being selected for analysis from the SINTA database. The search was conducted using the keywords “augmented reality” and “biology learning.” Screening based on the year of publication, namely 2016-2025, left 80 articles. In 2016, no articles were found in the database because SINTA was only officially launched in 2017, so articles from earlier periods did not meet the inclusion criteria. Further selection based on titles narrowed the list down to 15 articles, leaving 65 articles, as many titles were similar, such as literature reviews and systematic literature reviews (SLRs) using augmented reality in biology education. The articles were then analyzed based on their abstracts, resulting in 10 articles being selected and 55 articles remaining. The abstract screening was conducted to assess the relevance of the articles' themes. The selection process continued by reading the full articles, leaving 35 that best aligned with the research objectives, the use of augmented reality in biology education, and the availability of data for qualitative and quantitative meta-analysis.

A qualitative meta-analysis approach is used if the article does not contain complete statistical data, such as mean values, standard deviations, or statistical test results. Articles analyzed in a qualitative meta-analysis contain important information from the articles to be integrated and build a comprehensive understanding of the phenomenon, without sufficient statistical analysis support, particularly used for descriptive research. Meanwhile, articles included in quantitative meta-analyses must contain numerical data that allow for the calculation of effect sizes, such as pretest-posttest data, sample sizes, standard deviations, and other supporting statistics. The process of article selection in this study can be seen in full in Figure 1.

Statistical analysis is used to draw conclusions from the final results obtained through effect size calculations. Statistical tests can be conducted using the JASP software. JASP (Jeffrey's Amazing Statistics Program) was chosen as the analysis platform due to its comprehensive capabilities in supporting various meta-analysis approaches (Ghazali et al., 2023). Effect size is a measure used to describe the magnitude of the effect or difference between interrelated variables (Retnawati, 2018). The effect size calculation technique in each journal was performed to see its relationship with the creative thinking ability of students. The method of finding the effect size used in this study was based on Cohen's theory (Seftiani et al., 2021).

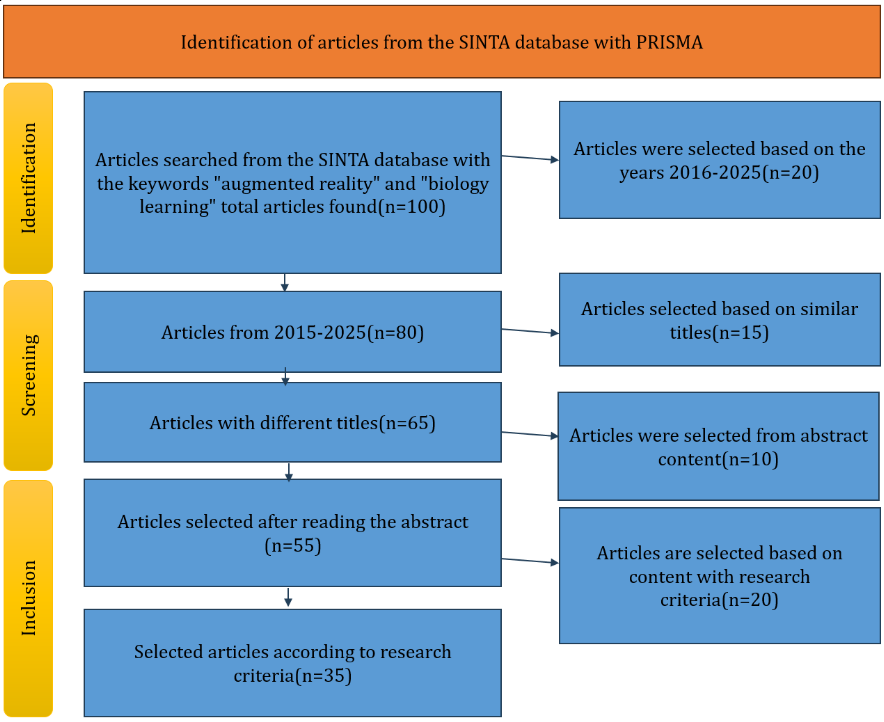

Figure 1. The PRISMA diagram in article selection

Group the data with quantitative meta-analysis included in the effect size formula criteria. Effect size formula :

$$d = \frac{M_e - M_c}{SD}$$

Meanwhile, the effect size criteria (Cohen, 1988), are as follows: 0.00 – 0.20 has a weak effect (very low). 0.21 – 0.50 has a low effect. 0.51 – 1.00 Has a moderate effect. More than 1.00 Has a high effect

RESULTS AND DISCUSSION

Qualitative Meta-analysis of trends in the use of augmented reality in biology learning

Trend of augmented reality based on publication year 2016-2025

The trend in the use of augmented reality shows significant fluctuations each year, indicating that articles are selected based on fairly strict criteria, as can be seen in Figure 3.1 below. In 2016, no articles with SINTA accreditation were found because SINTA had not yet been officially launched. SINTA (Science and Technology Index), as the national journal indexing system, was officially launched in 2017 by the Ministry of Research, Technology, and Higher Education (Kemenristekdikti, 2017). Before this year, research on augmented reality in biology education did not have a centralized platform for article selection.

Articles found in 2017, with 4 articles selected, continued to fluctuate annually until 2025. A decline occurred from 2018 to 2021, with 2-3 articles per year. This decline occurred because, of the many articles found, only a few met the inclusion criteria for the study. During this period, there was a lack of infrastructure and human resources readiness for the implementation of augmented reality. Teachers and many educational institutions did not have the necessary facilities and infrastructure. Many teachers were still unable to adapt and keep up with technological advancements, meaning they lacked understanding of the technology and were unable to master it (Adianti, 2023). This period also coincided with the COVID-19 pandemic, which caused issues in learning and research across various fields. The focus in education at that time was on implementing simple online learning that was easily accessible to students. Research activities requiring the development of interactive media and direct classroom testing were significantly hindered due to social restrictions and school closures (Anugrahana, 2020).

There was a significant increase in the graph in 2022, showing the number of articles found and those that met the inclusion criteria, totaling 9 articles. This occurred because post-pandemic, the focus of education shifted toward technology-based learning, one of which is augmented reality. The post-COVID-19 situation, which is more challenging, presents an important opportunity to rethink the design of digital technology-based learning that facilitates student engagement (Magfiroh, 2022). In 2023, the number of articles decreased to 3 because, out of the many articles selected, only a few were suitable, as it was a challenging task in analysis (Pettricrew & Roberts, 2008; Borup et al., 2020). There was another increase in 2024, with 8 articles meeting the criteria. One reason for this increase is the strong push from technological advancements (Lin & Yu, 2023). Augmented reality-based media has become one of the most effective interactive tools for biology education materials (Pranahadi et al., 2024; Dini et al., 2024; Husain & Herlinda, 2024). In 2025, only one article (Husain & Herlinda, 2024) met the inclusion criteria, primarily due to the limited number of published articles. Many studies are assumed to still be in the research process, and many scientific journals are still in the process of scientific publication. This decline does not indicate a decrease in research but rather challenges in publication. The peer-review process and journal publication are time-consuming stages (Björk & Solomon, 2013). The explanation above is illustrated in Figure 2.

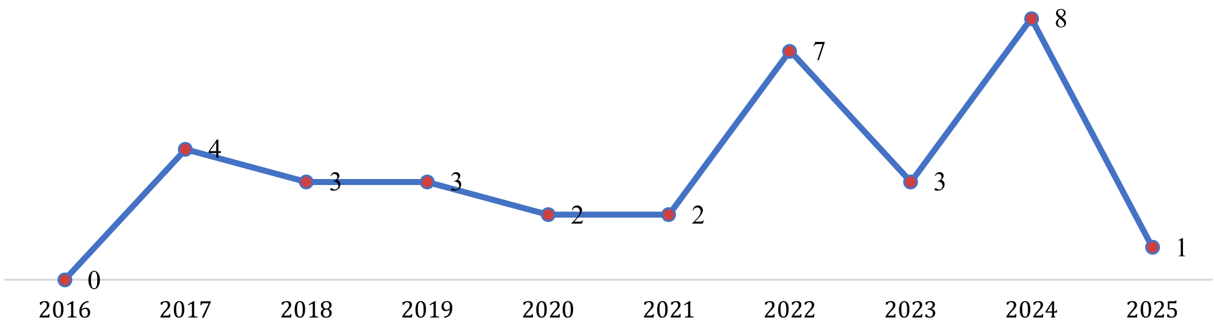

Figure 2. Trends in Publications on the Application of AR in 2016–2025

Trends based of Research Methods

Based on the analysis of the 35 studies that met the inclusion criteria, the most commonly used research method was Research and Development (R&D), with 13 articles. This finding indicates that the use of augmented reality technology in biology education is still focused on the development stage of educational media. R&D is a suitable method for developing educational technology products because it employs a systematic approach, including analysis, planning, development, and evaluation (Sugiyono, 2019). This aligns with advancements in science and technology, which have created a need for innovation in education. Additionally, there are 12 articles using a quasi-experimental approach, indicating that augmented reality is increasingly being used as a learning medium in classrooms. Quasi-experimental testing is not suitable for random environments and is more appropriate when the classroom has a clear structure (Creswell & Creswell, 2023; Sugiyono, 2019). The testing of augmented reality implementation has been widely conducted and has yielded satisfactory and effective results (Nurhasanah et al., 2019; Mardiyah et al., 2020; Fajriani et al., 2021; Nurfaizi et al., 2022). The analysis can be seen in Table 2.

The mixed-method experimental design research consists of 4 articles and 2 pre-experimental articles. This mixed-method approach integrates the development stage (R&D) with experimental testing, thereby not only developing augmented reality learning media but also directly testing its effectiveness in biology learning. This combination provides a more comprehensive understanding as it encompasses the product development process through to the evaluation of its impact on student learning outcomes (Mauludin et al., 2017; Romadhon et al., 2017; Mustaqim et al., 2018; Lestari et al., 2018). Meanwhile, pre-experimental research, although it has more limited control compared to a full experimental design, still provides initial indications of the potential effectiveness of augmented reality technology in improving biology learning outcomes (Sylvia et al., 2021; Padang et al., 2022).

Table 2.
Type of Research methods applied in the selected article

No.	Methods	References	Amount
1	Quasi experiment	(Nurhasanah et al., 2019), (Mardiyah et al., 2020), (Fajriani et al., 2021), (Nurfaizi et al., 2022), (Emawati & Haka, 2022), (Ahmad et al., 2022), (Tamam & Qomaria, 2023), (Wikanta et al, 2023), (Kamaruddin & Thahir, 2021), (Tika et al., 2024), (Husain & Herlinda, 2024), (Khaira et al., 2025)	12
2	RnD	(Qumillaila, 2017), (Hidayat et al., 2017), (Astiti et al., 2018, (Aripin & Suryaningsih, 2019), (Puspitasari et al., 2020), (Annisa et al., 2022), (Setiawan et al., 2022), (Rosadi & Maulidi., 2022), (Wibowo et al., 2022), (Oktavia, 2022), (Hernanda & Ajib, 2024), (Khanan & Wardhani, 2024), (Dini et al., 2024)	13
3	Pre-experiment	(Sylvia et al., 2021), (Padang et al., 2022)	2
4	True-experiment	(Mauludin et al., 2017), (Romadhon et al., 2017), (Mustaqim et al. 2018), (Lestari et al., 2018)	4
5	Community Service Study	(Areni et al., 2018)	1
6	SLR	(Yaumi & Rohmah, 2024)	1
7	Classroom Action Research	(Fitrianingsih et al., 2023), (Pranahadi et al., 2024)	2

There are two classroom action studies (CAS), with two articles, but CAS here is one of the most systematic types of research. CAS describes what is really needed in the classroom for problem solving and improving the quality of learning (Arikunto, 2015). The application of CAS is relevant and evaluative research that directly assesses the effectiveness of the need for augmented reality technology used. There is one article taken from a community service article. This article introduces augmented reality and its potential for biology education (Areni et al., 2018). Additional supporting research indicates that many teachers in Indonesia need to improve their literacy and technological proficiency to integrate new media such as augmented reality into the classroom (Minarti, 2023; Melisa, 2024). There is 1 study using SLR among the many similar methods. This article was selected because it has the most systematic review among the others. This article was chosen because it is the only one that discusses the topic most specifically. It has a rigorous methodology and broad scope (Yaumi & Rohmah, 2024).

Trends based on region were researched.

The regional distribution of the research analyzed in this article shows a dominant trend in Java, with the highest concentration in West Java (7 articles) and East Java (5 articles). Other regions such as South Sulawesi and West Kalimantan, contributed 4 articles each, while regions such as Central Java, Papua, West Sumatra, Bali, and others were only represented by one to two articles. There was also one national or global article, and two articles that did not explicitly state the location. The dominance of the Java Island region can be attributed to the level of availability of education and technology infrastructure that is more evenly distributed than in other regions in Indonesia. It also reflects that the development and application of Augmented Reality technology in biology learning is still concentrated in areas that have better access to digital resources and research institutions. This gap needs to be a concern in the development of education policy, so that the application of digital innovation is not only focused on certain regions, but also evenly distributed throughout Indonesia. It can be seen illustrated in Figure 3.

The dominance of Java Island can be attributed to the more equitable availability of educational and technological infrastructure compared to other regions in Indonesia. In terms of technology dissemination, Indonesia faces a significant Digital Divide (Ariyanti, 2013). This also reflects that the development and application of augmented reality technology in biology education remain concentrated in areas with better access to digital resources. Population density is also important because higher-density areas receive more research attention, and if the population is dense, it creates opportunities (Anugrah, 2025). This gap needs to be addressed in the development of education policies to ensure that the implementation of digital innovations is not only focused on certain regions but is also evenly distributed across all regions of Indonesia.

Figure 3. Research region of the articles

Trends based on Education Level

An analysis of 35 articles shows that the majority of augmented reality-based biology learning research was conducted at the senior high school level, with 23 articles (66%). This finding indicates that senior high school is the main focus in the implementation of augmented reality technology in the context of biology learning. The curriculum at the high school level for biology education contains a significant amount of abstract and microscopic content, as well as complex thinking processes (Omurtak & Zeybek, 2022; Tharir & Kamaruddin, 2021; Oktaviana, 2022; Sari et al., 2023). Meanwhile, the junior high school level ranks second with 7 articles (20%). The application of augmented reality at the junior high school level is aimed at stimulating students' interest in learning, as they are introduced to abstract yet relatively straightforward concepts such as cells, plants, viruses, and others (Sholikha et al., 2024; Khanan & Wardhani, 2024; Triyono, 2021). The elementary school level (SD) had 4 articles (11%). The low number of studies at the elementary school level is not based on its effectiveness in learning but rather on the success of augmented reality for the elementary school level, which depends on the availability of infrastructure, teacher training, and parental support in providing educational facilities (Aprilia et al., 2025). This finding is illustrated in Figure 4.

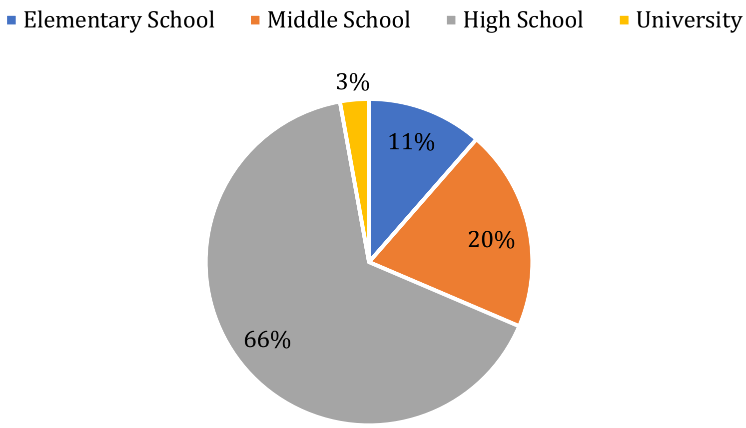

Figure 4. Level of education in the Article

At the elementary and junior high school levels, science subjects, including biology, still focus on basic concepts and introductions (Ichsan, 2018). Elementary school children's thinking abilities are still at a basic level that focuses on concrete thinking, while junior high school children are at a limited introductory level, and high school students are beginning to explore concepts in depth (Piaget, 2002). There is one article on the use of augmented reality at the university level that has been included. The application of augmented reality at the university level faces many challenges. One of the most significant factors is that the material presented at the university level is highly complex. Research by Hoog et al. (2020) states that 15% of students have problems using augmented reality due to device limitations and the fact that augmented reality displays too many concepts, leading to misconceptions among students. Augmented reality is rarely applied at the university level because university culture places greater emphasis on laboratory work and textbooks, and views augmented reality as a supplement that cannot replace them (López-Cortés et al., 2021).

Trends in Dependent Variables Examined in Biology Education Research

The results for the dependent variables in the study indicate that the most dominant variables are conceptual understanding and learning outcomes, as shown in Figure 3.4, each found in 7 articles. This finding reinforces previous research findings stating that the use of augmented reality can significantly improve mastery of biological concepts (Mauludin et al., 2017; Hernanda & Ajib, 2024; Nurhasanah et al., 2019; Mardiyah et al., 2020). Sweller et al. (2011) state that cognitive extrinsic load can be reduced through the use of technology in learning. In addition, learning motivation is also a major focus in 6 articles. Learning motivation can be linked to interactive learning that encourages student engagement in the learning process (Areni et al., 2018; Rosadi & Maulidi., 2022; Wibowo et al., 2022; Tamam & Qomaria, 2023).

According to Dale's theory, students can remember up to 90% of what they do directly. Augmented reality acts as a bridge that transforms learning from an abstract level to a more concrete and interactive experience. Augmented reality technology enables students to manipulate virtual 3D objects, interact directly with learning materials, and experience simulations that closely resemble real-world experiences, thereby shifting the learning process from the passive zone to the active zone in Dale's cone. Media feasibility variables were identified in three articles. Articles assessing media feasibility evaluate augmented reality from the aspects of validity, usability, and effectiveness as a technology-based medium (Qumillaila, 2017; Khanan & Wardhani, 2024; Dini et al., 2024).

Meanwhile, other variables such as cognitive learning outcomes (2 articles), critical thinking, creative thinking skills, HOTS, conceptual representation, habits of mind, and visual communication were each studied in only 1 article. These findings indicate that the application of augmented reality already involves higher-order thinking skills that require complex thinking abilities, but its use is still limited (Khaira et al., 2025; Sylvia et al., 2021; Emawati & Haka, 2022; Wikanta et al., 2023). In other articles, supporting mediums such as cognitive learning outcomes, conceptual representation, and visual communication are discussed in relation to the achievement of higher-order thinking skills. There are articles examining the characteristics of augmented reality learning media, such as the effectiveness of learning media, the practicality of media, the need for learning media, and the quality of learning media, each consisting of only one article. Such research is crucial to ensure that media are not only developed and implemented but also consider technical aspects that support their effectiveness in learning (Majeed & Ali, 2020). All of these analyses are illustrated in Figure 5.

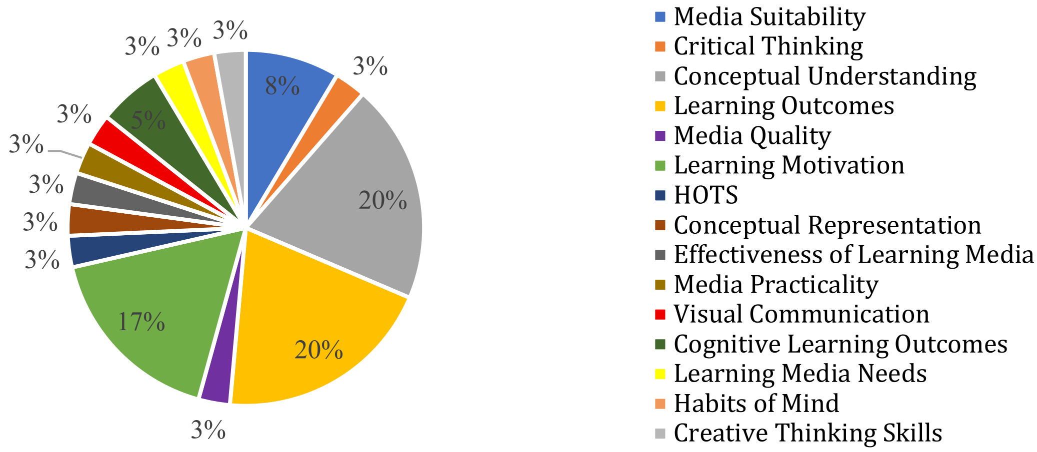

Figure 5. Variables tested in the article

Trends based on biology topics tested in articles

An analysis of biology learning topics in augmented reality-based research shows a dominance of material related to human organ systems, specifically the musculoskeletal system, with 5 articles, the excretory system, with 4 articles, and the nervous system, with 4 articles. The human system is a complex subject involving structure, physiological processes, and interconnections between organs. This material is difficult to understand if students only learn from textbooks; they require realistic depictions with spatial visualization to facilitate their understanding (Nurfaizi et al., 2022; Oktavia, 2022; Tika et al., 2024). According to Putra et al. (2023), complex and difficult-to-understand material requires high spatial visualization to transform abstract 2D concepts into complete 3D models.

Topics such as cell structure and function, biodiversity, classification of living things, blood circulation, coordination systems, and viruses each have two articles. These topics are difficult to understand because they require microscopic or abstract understanding (Khanan & Wardhani, 2024; Padang et al., 2022; Yaumi & Rohmah, 2024; Sylvia et al., 2021; Kamaruddin & Thahir, 2021). In line with the findings of Kadirhanogullari & ÖZAY KÖSE (2024), who state that misconceptions are the primary basis for science learning, topics such as cell biology, the circulatory system, and evolution—which form the foundation of biodiversity—have abstract and microscopic characteristics, necessitating effective teaching strategies.

Other topics such as plant and animal networks, ecosystems, digestive systems, sensory organs, body anatomy, endocrine systems, plant and animal reproduction, and animalia only appeared once in the study. Despite their low frequency, some articles still demonstrate positive impacts (Nurfaizi et al., 2022; Oktavia, 2022; Tika et al., 2024; Hernanda & Ajib, 2024). These findings demonstrate that augmented reality cannot be developed and applied arbitrarily because of the lack of ready-to-use content integrated with the curriculum, the need for expertise in developing it, and the fact that complex material remains complex even when augmented reality is applied, known as intrinsic cognitive load (Sweller, 2011). The analysis can be seen in the illustration in Figure 6.

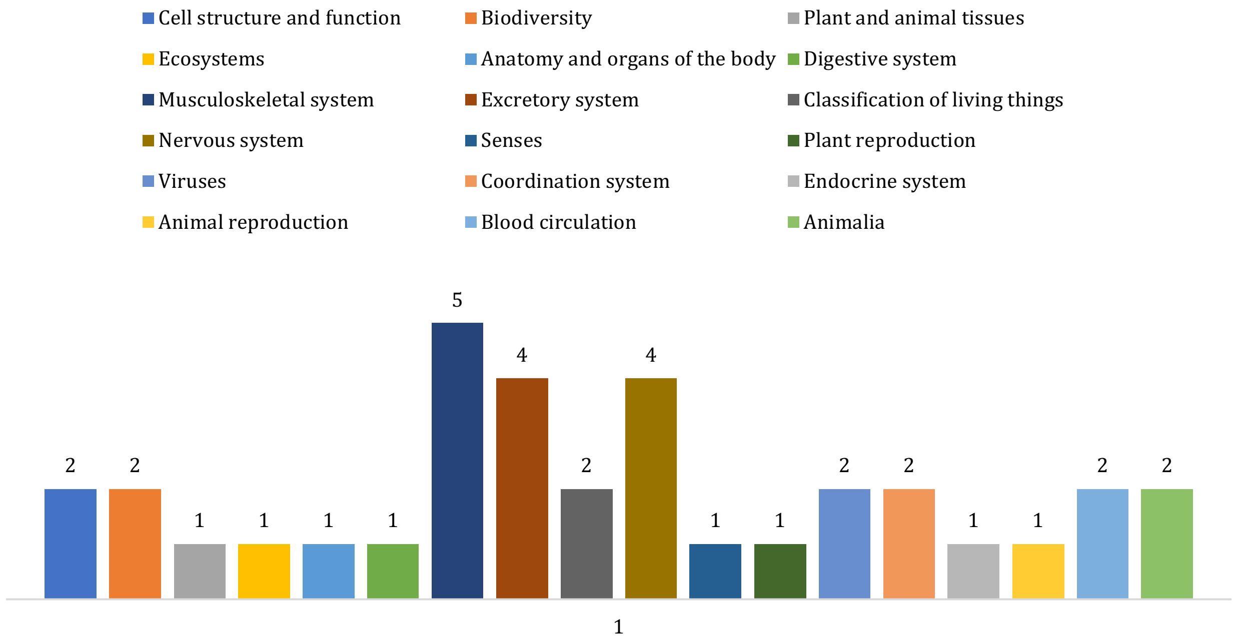

Figure 6. Biology topics in the articles

Trend based on Quantitative Analysis Results

From a total of 35 articles systematically screened, only six articles met the inclusion criteria for quantitative analysis and contained data that could be calculated for a complete effect size using Cohen's d through the JASP application. This meta-analysis was conducted on six selected articles from a total of 35 articles identified in the systematic review process related to the effectiveness of augmented reality media in biology and science education. The six articles met the criteria for quantitative effect size calculations using Cohen's d approach, with the values and standard errors then analyzed using the JASP application (meta-analysis version based on effect size). The results of the meta-analysis showed that the average effect size (Cohen's d) was 2.249 with a standard error of 0.962. This value is classified as a very large effect according to Cohen's (1988) categories, meaning that, in general, augmented reality media has an impact on improving learning outcomes or other cognitive abilities.

Table 3.
Results of quantitative meta-analysis of six articles

Article	Cohen's *d*	Standar Error	Interpretion Effect
(Emawati & Haka, 2022)	2.701	0.3936.	Very High
Wikanta et al. (2023)	1.367	0.2582	High
Tika et al. (2024)	7.071	0.9012	Very High
Husain & Herlinda (2024)	1.751	0.3557ds	High
Pranahadi et al. (2024)	0.92	0.2177	High
Khaira et al. (2025)	0.304	0.3179	Negligible effect

The application of augmented reality in education still faces various challenges, particularly related to infrastructure readiness and teacher capabilities. This study indicates that the main obstacle is the limited availability of high-quality development resources and sufficient devices to implement augmented reality. Additionally, some teachers struggle to adopt this technology due to a lack of the necessary skills (Perifanou, 2022). Adequate training must be provided before this technology is widely implemented.

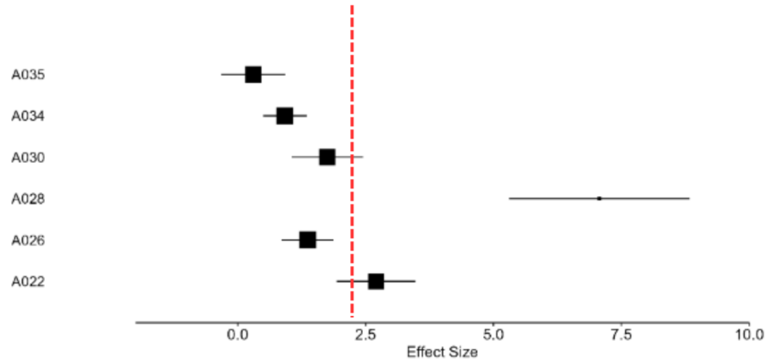

Figure 8. Forest Plot of Quantitative Meta-analysis of articles

Figure 8, shows that the red dotted vertical line indicates a pooled effect size of d = 2.249, as generated by the random effect model in JASP. This value is classified as a very large effect according to Cohen's (1988) classification, indicating that the use of augmented reality media in learning generally has a strong impact on improving learning outcomes, conceptual understanding, and other affective and cognitive aspects. The varying lengths of the confidence interval lines, along with one article (Khaira et al., 2025) having a lower CI bound touching zero, indicate that not all studies show statistically significant effects. The article (Tika et al., 2024) with an extreme effect size (d = 7.071) is the one causing high heterogeneity among studies, as also indicated by the I^2 value of 97.9% and Q = 68.08 ($p < 0.001$) in the heterogeneity test. Overall, the forest plot reinforces the finding that augmented reality media is effective in learning, but the results vary greatly depending on the study design, educational level, topic, and quality of media implementation.

The results of the meta-analysis show a fluctuating pattern in the publication of Augmented Reality research on biology learning during the period 2016-2025, with a peak publication occurring in 2022 with 9 articles, which can be attributed to the post-pandemic conditions of COVID-19, which encourage the accelerated adoption of digital learning technology. The post-pandemic period opens up great opportunities for the development of interactive digital technology-based learning media. Research activities that require the development of interactive media and direct testing in the classroom have been severely hampered by social restrictions and school closures (Anugrahana, 2020). The decline in publications in the 2018-2021 period can be explained by the limited technological infrastructure and human resource readiness in Indonesian educational institutions, as well as the impact of the COVID-19 pandemic which caused experimental research in education to experience significant obstacles due to restrictions on access to schools, There are still many teachers who are unable to adapt and keep up with technological advances. In other words, teachers still lack understanding of technology and are unable to master it (Adianti, 2023).

The Research and Development (R&D) method is the most widely used method in 13 out of 35 articles (37%), indicating that the field of AR in biology learning is still at the stage of development and innovation, in line with the characteristics of technology requires a continuous development process to achieve implementation maturity. Most augmented reality developments still use the R&D method because it has a fairly complex method (Sugiyono, 2019). Quasi-experiments following 12 articles show that the research community has begun to conduct empirical validation of the effectiveness of augemented reality media, which has been developed. Quasi-experimental testing is not suitable for random environments and is more suitable when the class already has a clear structure (Creswell & Creswell, 2023). While the combination of methods (mixed-method) with 4 articles shows a more comprehensive approach by integrating technical aspects of development and in-depth evaluation. The geographical concentration of research in Java, particularly West Java (7 articles) and East Java (6 articles), reflects the digital divide. Population density is also important because high density will attract research attention, especially if the population is dense, as this will create opportunities (Anugrah, 2025).

This geographical inequality needs to be a serious concern for national education policy makers because the development of augmented reality that is only concentrated in certain regions can widen the gap in the quality of education between regions. The dominance of research at the high school level (66%) can be explained by the cognitive maturity of students that allows them to interact with AR technology optimally, as well as the complexity of biological material at the high school level (Khanan & Wardhani, 2024) (Dini et al., 2024; Pranahadi et al., 2024). which is generally more abstract so that it requires threedimensional visualization that AR technology can provide. The low research at the elementary level (3 articles) shows a gap that needs to be filled,

The concentration of research on human systems (locomotion, excretory, and nervous systems) reflects a proper understanding of the power of augmented reality technology, as these topics best fit the characteristics of augmented reality involving complex three-dimensional structures, dynamic processes, and internal visualizations that are difficult to understand through conventional media (Putra et al., 2023). The movement system involves complex interactions between bones, muscles, and joints that can be visualized interactively through augmented reality; similarly, the nervous system, with its intricate network of neurons, can be better understood through interactive 3D models (Kadirhanogullari & ÖZAY KÖSE, 2024). However, augmented reality shows that the development opportunities are still wide open.

In the future, it is hoped that the application of augmented reality media can be expanded to other biological topics that have not been widely explored, such as ecology, genetics, and evolution. For example, the concept of ecological interactions in an ecosystem is difficult to visualize in the classroom (Aprilinda, et al., 2020). The same applies to the mechanism of trait inheritance in genetics, such as DNA. The use of augmented reality in genetics education, particularly in the topics of DNA and the process of trait inheritance, is of high urgency given the highly abstract and complex nature of the material (Dwisatyadini & Dini, 2022). Concepts such as DNA structure, replication, transcription, and translation are often difficult for students to understand through conventional media such as textbooks or lectures (Nasrullah & Octaviani, 2025). Evolution, which occurs over an extremely long timescale, is often only understood theoretically. With the help of augmented reality, these concepts can be visualized in an interactive, immersive, and contextual manner, thereby enhancing students' conceptual understanding and facilitating meaningful learning.

The dominance of research on concept understanding variables and learning outcomes shows that the focus is still on the cognitive aspects of learning, although learning motivation gets enough attention there are six articles, other affective variables such as science process skills, HOTS, or collaborative skills still receive less attention. This limitation reflects the learning evaluation paradigm that is still dominated by the measurement of cognitive learning outcomes (Pranahadi et al., 2024) (Hernanda & Ajib, 2024). In contrast, one of the strengths of augmented reality is its ability to increase student engagement and motivation, which are effective aspects of learning (Dewanto et al., 2024)

The average effect size value of 2.249, which is classified as very high, indicates the great potential of augmented reality in improving biology learning, but the high heterogeneity (I^2 = 95%) indicates that the effectiveness of augmented reality is highly dependent on contextual factors such as media. design, implementation quality, teacher readiness, and student characteristics. This high heterogeneity reflects the complexity of technology implementation in an educational context that involves many variables that are difficult to control such as teacher teaching style, student motivation, and learning environment conditions, thus confirming the importance of a contextual approach in augmented reality implementation.

This high level of heterogeneity can be influenced by several factors found in the analyzed articles. First, differences in the design of the augmented reality media used, such as mobile app-based AR, marker-based AR, and web-based AR, affect the level of interactivity, visual quality, and ease of use for students. Media with more interactive designs and real-time 3D visualization capabilities tend to have a greater impact compared to media with limited interactivity (Ciloglu & Ustun, 2023). Second, variations in research methods, ranging from R&D, quasi-experiments, to pre-experiments, affect the level of variable control and internal validity of the research. Studies with stricter experimental designs generally yield more consistent results (Rhodes et al., 2018).Third, differences in educational contexts, such as educational levels (elementary school, junior high school, high school, or university) and infrastructure conditions in the research area, also play a role. Regions with adequate technological facilities and teachers skilled in operating augmented reality tend to produce more positive results compared to regions with limited infrastructure and technological literacy. This is in line with international studies indicating that, although teachers generally have a positive attitude towards the integration of AR into learning, many are still not confident in developing, utilizing, or managing AR-based learning resources effectively (Nikou et al., 2024). The combination of these factors contributes to the variation in research results and should be considered in interpreting the findings of this meta-analysis.

Based on the findings of this meta-analysis, future directions of augmented reality development include diversity of topics in biology that have not been widely researched such as ecology, genetics, and biotechnology, geographical equity with special initiatives to develop augmented reality research in areas outside Java, development for elementary and junior high school levels with designs that match the characteristics of students' cognitive development, integration of affective aspects in exploring the impact of augmented reality on students' attitudes and social skills, and standardization of methodologies to facilitate synthesis of research results. Although there are limitations in the form of a focus on SINTA-accredited national journals that can cause publication bias, high heterogeneity that makes generalization of results limited. This meta-analysis provides an overview of the current state of augmented reality research in biology learning in Indonesia and provides a solid foundation for future research development.

CONCLUSION

From this study, it can be concluded that a mixed meta-analysis was conducted to describe the trends and effectiveness of augmented reality use in biology education over the past ten years (2016–2025). Augmented reality was most commonly used at the high school level, with a focus on the topic of the human organ system. The dominant research designs were R&D and quasi-experimental, with frequently studied variables including conceptual understanding, learning outcomes, and motivation. Out of 35 articles, 6 met the criteria for quantitative analysis and showed an average effect size of 2.249, which is considered very high. However, the level of heterogeneity among studies is also high (I^2 = 95%), indicating variations in context and research design. Therefore, this study can serve as a reference for the development of augmented reality, and its application remains promising as an innovative learning tool for the future.

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