Jurnal Pendidikan Progresif
e-ISSN: 2550-1313 | p-ISSN: 2087-9849
URL: https://jpp.fkip.unila.ac.id/index.php/jpp
Jounal's DOI: http://doi.org/10.23960/jpp

Vol. 16, No. 4, 2026
Article ID: 2012
Pages: 2268-2281

The Effectiveness of Interactive Media on Biology Learning Outcomes: A Meta-Analysis of the Scopus and Web of Science Databases (2021–2026)

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Received: 15 September 2026 *Accepted: 30 October 2026* *Published: 13 November 2026*

Abstract: Biology education faces challenges regarding abstract concepts that are difficult to visualize through conventional methods. Technology-based interactive media, such as Augmented Reality (AR), Virtual Reality (VR), interactive multimedia, virtual laboratories, and interactive videos, are believed to bridge this gap. However, various empirical studies have yielded mixed results regarding their effectiveness. This study aims to determine the effectiveness of interactive media on biology learning achievement using a meta-analytic approach. A meta-analysis was conducted. A systematic literature search was performed across Scopus databases for articles published between 2021 and 2026, following the PRISMA protocol. Of 487 identified articles, 12 primary studies met the inclusion criteria and included 1,219 students. Effect sizes were calculated using Hedges' g with a random-effects model. The results revealed an overall effect size of $g = 0.78$ (95% CI: 0.61–0.94; $p < 0.001$), classified as a large effect according to Cohen's criteria. Heterogeneity tests indicated high variability ($Q = 21.12$; $I^2 = 71.4\%$), prompting a moderator analysis. The variables of interactive media type, educational level, and accompanying pedagogical strategy were found to significantly moderate the effect size, whereas intervention duration and geographic region were not significant. These findings confirm that interactive media effectively enhance biology learning achievement; however, their effectiveness depends on the pedagogical context. Practical implications and recommendations for future research are discussed.

Keywords: biology, meta-analysis, interactive media, learning achievement.

Article's DOI: https://doi.org/10.23960/jpp.v16i4.pp2268-2281

INTRODUCTION

Biology is a branch of natural science that examines phenomena in living organisms, from the molecular level to ecosystems (Burley et al., 2021; Luft et al., 2022). The characteristics of biological content, which is largely abstract, dynamic, and cannot be directly observed with the naked eye, such as the processes of photosynthesis, DNA replication, membrane transport, and cell division, pose particular challenges for both educators and students. Various studies have reported that low achievement in biology often stems from students' difficulty visualizing these abstract concepts, as well as the limited availability of conventional laboratory facilities in schools, particularly in developing countries (Husna et al., 2023; Yustina et al., 2020).

The Program for International Student Assessment (PISA) 2025 results indicate that Indonesian 15-year-old students achieved an average science literacy score of 389, below the OECD average of 482. Furthermore, 63.2% of Indonesian students performed below Level 2, the baseline proficiency level in science literacy (OECD, 2026). More specifically, in biology education, Silaban and Pranoto (2022) found that 36.03% of students in their sample held misconceptions about cell biology, with the highest proportion (48.57%) identified in the indicator

on membrane transport mechanisms. These findings demonstrate that learning challenges are reflected not only in overall science literacy performance but also in students' understanding of specific biological concepts. Although the two studies differ in scope and measurement indicators, their findings provide empirical evidence of the challenges students face in science and biology education.

Challenges in biology education are also associated with limited access to learning facilities that enable students to conduct direct observations and experiments. Not all schools have adequate laboratories, equipment, or practical materials to support experiential learning. These limitations may restrict students' opportunities to observe biological phenomena, manipulate variables, and connect the concepts they learn with the results of their observations. Therefore, instructional approaches need to do more than convey information; they should also help students visualize biological phenomena, explore complex processes, and actively construct their understanding. One alternative that has emerged alongside digital transformation is technology-based interactive learning media.

Interactive media enable students to engage with learning materials through simulations, object manipulation, information exploration, and responses to presented activities (Daryanes et al., 2023; Roemintoyo & Budiarto, 2021; Tuma, 2021). In biology education, such media may include augmented reality (AR), virtual reality (VR), interactive multimedia, virtual laboratories, interactive videos, and digital learning modules. Each type of media has distinct characteristics and potential benefits. AR can integrate virtual objects into real-world environments, helping students examine three-dimensional representations of biological structures. VR allows students to enter virtual environments to explore objects or processes that are difficult to access directly. Meanwhile, virtual laboratories provide simulated environments in which students can conduct experiments, manipulate variables, and observe outcomes without relying entirely on physical laboratory facilities. Interactive multimedia and videos can also support learning by presenting visual and verbal information and giving students opportunities to interact with the material.

Several theoretical perspectives explain the potential of interactive media in learning. The Cognitive Theory of Multimedia Learning suggests that learning is supported when verbal and visual information are presented in a coordinated way to help students construct meaningful understanding (Mayer, 2005). In biology education, appropriate visualization can help students understand structure–function relationships, identify process sequences, and connect visual representations with conceptual explanations. Furthermore, Cognitive Load Theory emphasizes managing cognitive load so students can devote mental resources to processing information relevant to learning objectives (Sweller et al., 2011). Interactive media may support this process when their design facilitates students' understanding of the material. Conversely, overly complex displays, irrelevant features, or excessive visual information may increase cognitive load and distract students from the central learning content. The constructivist perspective also emphasizes the importance of students' active involvement in constructing knowledge through learning experiences. Accordingly, the benefits of interactive media depend not only on technological sophistication but also on design quality, alignment with the subject matter, and the pedagogical strategies that accompany their use.

Several empirical studies have demonstrated the potential of interactive media to support biology learning outcomes, although the reported effects have not always been consistent in magnitude. For example,

Christopoulos et al. (2023) compared video-assisted biology instruction with instruction using stereoscopic 360-degree VR among secondary school students. Al-Nakhle (2022) investigated scenario-based virtual laboratory simulations and reported benefits for learning outcomes and scientific report-writing skills. Tsirulnikov et al. (2023) also examined immersive virtual laboratory simulations in relation to students' learning outcomes and motivation. These findings suggest that interactive technologies can provide more exploratory learning opportunities, particularly when students need to understand phenomena that are difficult to observe directly.

Further empirical evidence was reported by Sattar et al. (2025), who evaluated the use of an AR application in biology instruction involving 60 ninth-grade students in Pakistan. This quasi-experimental study reported a post-test score of 81.0% for the group learning with AR, compared with 76.1% for the group receiving conventional instruction. The difference was statistically significant ($p = 0.022$), with a Cohen's d effect size of 0.61. These findings provide preliminary evidence that AR may improve biology learning outcomes. However, the study involved a seven-day intervention at a single location, limiting how far the findings can be generalized across educational levels and learning contexts. Furthermore, not all studies have found significant differences across every measured learning outcome. For example, Ciloglu and Ustun (2023) found varying outcomes in motivation, self-efficacy, and attitudes among students using mobile AR-based biology learning. Hamizi & Mokmin (2026) also reported relatively small differences in learning outcomes between VR-based learning conditions and different pedagogical strategies. These variations suggest that the effectiveness of interactive media should be examined systematically rather than assumed to be uniform across all instructional conditions.

Although research on technology use in education continues to expand, individual studies have not yet provided a comprehensive picture of the overall effectiveness of different types of interactive media on biology learning outcomes. Differences in media characteristics, educational levels, subject matter, intervention duration, pedagogical strategies, research designs, and geographical contexts may produce variations in effect sizes. Consequently, conclusions based on only one or a few studies may provide a limited understanding of the available evidence. Quantitative synthesis is therefore needed to integrate findings across studies and generate effect estimates that reflect the overall body of available evidence rather than the results of individual investigations alone.

Several meta-analyses have examined the effectiveness of educational technology in science and biology education. For example, Vekli and Çalik (2023) conducted a meta-analysis of web-based biology learning environments and reported a positive effect on academic achievement. Dong et al. (2024) examined the effects of mobile learning on science achievement among school-aged students across several science disciplines. These studies provide an important foundation for understanding technology's contribution to learning. However, web-based learning environments and mobile learning do not fully encompass the range of interactive media considered in this study, including AR, VR, interactive multimedia, virtual laboratories, and interactive videos. Therefore, findings from meta-analyses focusing on a single technology type or a specific learning category do not directly establish the effectiveness of diverse forms of interactive media on biology learning outcomes when considered collectively.

Given this gap, a meta-analysis is needed to synthesize findings from experimental and quasi-experimental studies on the effectiveness of interactive media for biology learning outcomes. In addition to estimating the overall effect size, the analysis should account for variation across studies and explore factors

associated with differences in effect sizes. This study examines the type of interactive media, educational level, intervention duration, accompanying pedagogical strategies, research design, and geographical region as potential moderators. The moderator analysis is expected to provide a more detailed understanding of the conditions under which interactive media use is associated with biology learning outcomes. Nevertheless, the results for each moderator should be interpreted in light of the number of studies available in each category.

This study aims to analyze the effectiveness of interactive media on biology learning outcomes based on studies published between 2021 and April 2026. Specifically, it addresses three research questions: (1) What is the overall effect size of interactive media on biology learning outcomes? (2) How much do effect sizes vary across the studies included in the analysis? (3) Do the type of interactive media, educational level, intervention duration, accompanying pedagogical strategies, research design, and geographical region act as moderators of effect size? Using a meta-analytic approach, this study is expected to provide a quantitative estimate of the effectiveness of interactive media while clarifying variations in published findings. The findings may help biology teachers, instructional media developers, and educational researchers make informed decisions about media selection based on learning objectives, subject matter characteristics, and students' needs. Furthermore, the results may help identify limitations in the existing evidence and inform future research directions on using interactive technologies in biology education.

METHOD

Design Method

This study used a quantitative meta-analysis design with a systematic review approach following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. Meta-analysis was chosen because it allows statistical integration of findings from various relevant primary studies to produce more robust and generalizable effect estimates.

Literature Search Strategy

A systematic literature search was conducted using Scopus to identify research articles relevant to the use of interactive media in biology education. Scopus was selected as the primary search database because of its broad multidisciplinary coverage of scholarly publications, structured bibliographic records, and support for systematic article identification and screening. Using Scopus as the primary search source also enabled consistent application of the search strategy and systematic documentation of the article identification process.

Articles were considered eligible for inclusion in the meta-analysis if they were indexed in at least one of the two databases, Scopus or Web of Science (WoS). These databases were used as benchmarks for verifying publication indexing and ensuring the traceability of the scientific literature included in the analysis. This criterion also reflects that Scopus and WoS have overlapping but not identical coverage, allowing inclusion of relevant articles indexed in either database. The search covered articles published between 2021 and April 2026, with the final search update conducted in April 2026. The search strategy combined terms related to interactive media, biology education, and learning outcomes as follows: ("interactive media" OR "interactive multimedia" OR "augmented reality" OR "virtual reality" OR "virtual laboratory" OR "interactive video" OR "interactive simulation") AND ("biology" OR "biology learning" OR "biology education") AND ("achievement" OR "learning outcomes" OR "performance" OR "academic achievement").

Inclusion and Exclusion Criteria

The inclusion criteria were: (1) English-language articles published in journals indexed by Scopus and/or Web of Science; (2) using experimental or quasi-experimental designs with a control group; (3) using interactive media as an intervention variable; (4) the dependent variable being biology learning achievement/outcomes; (5) reporting statistical data that allows for the calculation of effect size (mean, standard deviation, sample size, or t/F value). The exclusion criteria included: (1) purely qualitative studies; (2) systematic reviews or meta-analyses (used only as comparative references); (3) non-indexed proceedings articles; (4) studies that did not report adequate statistical data; and (5) studies on general science subjects without a clear separation of biology.

Study Selection Procedures

The selection process followed the three PRISMA stages: identification, screening, and inclusion (Haddaway et al., 2022). The initial search identified 487 articles. After removing 73 duplicate articles, 414 articles were screened by title and abstract. At this stage, 362 articles were excluded as irrelevant. A total of 52 articles were assessed for eligibility through full-text reading, and 40 articles were excluded for not meeting any of the inclusion criteria (12 articles without a control group, 14 articles with insufficient statistical data, 8 articles with non-biology-specific content, and 6 articles with duplicate samples). Finally, 12 articles were identified as the primary studies for analysis. Figure 1 presents the study selection process using the PRISMA stages.

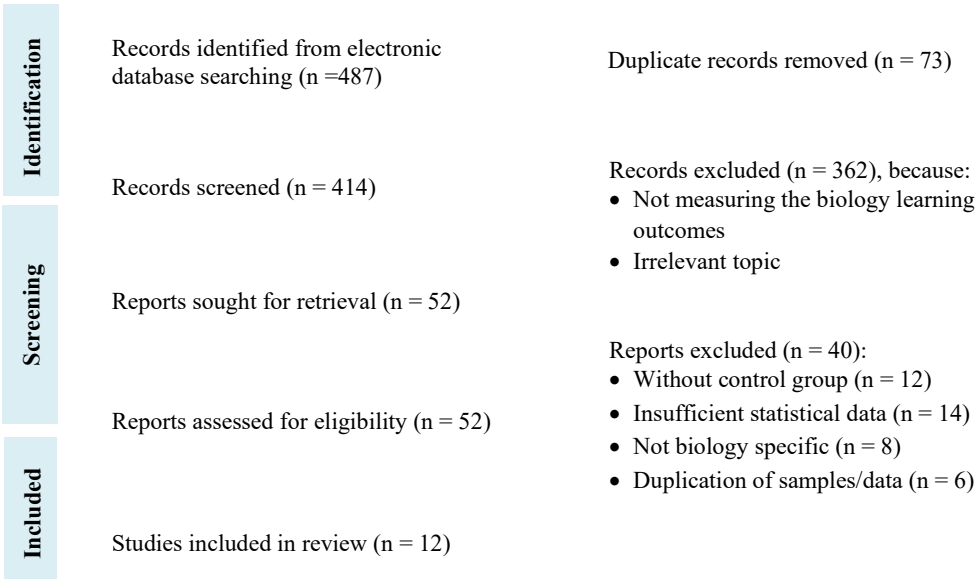


Figure 1. Study selection process using PRISMA

Data Extraction and Coding

Data extraction was performed independently by two coders using a standard extraction form. Extracted variables included study identity (author, year, country), participant characteristics (education level, sample size of experimental and control groups), intervention characteristics (type of interactive media, duration, pedagogical strategy), study design, and statistical data (mean, SD, t/F, p-value). Intercoder reliability was tested using Cohen's kappa coefficient, with a value of 0.87 indicating excellent agreement. Discrepancies were resolved through discussion with a third researcher.

Data Analysis

Effect sizes were calculated using Hedges' g with small sample correction, which is more accurate than Cohen's d for studies with small n. For studies reporting only t or F values, effect sizes were converted using the standard formula of Borenstein et al. (2009). Given the high heterogeneity between studies, a random-effects model with the DerSimonian-Laird estimator was used for the calculation of overall effect sizes (DerSimonian & Laird, 1986). Heterogeneity was evaluated using the Cochran Q statistic and I^2. The interpretation criteria for I^2 were "<25% low," "25–50% moderate," "50–75% substantial," and ">75% high." Moderator analyses were performed using subgroup analysis and meta-regression. Publication bias was evaluated through visual inspection of funnel plots and Egger's test. All analyses were performed using Comprehensive Meta-Analysis (CMA) version 4.0.

■ RESULT AND DISCUSSION

Characteristics of the Studies Analyzed

This meta-analysis analyzed 12 primary studies that met the inclusion criteria, with 1,219 students participating (657 in the experimental group, 562 in the control group). Study characteristics are presented in Table 1. The distribution of study characteristics shows that most studies were conducted at the high school level (7 studies; 58.3%), followed by universities (4 studies; 33.3%), and junior high schools (1 study; 8.3%). The most frequently studied type of interactive media was VR (4 studies), followed by AR (2 studies), interactive multimedia (2 studies), virtual laboratories (2 studies), interactive video (1 study), and instructional video (1 study). Geographically, the studies spanned Asia (5 studies), Europe (3 studies), Africa (2 studies), and the Americas (2 studies), indicating diverse cultural contexts and strong educational infrastructure.

Table 1. Characteristics of the studies analyzed

Code	Author (Year)	Country	Level	Media Type	Design
S01	Christopoulos et al. (2023)	Greece	SHS	360° VR	Quasi-Experimental
S02	Tsirulnikov et al. (2023)	Canada	College	Virtual Lab	Quasi-Experimental
S03	Al-nakhle (2022)	Saudi Arabia	College	SB-VLS	RCT
S04	Lacey et al. (2024)	England	College	Interactive Video	Quasi-Experimental
S05	Kassa et al. (2024)	Ethiopia	SHS	Multimedia + DCII	Quasi-Experimental
S06	Ntaila and Mbaraka (2023)	Malawi	SHS	Interactive Multimedia	Quasi-Experimental
S07	Ciloglu and Ustun (2023)	Türkiye	SHS	Mobile AR	Quasi-Experimental
S08	Sattar et al. (2025)	Pakistan	JHS	AR	Quasi-Experimental
S09	Hamizi and Mokmin (2026)	Malaysia	SHS	Desktop VR + IBL/PBL	Quasi-Experimental
S10	Ferdinand et al. (2023)	Germany	SHS	Immersive VR	RCT
S11	Foley et al. (2025)	United States	College	VR 3D Anatomy	Quasi-Experimental
S12	Miezah and Whajah (2023)	Ghana	SMA	Video	Quasi-Experimental

Overall Effect Size

The results of the individual effect size calculations for each study and the overall effect size are presented in Table 2. The analysis results show that all 12 primary studies produced positive effect sizes ranging from 0.38 to 1.46. Five studies (41.7%) had large effect sizes ($g \geq 0.80$), five studies (41.7%) had medium effect sizes ($0.50 \leq g < 0.80$), and two studies (16.7%) had small-to-medium effect sizes ($g < 0.50$). The random-effects model yielded a combined effect size of $g = 0.78$ (95% CI: 0.61–0.94; $Z = 9.67$; $p < 0.001$). Based on Cohen's criteria, this value is classified as a large effect (Cohen, 1988), indicating that interactive media substantially improves biology learning achievement compared with conventional learning.

Table 2. Individual and overall effect size (random-effects model)

Code	Author (Year)	Hedges' g	SE	95% CI	Category
S01	Christopoulos et al. (2023)	0.72	0.242	[0.25; 1.19]	Medium
S02	Tsirulnikov et al. (2023)	0.68	0.182	[0.32; 1.04]	Medium
S03	Al-nakhle (2022)	1.46	0.378	[0.72; 2.20]	Large
S04	Lacey et al. (2024)	0.54	0.196	[0.16; 0.92]	Medium
S05	Kassa et al. (2024)	1.11	0.217	[0.69; 1.53]	Large
S06	Ntaila and Mbaraka (2023)	0.82	0.151	[0.52; 1.12]	Large
S07	Ciloglu and Ustun (2023)	0.61	0.247	[0.13; 1.09]	Medium
S08	Sattar et al. (2025)	0.95	0.267	[0.43; 1.47]	Large
S09	Hamizi and Mokmin (2026)	0.38	0.184	[0.02; 0.74]	Small
S10	Ferdinand et al. (2023)	0.48	0.144	[0.20; 0.76]	Small
S11	Foley et al. (2025)	1.18	0.217	[0.75; 1.61]	Large
S12	Miezah and Whajah (2023)	1.02	0.272	[0.49; 1.55]	Large
	Combined Effect Size	0.78	0.085	[0.61; 0.94]	Large

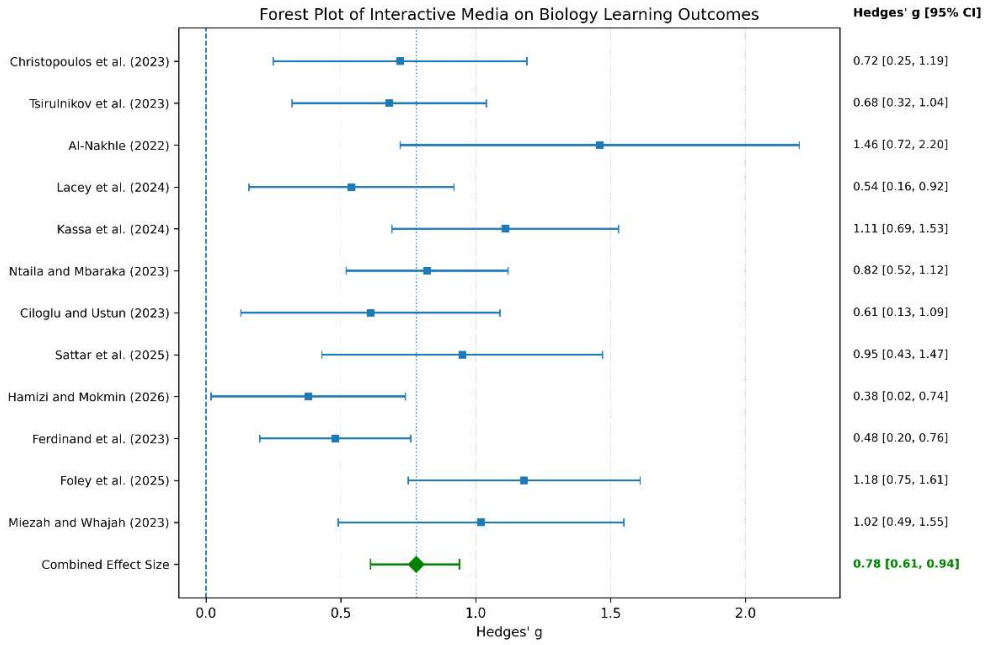


Figure 2. Forest plot

Heterogeneity Analysis

The heterogeneity test showed a Cochran's Q value of 21.12 with 11 degrees of freedom (df) and a p-value < 0.001, indicating a statistically significant difference in effect size between studies. The I^2 index of 71.4% indicated substantial heterogeneity. The $\hat{o}^2$ value of 0.082 indicated the estimated between-study variance in a random-effects model. The high heterogeneity suggests moderating factors influence effect size, so we conducted subgroup analyses for the established moderator variables.

Moderator Variable Analysis

The results of the subgroup analysis of the six moderator variables are presented in Table 3 below. Three moderator variables significantly influenced the magnitude of the effect size: the type of interactive media (Q-between = 11.84; p = 0.037), educational level (Q-between = 7.52; p = 0.023), and the accompanying pedagogical strategy (Q-between = 9.21; p = 0.027). In contrast, intervention duration, geographic region, and research design did not significantly moderate the effect size. Virtual laboratory produced the largest effect size (g = 1.06), followed by interactive multimedia (g = 0.95) and AR (g = 0.87), while VR produced the smallest effect size among the six categories (g = 0.57). For the moderator of educational level, tertiary education (g = 0.98) and junior high school (g = 0.95) produced larger effect sizes than senior high school (g = 0.72). However, the number of studies at the junior high school level was limited. Inquiry-Based Learning combined with interactive media produced the highest effect size (g = 1.12), far exceeding Direct Instruction (g = 0.78) and Problem-Based Learning (g = 0.68).

Table 3. Sub-Group analysis of moderator variables

Moderator Variable	K	Hedges' g	95% CI	Q-between	p-value
Type of Interactive Media					
Virtual Laboratory	2	1.06	[0.68; 1.44]	11.84	0.037*
Augmented Reality (AR)	2	0.87	[0.52; 1.22]		
Virtual Reality (VR)	4	0.57	[0.38; 0.76]		
Interactive multimedia	2	0.95	[0.70; 1.20]		
Interactive/Conventional Video	2	0.77	[0.44; 1.10]		
Educational Level					
Junior High School (JHS)	1	0.95	[0.43; 1.47]	7.52	0.023*
Senior High School (SHS)	7	0.72	[0.55; 0.89]		
College	4	0.98	[0.73; 1.23]		
Pedagogical Strategy					
Inquiry-based Learning	3	1.12	[0.82; 1.42]	9.21	0.027*
Problem-based Learning	2	0.68	[0.38; 0.98]		
Direct Instruction	7	0.78	[0.60; 0.96]		
Intervention Duration					
≤ 4 weeks	7	0.84	[0.65; 1.03]	1.84	0.175
> 4 weeks	5	0.96	[0.69; 1.23]		
Geographical Region					
Asia	5	0.80	[0.58; 1.02]	4.12	0.249
Europe	3	0.58	[0.38; 0.78]		
Africa	2	0.95	[0.60; 1.30]		
America	2	0.93	[0.55; 1.31]		
Study Design					
RCT	2	0.72	[0.42; 1.02]	2.81	0.094
Quasi-experimental	10	0.93	[0.73; 1.13]		

Note. k = number of studies; Q-between = between-group heterogeneity statistic; p < .05 indicates statistical

Publication bias was assessed using Egger's regression test, Begg and Mazumdar's rank correlation test, and the trim-and-fill method. As shown in Figure 3, the funnel plot visually assesses the symmetry of the effect-size distribution around the overall effect estimate. Egger's regression test yielded an intercept of 0.84 (SE = 1.12, $t = 0.75$, $p = 0.470$), while Begg and Mazumdar's test produced a Kendall's tau of 0.182 ($p = 0.387$). Neither test indicated statistically significant evidence of publication bias. Furthermore, the trim-and-fill analysis did not impute any additional studies. Taken together, these findings suggest no statistically significant evidence of publication bias in the included studies. However, interpret the results cautiously because nonsignificant tests do not conclusively rule out publication bias.

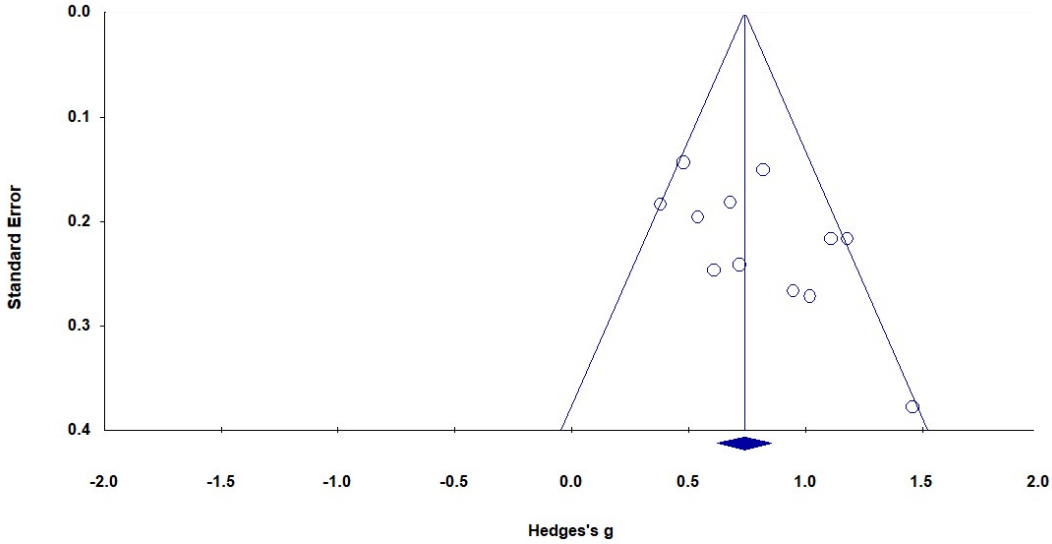


Figure 3. Funnel plot of standard error by hedge's g

The results of this meta-analysis consistently confirm that interactive media significantly improves biology learning achievement (g = 0.78; 95% CI: 0.61–0.94). This finding aligns with, and is slightly higher than, previous meta-analyses. Dong et al. (2024) reported g = 0.857 for mobile science learning in the biology sub-subject, while Vekli and Çalik (2023) found a moderate effect size for Web-Based Biology Learning Environment. In their meta-analysis on AR, Lin and Yu (2023) found a significant effect size on learning achievement across subjects. The slightly higher effect size in this study is likely related to the publication period of 2021–2025, which was post-COVID-19, when the quality of interactive media implementation and the digital literacy of both educators and students had significantly improved.

The finding that virtual laboratories produced the largest effect size (g = 1.06) makes sense considering the nature of biology, which is heavily influenced by experimental activities. Virtual laboratories provide authentic manipulative experiences without the cost, security, and logistical constraints of physical laboratories (Al-Nakhle, 2022; Tsirulnikov et al., 2023). In a virtual environment, students control variables, observe results, and generate hypotheses, activating higher-order cognitive processes. This aligns with Kolb's experiential learning theory (Kolb, 1984) and constructivism (Fosnot, 2013), which emphasize direct experience as the primary pathway for knowledge formation.

An interesting and paradoxical finding is VR's relatively lower effect size (g = 0.57) compared to other technologies. Several

explanations can be offered. First, fully immersive VR creates greater extraneous cognitive load because of intensive audio-visual processing demands, diverting cognitive resources from processing learning content (Mayer, 2005). Second, VR's novelty effect may divert focus from learning content. Third, the duration of VR interventions in the analyzed studies tended to be short (mostly d" 4 weeks), leaving insufficient time for students to adapt to this new modality. Hamizi & Mokmin (2026) found only a marginal difference (p = 0.052), suggesting that VR requires a careful pedagogical framework to realize its potential.

The significance of pedagogical strategies as moderators reaffirms Clark's (1994) classic message that "media will never influence learning." Media is not the primary determinant; the pedagogy inherent in it is. Inquiry-based learning paired with interactive media yielded the highest effect size (g = 1.12), as the characteristics of IBL, which require students to ask questions, formulate hypotheses, and interpret data, align closely with the affordances of interactive media that allow for open exploration. This finding confirms Dong et al. (2024), who also found inquiry-based and game-based learning to be the most effective strategies in mobile science learning.

The findings across educational levels suggest that the effect of interactive media may vary by educational context. The estimated effect sizes were larger for college students ($g = 0.98$) and junior high school students ($g = 0.95$) than for high school students ($g = 0.72$). However, interpret these differences cautiously, particularly for the junior high school category, which was represented by only one primary study ($k = 1$). Because a single study does not estimate within-group variability, the effect size for this educational level cannot serve as a robust basis for comparison or generalization. Future research should include more studies across educational levels to provide more reliable estimates and enable meaningful comparisons of interactive media effectiveness. Researchers should also investigate how factors such as students' digital literacy, learning autonomy, motivation, and instructional context may relate to differences in effect sizes across educational levels. Such investigations would help clarify whether the observed differences reflect genuine variations in effectiveness or are attributable to the limited evidence currently available.

The finding that intervention duration did not significantly moderate effect size (p = 0.175) has important practical implications: brief interventions (d" 4 weeks) can produce significant impacts, so adopting interactive media need not wait for long-term curriculum changes. Similarly, the insignificance of geographic region as a moderator (p = 0.249) implies that the effectiveness of interactive media is relatively consistent across cultural contexts, although technological infrastructure remains a prerequisite.

The larger effect size in quasi-experimental studies (g = 0.93) compared to RCTs (g = 0.72), although not statistically significant, is noteworthy. This pattern is common in educational meta-analyses and is usually attributed to more stringent confounding controls in RCTs, which yield more conservative effect estimates. This suggests that researchers should use RCT designs whenever possible to strengthen internal validity.

The practical implications of these findings are quite broad. For biology educators, the highest priority is integrating virtual laboratories and interactive multimedia with inquiry-based learning strategies, especially for abstract topics. For content developers, the focus should be on meaningful interactivity, not simply passive visualizations with attractive packaging. For education policymakers, investments in technological infrastructure must be paired with pedagogical training for teachers to optimally realize the potential of interactive media. For

researchers, more RCTs, studies at the junior high school level, and studies that directly compare different types of interactive media within a single research design are needed.

This study has several limitations that warrant acknowledgment. First, the number of primary studies analyzed (k = 12) is moderate, so the moderator test has limited statistical power, especially for categories with few studies. Second, the analysis included only English-language articles, which may introduce language bias. Third, some studies did not report complete statistical data, so we calculated effect sizes by converting t/F values, which may introduce small estimation errors. Fourth, this meta-analysis focused on cognitive learning achievement; other aspects such as motivation, attitudes, and science process skills were not thoroughly analyzed. Fifth, the relatively short intervention duration in most studies makes it difficult to assess long-term effects (retention).

■ CONCLUSION

A meta-analysis of 12 primary studies indexed in Scopus and/or Web of Science, published between 2021 and 2026 and involving a total of 1,219 participants, found that interactive media had a statistically significant large effect on biology learning achievement, with a pooled effect size of $g = 0.78$ (95% CI: 0.61–0.94; $p < 0.001$). Substantial heterogeneity was observed ($I^2 = 71.4\%$), and moderator analyses indicated significant differences by interactive media type, educational level, and accompanying pedagogical strategies. Virtual laboratories and interactive multimedia combined with inquiry-based learning at the tertiary level showed promising results. However, the effectiveness of interactive media varied across categories, and virtual reality (VR) yielded the lowest effect size among the media types examined ($g = 0.57$). This finding does not necessarily mean VR is ineffective; rather, it suggests that its educational benefits may depend on instructional design, learning objectives, and how the technology is integrated into teaching. Intervention duration, geographical region, and research design were not statistically significant moderators, although these findings should be interpreted in light of the number and characteristics of the available studies.

Based on these findings, several recommendations emerge. First, biology educators may consider using virtual laboratories and interactive multimedia integrated with inquiry-based learning, particularly for abstract topics such as cell biology, genetics, and molecular biology, while adapting their use to students' needs and available resources. Second, teachers should select VR selectively rather than assume it is superior to other forms of interactive media. Teachers should use VR when its immersive features directly support specific learning objectives, such as exploring complex biological structures or processes that are difficult to observe directly. Implementation should include clear learning tasks, appropriate guidance, and post-activity reflection to connect virtual experiences with biological concepts. Educators should also evaluate whether the benefits justify the costs, technical requirements, and potential usability challenges. Third, schools and higher education institutions should provide adequate technological infrastructure and professional development in digital pedagogy. Fourth, future research should include more randomized controlled trials, expand investigations at the junior high school level, examine non-cognitive outcomes such as motivation, science process skills, and scientific attitudes, and conduct longitudinal studies to assess long-term retention. Further studies should also investigate the instructional conditions under which VR can produce stronger learning outcomes. Finally, educational content developers should prioritize meaningful interactivity and pedagogical alignment over visual appeal alone. These measures may help ensure that interactive media are implemented critically and effectively to support meaningful, inclusive, and adaptive biology education.

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