



Digital Learning Media Innovation in Science Learning: A Systematic Literature Review

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Abstract

This systematic literature review analyzes the types, effectiveness, and implementation of digital learning media in junior high school science education in Indonesia (2020–2025). Following PRISMA 2020 guidelines, literature searches were conducted on January 15, 2025 across four databases (Crossref, Google Scholar, Semantic Scholar, and OpenAlex), yielding 3,114 articles. After screening, 7 articles met the inclusion criteria requiring quantitative effectiveness data. Seven media types were identified: Virtual Laboratory, Powtoon, Digital Comics, Genially+TGT, Interactive E-Modules, Learning Websites, and Educational Games. All studies reported improvements in measured learning dimensions, with N-Gain scores ranging 0.31–0.70 and mastery increases of 10–50 percentage points, suggesting digital media can support learning outcomes. However, findings require cautious interpretation as most studies used one-group pretest-posttest designs without control groups. Effectiveness depends on alignment with material characteristics, pedagogical integration, user-friendly design, and infrastructure support. This review contributes to a comprehensive mapping of digital media in Indonesian science education, identification of media-material compatibility patterns, and synthesis of implementation factors. Implications for educators, developers, and policymakers are discussed.

INTRODUCTION

Digital transformation has brought fundamental changes to 21st-century learning practices, particularly in Natural Science (IPA) education. Science learning at the junior high school level presents unique challenges because much of its content is abstract and complex, requiring media capable of concretizing and visualizing scientific phenomena (Sintia & Manuaba, 2021). The characteristics of *digital native* students—who have grown up with digital technology and prefer visual, interactive, and technological learning styles—increasingly demand teaching methods that align with their needs (Priana, 2017). In this context, digital learning media offer a strategic solution, not only enriching learning resources but also playing a crucial role in organizing information visually and verbally to create more meaningful and interactive learning experiences (Xuan & Della, 2024). The integration of digital media in science education has become an urgent necessity within the Indonesian education system to improve learning quality, develop 21st-century skills, and enhance global competitiveness.

Various studies have examined the use of digital media in learning from different perspectives. At the conceptual level, Zubaidah (2016) highlighted the importance of developing 21st-century skills in learning, while Damayanti et al. (2024) examined the strategic utilization of digital learning platforms in the era of the *Kurikulum Merdeka* (Independent Curriculum) with a focus on macro-level policy aspects. At the media development level, several studies have focused on specific media types, such as interactive PowerPoint media for social studies learning (Anggraeni, 2021), the Canva application for elementary science education (Indriani, 2024), and the role of social media in high school physics learning (Yuniani et al., 2019). More specific research on digital media in science education includes the development of Augmented Reality (AR) for atmospheric layer material (Pangestu et al., 2020), Ethno-Augmented Reality integrating Balinese local wisdom (Pusparani & Selamat, 2021), and virtual laboratories for electricity

material (Kurniawan, 2021). Although valuable, these studies remain partial and limited to a single media type, one learning topic, or a specific educational level, thus failing to provide a comprehensive picture of the digital media landscape in Indonesian science education.

Based on the review of previous studies, four research gaps underpin the need for this systematic review. *First*, there has been no systematic effort to synthesize findings from various studies on the development and implementation of digital media within a single, integrated review framework; previous research tends to be isolated and unintegrated. *Second*, there is no systematic comparative analysis of the strengths, weaknesses, and effectiveness of different types of digital media—such as AR, virtual laboratories, digital comics, gamification platforms, and interactive e-modules—across different science topics. *Third*, the factors influencing the successful implementation of digital media—both supporting and inhibiting factors—have not been analyzed in an integrated manner across studies, resulting in limited and insufficiently evidence-based practical recommendations for educators and media developers. *Fourth*, previous reviews have not specifically mapped the Indonesian context with its diverse infrastructure characteristics, evolving curriculum dynamics (from the 2013 Curriculum to the *Kurikulum Merdeka*), and rich local wisdom integrated into media development. These gaps indicate the need for a systematic review that can answer fundamental questions about what, how, and how effectively digital media are used in science education in Indonesia.

This systematic review limits its scope to Indonesia based on the following considerations: (a) the unique context of national education with its geographical diversity and technological infrastructure disparities; (b) the existence of digital education transformation policies through initiatives such as the *Platform Merdeka Mengajar* (Teaching Independence Platform) that require contextual study; (c) the integration of local wisdom in digital media development, which is a distinctive feature of Indonesia; and (d) direct relevance to the

national curriculum so that review findings can be immediately implemented by educators in Indonesia. The 2020–2025 time frame was selected because this period marks the acceleration of digital technology adoption following the COVID-19 pandemic, the rapid development of digital education platforms, the availability of sufficient studies for analysis, and the coverage of the curriculum transition period that provides perspective on the adaptation of digital media to changing educational policies.

The *novelty* of this review lies in five main contributions: (1) a comprehensive mapping of seven categories of digital media in junior high school science education that has never been conducted before; (2) identification of compatibility patterns between science material characteristics and the most effective types of digital media, which can serve as practical guidance for educators; (3) a holistic synthesis of supporting and inhibiting factors for digital media implementation; (4) analysis of digital media effectiveness across multiple learning dimensions (cognitive, HOTS, scientific representation, digital literacy, and conceptual understanding); and (5) development of a contextual *Technological Pedagogical Content Knowledge* (TPACK) framework for science education in Indonesia.

Based on the above description, this research aims to analyze the effectiveness and implementation of various types of digital learning media in junior high school science education during the 2020–2025 period. Specifically, this review answers four research questions: (1) what types of digital media are used in junior high school science learning; (2) how effective are digital media in improving student learning outcomes and skills; (3) what science materials are applied in digital media; and (4) what are the supporting and inhibiting factors for digital media implementation. The findings of this review are expected to provide theoretical contributions in the form of a more comprehensive understanding of the digital media landscape in Indonesian science education, as well as practical contributions in the form of evidence-based recommendations for educators in selecting

and integrating appropriate digital media, for media developers in designing effective media, and for policymakers in formulating contextual and sustainable digital education transformation strategies.

METHOD

Research Design

This study is a Systematic Literature Review (SLR) that uses the PRISMA 2020 (*Preferred Reporting Items for Systematic Reviews and Meta-Analyses*) guidelines as a reporting standard to ensure transparency, completeness, and reproducibility in the review process (Page et al., 2021). PRISMA 2020 provides a 27-item checklist and a four-phase flow diagram that guides authors in reporting systematic reviews, minimizing bias, and enabling critical appraisal of the review methodology. The methodological approach of this review is grounded in established SLR procedures as outlined by Snyder (2019), which include systematic searching, screening, data extraction, and thematic synthesis.

1. Research Questions

The literature review process was guided by four research questions (RQ) presented in Table 1. These questions were formulated using the PICO (*Population, Intervention, Comparison, Outcome*) framework adapted for qualitative synthesis, aiming to focus the search strategy and facilitate the discovery of relevant data.

Table 1. Research questions

No.	Research Questions	Purpose of Analysis
1	What types of digital learning media are used in science learning at junior high school level?	Identification and categorization of types of digital learning media developed in the 2020-2025 period
2	How effective is digital learning media in improving learning outcomes and skills of junior high school students?	Analysis of media effectiveness on cognitive, affective, and 21st century skills aspects

No.	Research Questions	Purpose of Analysis
3	What science materials are applied in digital learning media at the junior high school level?	Identification of the suitability between media types and the characteristics of science materials
4	What are the supporting and inhibiting factors for the implementation of digital learning media?	Synthesis of factors influencing successful implementation

2. Search Strategy

A comprehensive literature search was conducted on January 15, 2025 across four electronic databases: Crossref, Google Scholar, Semantic Scholar, and OpenAlex. These databases were selected for their complementary strengths: Google Scholar provides broad access to diverse scholarly publications; Crossref ensures consistent scholarly discovery through permanent DOIs; Semantic Scholar offers advanced features such as automated summaries (TLDRs), research recommendations, and citation impact analysis; and OpenAlex provides open access to comprehensive academic research metadata. The combination of these databases enabled the acquisition of credible, diverse, and relevant references while minimizing database bias.

The search was limited to articles published between January 1, 2020 and December 31, 2025. The search strategy employed Boolean operators (AND, OR) with keywords adapted for each database's specific search syntax. The primary keywords used were:

Google Scholar & Semantic Scholar:

("digital learning media" OR "digital media" OR "multimedia learning" OR "interactive media") AND ("science learning" OR "science education" OR "natural science" OR "IPA learning") AND ("junior high school" OR "middle school" OR "SMP" OR "secondary school")

Crossref & OpenAlex:

title:("digital learning media" OR "digital media" OR "multimedia") AND abstract:("science learning" OR "science education" OR "IPA") AND affiliation.country:("Indonesia")

Filters Applied to All Databases:

- Publication date: 2020-2025

- Document type: journal articles (excluding proceedings, books, book chapters, and reviews)
- Language: Indonesian or English
- Peer-reviewed journals only (where applicable)

The complete search strings with database-specific syntax and filters are presented in Table 2.

Table 2. Search strings and database specifications

Database	Search String / Query	Filters Applied	Results
Google Scholar	("digital learning media" OR "digital media" OR "multimedia learning" OR "interactive media") AND ("science learning" OR "science education" OR "natural science" OR "IPA learning") AND ("junior high school" OR "middle school" OR "SMP" OR "secondary school")	Since 2020; Sort by relevance	1,847
Crossref	title:("digital learning media" OR "digital media" OR "multimedia") AND abstract:("science learning" OR "science education" OR "IPA") AND affiliation.country:("Indonesia")	From 2020-2025; Type: journal articles	453

Semantic Scholar	("digital learning media" OR "digital media" OR "interactive media") AND ("science learning" OR "science education" OR "natural science") AND ("junior high school" OR "middle school")	Year: 2020-2025; Publication types: Journal Article	287
OpenAlex	search ("digital learning media" AND "science learning") AND primary_location.source.type = "journal" AND publication_year >= 2020 AND publication_year <= 2025	Type: article; Country: id	527
Total			3,114

Criteria	Description
Inclusion Criteria	1. Peer-reviewed research articles published 2020-2025 2. Research topic: digital learning media in science learning 3. Research subjects: junior high school students/equivalent in Indonesia 4. Research method: experiment (<i>quasi-experimental</i> or <i>true experimental</i>) with control group or <i>one-group pretest-posttest</i> design measuring learning effectiveness 5. Articles in Indonesian or English 6. Articles presenting quantitative media effectiveness data (N-Gain, mastery percentage, t-test, or effect size).
Exclusion Criteria	1. Articles without full text 2. Articles outside the context of formal education 3. Studies without involving teachers or classroom implementation 4. Duplicate articles 5. Review articles, proceedings, or books 6. Development research without field trials 7. Studies reporting only validity, practicality, or student responses without measurable learning effectiveness data

3. Selection Procedure

The article selection procedure followed the PRISMA 2020 four-phase flow diagram (identification, screening, eligibility, and inclusion). The process was conducted independently by two reviewers (Mardhiah and a second reviewer with expertise in educational technology) to minimize bias, with disagreements resolved through consensus or consultation with a third reviewer when necessary.

Inclusion and Exclusion Criteria

The inclusion and exclusion criteria were established *a priori* based on the research questions and are presented in Table 3. These criteria were applied consistently during the screening process.

Table 3. Inclusion and exclusion criteria

Screening Process (Detailed)

Phase 1: Identification (n = 3,114)

- Records identified through database searching: n = 3,114 (Google Scholar: 1,847; Crossref: 453; Semantic Scholar: 287; OpenAlex: 527)
- All records were exported to reference management software (Zotero) for collation and duplicate removal.

Phase 2: Duplicate Removal (n = 2,941)

- After import, 173 duplicate records were identified and removed using Zotero's duplicate detection feature, followed by manual verification.

Phase 3: Title and Abstract Screening (n = 2,941 → n = 246)

- Two independent reviewers screened titles and abstracts against the inclusion criteria. Articles were excluded if they clearly did not meet the criteria based on title and abstract alone. At this stage, 2,695 articles were excluded, primarily because they: (a) were not about digital learning

media, (b) did not focus on science learning, (c) were not conducted in Indonesia, (d) did not involve junior high school students, or (e) were review articles, proceedings, or books.

- **Remaining after title/abstract screening:** $n = 246$

Phase 4: Full-Text Eligibility Assessment ($n = 246 \rightarrow n = 7$)

- The full text of the 246 remaining articles was retrieved and assessed for eligibility by both reviewers independently.
- Reasons for exclusion at this stage: $n = 239$ excluded with the following distribution:
 - 68 articles lacked quantitative effectiveness data
 - 54 were development studies without field trials
 - 42 did not involve actual classroom implementation
 - 38 did not focus on junior high school
 - 28 did not provide full-text access
 - 6 were duplicate articles missed in the earlier phase
 - 3 articles were excluded because they only reported validity, practicality, or student responses without measurable learning effectiveness data
- **Final included studies:** $n = 7$

The complete screening process is visualized in Figure 1 (PRISMA 2020 Flow Diagram).

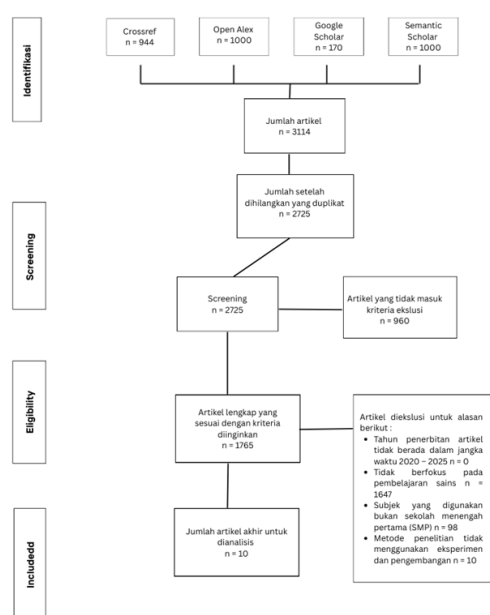


Figure 1. PRISMA 2020 flow diagram

4. Data Extraction

Data extraction was conducted independently by two reviewers using a standardized data extraction form developed specifically for this review. The form was piloted on three articles prior to full data extraction and revised accordingly to ensure consistency and completeness. The extracted data elements included:

1. Bibliographic information: Author(s), year of publication, journal name, volume/issue, and DOI
2. Study characteristics: Research design (R&D/experimental), research subjects (school level, sample size, class), and research location
3. Intervention details: Type of digital learning media, science material/topic, learning model integrated, and implementation duration
4. Effectiveness data: N-Gain scores, mastery rates, t-statistics, p-values, and effect sizes (if reported)
5. Outcome dimensions: Cognitive learning outcomes, HOTS, representation skills, motivation, science process skills, digital literacy, conceptual understanding
6. Supporting factors: As reported in studies (e.g., user-friendly design, model integration, curriculum relevance, interactivity)
7. Inhibiting factors: As reported in studies (e.g., infrastructure limitations, digital distraction, teacher readiness, material characteristics)

Any disagreements between the two reviewers during data extraction were resolved through discussion and consensus. A third reviewer was consulted for unresolved disagreements, though this was not required as all disagreements were resolved through discussion.

5. Data Analysis Procedure

The data synthesis employed a thematic synthesis approach as described by Thomas and Harden (2008), which is appropriate for integrating findings from studies with heterogeneous designs and outcomes. The synthesis was conducted in three stages:

Stage 1: Coding Text

All extracted data were entered into a Microsoft Excel spreadsheet and organized

into thematic categories based on the research questions. Initial codes were generated from the data, identifying patterns related to media types, effectiveness, materials, and factors influencing implementation.

Stage 2: Descriptive Synthesis

The coded data were organized into descriptive themes. A narrative synthesis was conducted to describe the characteristics of each study and the types of digital learning media identified. Frequency counts were calculated for media types, science materials, and effectiveness dimensions to identify patterns and trends across studies.

Stage 3: Analytical Synthesis

The descriptive themes were further analyzed to generate analytical themes that went beyond the original findings of individual studies. This stage involved:

- Comparing and contrasting effectiveness data across different media types while considering each study's context
- Identifying patterns of congruence between media types and science material characteristics
- Synthesizing supporting and inhibiting factors into a coherent framework
- Drawing conclusions about the overall effectiveness and implementation conditions of digital learning media in Indonesian junior high school science education

The synthesis was conducted by the lead reviewer and verified by the second reviewer to ensure accuracy. The findings are presented narratively in the Results and Discussion section, supported by summary tables and figures.

6. Quality Assessment

Quality assessment of the included studies was performed using adapted criteria based on the Critical Appraisal Skills Programme (CASP) checklist for qualitative and quantitative studies. The following criteria were assessed for each study:

1. Clarity of research objectives and research questions
2. Appropriateness of research design for the stated objectives
3. Clarity of sample description and sampling procedure
4. Appropriateness of data collection methods and instruments

5. Validity and reliability of instruments reported
6. Appropriateness of data analysis techniques
7. Clarity of findings presentation
8. Discussion of limitations
9. Ethical considerations mentioned

Each criterion was rated as "Yes," "No," or "Unclear." Studies were not excluded based on quality assessment scores; instead, quality ratings were used to contextualize findings and inform the strength of conclusions. All seven included studies met at least 7 of the 9 quality criteria, indicating acceptable methodological quality for inclusion in the review.

RESULT AND DISCUSSION

Based on a systematic literature review, 7 articles were identified as suitable for analysis. These articles originated from Indonesia and discussed digital learning media for junior high school students in science learning. Of the seven studies analyzed, five were development research (*Research & Development*) with field trials that measured effectiveness, while two used experimental or classroom action research methods.

Individual Findings from Each Study

The characteristics and individual findings of the seven studies are presented in Table 4.

Table 4. Characteristics and individual findings of studies on digital learning media in junior high school science learning

No	Author (Year)	Media Types	Science material	Research Design	Success Measure	Quantitative Findings
1	Kurniawan (2021)	Virtual Laboratory (VLCK)	Dynamic Electricity	Classroom Action Research (2 cycles)	Learning mastery	Cycle I: 75%; Cycle II: 85%
2	Arif & Muthoharoh (2021)	Powtoon-Based Media	Human Respiratory System	Quasi-experimental/control	N-Gain of representation skills	Experimental: 61.38%; Control: 48.20%
3	Alfarisi et al. (2022)	Chibi Manga Digital Comics	Solar System	One-group pretest-posttest	N-Gain of HOTS	0.31 (moderate category)
4	Sari et al. (2025)	Genially + TGT Model	Ecology and Biodiversity	Classroom Action Research (2 cycles)	Learning mastery	Cycle I: 38%; Cycle II: 88%

5	Lestari & Parmiti (2020)	Interactive E-Module	Grade VII Integrated Science	One-group pretest-posttest	Cognitive learning outcomes	$t = -31.27$ ($p < 0.05$)
6	Rosita et al. (2025)	Learning Website	Human Respiratory System	One-group pretest-posttest	N-Gain of digital literacy	0.70 (high category)
7	Hidayatulloh et al. (2020)	Educational Game (<i>Adventure Game</i>)	Temperature and Its Changes	One-group pretest-posttest	Conceptual understanding	$t = -5.806$ ($p < 0.001$)

Summary of Media Types Identified

Based on the analysis of the seven studies, seven types of digital learning media were identified in junior high school science learning:

1. Virtual Laboratory (Kurniawan, 2021)

The Virtual Laboratory Circuit Construction Kit (VLCKK) was applied to Dynamic Electricity material. This media allows students to conduct virtual experiments safely and repeatedly without the risk of electrical hazards or equipment damage. The study reported an increase in learning mastery from 75% in Cycle I to 85% in Cycle II, representing a 10 percentage point improvement.

2. Powtoon-Based Media (Arif & Muthoharoh, 2021)

Powtoon-based media was developed for Human Respiratory System material. This media integrates animation, audio, and text in a multimodal presentation format. The experimental class achieved an N-Gain of 61.38%, while the control class achieved 48.20%, indicating a positive contribution to students' scientific representation skills.

3. Chibi Manga Digital Comics (Alfarisi et al., 2022)

Digital comics with a Chibi Manga style were developed for Solar System material. This media uses a visual narrative approach with metacognitive scaffolding to develop Higher Order Thinking Skills (HOTS). The study reported an N-Gain of 0.31, categorized as moderate.

4. Genially Integrated with TGT Model (Sari et al., 2025)

The Genially platform was integrated with the Teams Games Tournament (TGT) cooperative learning model for Ecology and Biodiversity material. This media combines gamification elements with collaborative competition.

Learning mastery increased from 38% in Cycle I to 88% in Cycle II, representing a 50 percentage point improvement.

5. Interactive E-Module (Lestari & Parmiti, 2020)

An interactive e-module containing online tests was developed for Grade VII Integrated Science. This media features a clear curriculum structure, instant feedback on formative tests, and supports self-paced learning. The t-test results showed $t = -31.27$ ($p < 0.05$), indicating a significant difference between pretest and posttest scores.

6. Learning Website (Rosita et al., 2025)

A comprehensive learning website integrating text, video, games, and e-books was developed for Human Respiratory System material. This media can be accessed anytime and anywhere, supporting the development of digital literacy. The study reported an N-Gain of 0.70 (high category).

7. Educational Game (Hidayatulloh et al., 2020)

An adventure educational game with a reward system (coins, levels) was developed for Temperature and Its Changes material. This media presents learning content through adventure missions, making learning engaging and motivating. The t-test results showed $t = -5.806$ ($p < 0.001$), indicating a statistically significant improvement in conceptual understanding.

Distribution of Science Materials in Digital Media

Based on the analysis of the seven studies, the distribution of science materials applied in digital media is presented in Table 5.

Table 5. distribution of science materials in digital media

Science Field	Specific Material	Suitable Media Types	Number of Studies
Biology	Human Respiratory System	Powtoon, Learning Website	2
Physics	Ecology and Biodiversity	Genially + TGT	1
	Dynamic Electricity	Virtual Laboratory	1
			1

	Temperature and Its Changes	Educational Game	
Astronomy	Solar System	Digital Comics	1
Integrated Science	Grade VII Integrated Content	Interactive E-Module	1
Total			7

Dimensions of Effectiveness Measured

The seven studies measured various dimensions of learning effectiveness. The distribution of effectiveness dimensions is presented in Figure 2.

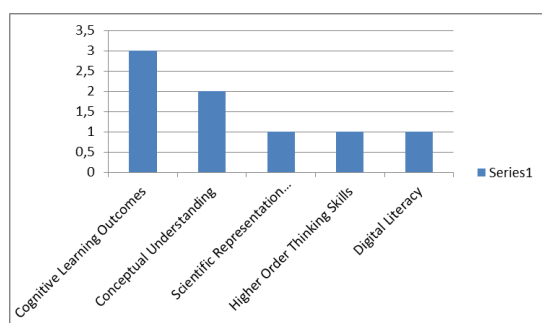


Figure 2. Dimensions of effectiveness measured in the seven studies

Supporting and Inhibiting Factors for Implementation

Based on the analysis of the seven studies, several supporting and inhibiting factors for the implementation of digital learning media were identified.

Supporting Factors:

1. **User-Friendly Design:** Media with intuitive and easy-to-navigate interfaces demonstrated higher adoption rates and learning impact. For example, the virtual laboratory by Kurniawan (2021) allowed students to conduct repeated experiments safely.
2. **Integration with Learning Models:** Media integrated with relevant models showed higher effectiveness than standalone use. The integration of Genially with the TGT model by Sari et al. (2025) resulted in a 50 percentage point increase in learning mastery.
3. **Relevance to the Curriculum:** Media developed with Core Competencies (KI) and Basic Competencies (KD) in mind

demonstrated a more measurable impact on achieving learning objectives (Alfarisi et al., 2022).

4. **Elements of Interactivity and Gamification:** Interactive features such as quizzes, simulations, and game elements created engaging and motivating learning experiences (Hidayatulloh et al., 2020).
5. **Multimodal Content:** Integration of text, video, audio, and animation accommodated diverse learning styles (Arif & Muthoharoh, 2021; Rosita et al., 2025).

Inhibiting Factors:

1. **Infrastructure Limitations:** Issues with internet quotas, device ownership, and adequate device specifications were often major obstacles, especially in schools with limited resources.
2. **Digital Distraction:** Several studies reported a tendency for students to open other applications, such as games and social media, during learning.
3. **Teacher Readiness:** Teachers' abilities to manage learning with digital media were a determining factor. Readiness included not only technical competence but also pedagogical competence in meaningfully integrating media (Kurniawan, 2021).
4. **Material Characteristics:** The characteristics of the material determined the suitability and effectiveness of certain media types. Procedural and experimental materials were better suited to virtual laboratories, while anatomical materials were more effectively visualized through other media.
5. **Limited Offline Access:** Some media required internet connectivity, which was a barrier for students with limited connectivity (Muharromah & Sartika, 2025).

CONCLUSION

This systematic review analyzed seven studies on digital learning media in junior high school science education during the 2020–2025 period, with the finding that all studies reported improvements in the measured learning dimensions, although the magnitude

and measures of success varied across studies—ranging from 10 to 50 percentage point increases in learning mastery, N-Gain scores between 0.31–0.70, to statistically significant t-test results—which collectively indicates that digital media has the potential to support improved student learning outcomes and skills; however, this interpretation must be made with caution given that the majority of studies used *one-group pretest-posttest* designs without control groups, so causality cannot yet be conclusively established. The seven types of media identified—Virtual Laboratory, Powtoon, Digital Comics, Genially integrated with TGT, Interactive E-Modules, Learning Websites, and Educational Games—demonstrate that successful implementation of digital media depends heavily on three main factors: alignment with material characteristics (e.g., virtual laboratories for experimental material and narrative visual media for abstract material), integration with appropriate learning models (such as TGT for cooperative learning), and infrastructure support and teacher readiness, all of which align with the *Technological Pedagogical Content Knowledge* (TPACK) framework emphasizing synergy between technology, pedagogy, and content. The main contributions of this review are a comprehensive mapping of digital media types in Indonesian science education, identification of media-material compatibility patterns, and synthesis of supporting and inhibiting implementation factors that have previously been fragmented across separate studies. However, the limitations of this review include the limited number of studies (only seven studies), the geographical scope limited to Indonesia, the heterogeneity of success measures used across studies, and the predominance of *one-group pretest-posttest* designs that limit the generalizability of findings. Practically, the findings of this review imply that educators should select media based on alignment with material characteristics and learning models, media developers are advised to conduct effectiveness testing with stronger research designs (*quasi-experimental* or *randomized controlled trials*) after validity and practicality testing, and future researchers are recommended to conduct meta-analyses to measure the combined effect sizes of various types of digital media and to explore the development of hybrid media that combine the advantages of multiple media types

simultaneously, so that digital transformation in science education can proceed in a more measurable, contextual, and sustainable manner.

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