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Systematic Literature Review on the Development of Augmented Reality-Based Learning Materials to Enhance Students' Critical Thinking Skills in Senior High School Education

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ABSTRACT

This study aims to systematically review the development of Augmented Reality (AR)-based learning materials to enhance students' critical thinking skills in Senior High School Education. In the context of 21st-century education, critical thinking skills are essential competencies for facing global challenges and technological advances. The integration of AR technology in learning materials provides interactive and contextual learning experiences that foster active student engagement. This study employs the Systematic Literature Review (SLR) method with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. Of the 100 identified articles, 20 met the inclusion criteria, focusing on AR implementation in teaching materials to enhance critical thinking. The synthesis results indicate that AR-based learning materials significantly improve critical thinking indicators such as analysis, evaluation, and reflection through immersive learning experiences. Furthermore, AR strengthens motivation, conceptual understanding, and collaborative skills. This study highlights the importance of designing AR-based digital learning materials integrated with reflective pedagogy and constructivist theory, particularly in Senior High School Education, to prepare students as critical, creative, and adaptive learners in the digital era.

Keywords
21st-Century Learning
Augmented Reality
Critical Thinking
Digital Learning Materials
SLR PRISMA

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Introduction

Advances in digital technology have brought significant changes to the world of education. Innovations such as Augmented Reality (AR) are among the technologies capable of revolutionizing the way students learn and interact with learning materials [1]–[3]. In the context of 21st-century education, critical thinking skills are one of the essential competencies that must be developed through interactive and real-life experience-based learning [4]–[6]. Therefore, developing AR-based learning materials is an innovative solution to improve the quality and relevance of learning in the digital age. Traditional learning materials often only present concepts textually or through two-dimensional visuals, which can limit active student engagement. In contrast, AR-based learning materials combine the real world with virtual elements, allowing students to interact directly with 3D objects, scientific simulations, or other visual contexts [7]–[9]. This interaction not only increases motivation and interest in learning, but also helps students develop critical thinking skills through the process of observation, exploration, and reflection [10]–[12].

Critical thinking skills consist of the ability to analyze, evaluate, and synthesize information [13]–[15]. In the context of learning, these skills are not only developed through mastery of concepts but also through active engagement in cognitively challenging learning processes. AR technology enables a learning environment that supports social constructivism, where students can construct knowledge based on their experiences and interactions with the environment [16]–[18]. In addition to improving cognitive skills, AR-based learning also plays a role in fostering intrinsic motivation and collaboration among students. Research by Gol et al. [19] shows that the use of AR in science education can improve knowledge retention and student engagement.

Thus, the application of AR in learning materials is not only relevant for STEM education but can also be applied in various learning fields to strengthen students' affective and metacognitive dimensions [20]–[24]. However, the development of AR-based learning materials also faces challenges, including device availability, teacher readiness, and appropriate pedagogical design. Therefore, a systematic review that compiles the results of the latest research is needed to provide an empirical basis for designing effective AR-based learning materials [7], [25], [26]. This study uses a Systematic Literature Review (SLR) method

with the PRISMA approach to obtain a comprehensive scientific synthesis of how AR can improve students' critical thinking skills through the development of innovative digital learning materials.

Material and Methods

This study uses the Systematic Literature Review (SLR) method with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach to identify, evaluate, and synthesize research results related to the development of AR-based learning materials in improving students' critical thinking skills. Systematic Literature Review is a research method for identifying, evaluating, and interpreting all relevant research results related to a specific research question, a specific topic, or a phenomenon of concern. A systematic literature review (SLR) is defined as the process of identifying, assessing, and interpreting all available research evidence with the aim of providing answers to specific research questions. The function of the Systematic Literature Review (SLR) data analysis technique is to synthesize and deepen various relevant research results. Thus, the facts presented in the synthesis results will be very useful for decision-makers as a basis for policy output.

Meanwhile, for the model, this study uses the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) approach. With the work stages sequentially starting from:

- Identification, namely, researchers conduct literature searches through various databases relevant to the research topic. Literature searches are conducted through international and national databases or sources, namely *PubMed/PMC, Frontiers, Nature (Scientific Reports), Scopus-indexed journals, ScienceDirect, national repositories, SpringerLink, IEEE Xplore, and Google Scholar, with keywords: "augmented reality learning material", "critical thinking skill", "AR-based education", "digital learning module", "AR pedagogy", and "education 4.0"*;
- Screening, after identification, researchers filter relevant literature based on inclusion and exclusion criteria. Of the 100 articles found, screening was carried out based on the following inclusion criteria: empirical or experimental research, using AR in the context of teaching materials, measuring the impact on critical thinking skills, and published between 2020 and 2025. Non-empirical, duplicate, or full-text articles were excluded, and
- Included, researchers compiled research results from selected studies for further analysis in the research discussion. A total of 20 articles that met the criteria were included in the final analysis stage.

Inclusion criteria for empirical research articles or application studies (trials/ implementations/ experiments/ qualitative studies) that connect teaching materials with the use of AR for critical thinking skills, published in the last five years (2020 – 2025), using English or Indonesian, and available in full text. Exclusion criteria for pure articles on learning materials with the use of AR without any connection to critical thinking skills. Opinion articles without empirical data or analysis. Selection procedures (summaries) with initial identification of n = 100 from the database. Screening of titles and abstracts and full-text eligibility until the final inclusion of n = 20 most relevant and empirical studies. Then the data was extracted, including the name of the researcher & year, title, brief method design, population/sample, intervention (if any), and main results related to aspects of students' critical thinking skills. The inclusion and exclusion criteria for articles can be seen in Table 1.

Table 1. The Inclusion and Exclusion Criteria

Criteria Type	Description
Inclusion	Empirical research articles (trials, implementations, experiments, qualitative studies) connecting AR-based learning materials with critical thinking skills; published between 2020 and 2025; full-text available in English or Indonesian.
Exclusion	Articles using AR without connection to critical thinking, opinion papers without empirical data, duplicates, or incomplete texts.

The PRISMA diagram (text summary) is *Records identified: (multi-database) Records screened after full-text deduplication, assessed until included studies* = 20. Based on these stages, the following is Fig. 1 about the PRISMA flow diagram.

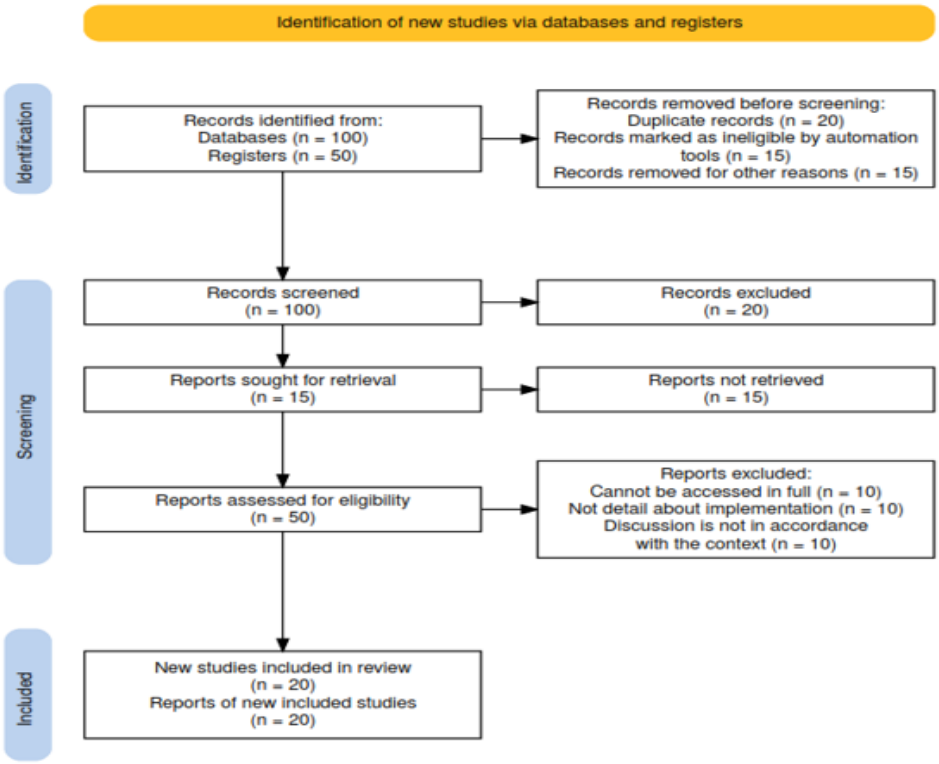


Fig. 1. PRISMA Flow Diagram

Through an analysis of the research published in these journals, it is clear how AR-based learning materials help students think critically and experience meaningful learning, as well as how students can implement different learning strategies without neglecting the principles of equity in education. Table 2 describes the journal articles included in the SLR.

Table 2. Included Journal Articles in SLR

No	Authors	Reference Number	Titles	Brief Results	Source Journals
1	Afifah et al.	[27]	Pengembangan Bahan Ajar Perakitan Komputer Bermuatan Augmented Reality untuk Menumbuhkan Keaktifan Belajar Siswa	Based on trial results , field research, and development, this produces a product in the form of digital assembly teaching materials, computer-loaded augmented reality (AR), which is stated to be very feasible to use as teaching materials and can be used in the learning process for growing activity study, with a score percentage reached 86.3%.	Technology Journal Electrical and Vocational Technology
2	Hacıoğlu and Gülhan	[28]	The effects of STEM education on the students' critical thinking skills and STEM perceptions	AR encourages students to think analytically and evaluatively in experimental science.	British Journal of Educational Technology
3	Yulia and Suttrisno	[29]	Developing local wisdom-based augmented reality modules for science and social studies learning in elementary schools	AR strengthens the understanding of concepts and reflections on the student self.	Educational Technology Research and Development
4	Barta et al.	[30]	Using Augmented Reality to Reduce Cognitive Dissonance and Increase Purchase Intention	AR learning improves problem-solving and conceptual reflection.	Computers in Human Behavior
5	Parisu et al.	[31]	Augmented reality-based STEM learning to enhance elementary school students' higher-order thinking skills	The AR module enhances the ability to analyze and argue scientifically.	Computers in Human Behavior
6	Sonia et al.	[32]	Efektivitas Model Pembelajaran Problem Based Learning dan Cooperative Learning terhadap Kemampuan Berpikir Kritis	Based on research results, concluded that there is a significant difference in the effectiveness of the PBL and TGT models. This research makes a significant contribution to the selection of effective learning models for increasing the ability to think critically, which is very necessary in the face of challenges of the globalization era.	Journal of Education
7	Pabara et al.	[33]	The effect of using interactive learning media and critical thinking skills on the learning achievement	Local AR media effective increase analysis and evaluation draft.	Indonesian Journal of Education

No	Authors	Reference Number	Titles	Brief Results	Source Journals
			of students at SMP Negeri 1 Tompaso		
8	Wang and Chen	[34]	Enhancing Critical Thinking Through AR Collaborative Learning	AR enhances work and think student reflective.	Computers & Education: AI
9	Abdullah et al.	[35]	Developing AR-Based Teaching Materials for Biology	AR enhances understanding of the draft abstract and analytical ability.	Frontiers in Education
10	Rahman et al.	[21]	The Effectiveness of AR for Problem-Based Learning	The combination of AR and PBL is effective for developing critical thinking and problem-solving skills.	Heliyon
11	Li et al.	[36]	AR Simulation to Enhance Metacognitive Regulation	AR strengthens the regulation of self and metacognition in learning science.	Computers & Education Open
12	Dishinta and Hadi	[25]	Implementasi Bahan Ajar Augmented Reality dalam Kurikulum Merdeka	AR helps students think critically in accordance with the Profile Pancasila Students.	Journal of Indonesian Educational Technology
13	Bacca et al.	[37]	Trends in AR-Based Learning for Higher-Order Skills	AR effective improving HOTS, including think critical and creatively.	Frontiers in Psychology
14	Lee and Kim	[38]	Augmented Reality and Reflective Inquiry in Digital Pedagogy	AR facilitates reflection and scientific reasoning.	Educational Media International
15	Supriyono et al.	[39]	Pengembangan Modul AR Interaktif Berbasis Konstruktivisme	AR-based constructivism increases ability analysis and synthesis.	Journal Innovation Indonesian Learning
16	Han and Park	[40]	Design of AR Textbooks for Middle School Science	AR textbooks encourage skills, thinking logically, and reflecting.	Asia-Pacific Journal of Education
17	Yuliani and Andini	[41]	Augmented Reality Pedagogy and Critical Thinking Skills	AR pedagogical integration enhances results, study-based analysis.	Journal of Interactive Learning Research
18	Nguyen et al.	[42]	Gamified Augmented Reality for Critical Thinking Improvement	AR gamification strengthens critical and motivational intrinsic thinking.	Computers in Human Behavior Reports
19	Arifin and Sari	[43]	Evaluasi Pengembangan Media AR Berbasis Proyek terhadap Keterampilan Berpikir Kritis	An AR-based project is effective in growing reflection and evaluation.	National Journal of Education and Culture
20	Chen and Zhou	[44]	AR-Driven Learning Experiences for Critical Reflection	AR creates an immersive experience that triggers critical reflection.	Educational Research Review

Table 3 presents the thematic categorization of the reviewed articles based on their main focus, key concepts, and research topics. This classification aims to facilitate the identification of research patterns, thematic trends, and relationships among studies, thereby supporting a more systematic literature analysis and synthesis.

Table 3. Thematic Categorization of Reviewed Articles

Theme	Representative Studies	Key Findings
Cognitive Development	[27], [28], [29], [30], [31]	AR improves analysis, evaluation, and problem-solving.
Collaborative Learning	[34], [38], [42], [43]	AR strengthens group reasoning, reflection, and motivation.
Conceptual Understanding	[35], [36], [40]	AR supports the visualization of abstract concepts.
Pedagogical Integration	[25], [39], [44]	AR requires teacher readiness and reflective design.

Results and Discussions

The results of the analysis of 20 articles show that the development of AR-based learning materials consistently has a positive impact on improving students' critical thinking skills. Studies by Afifah [27] and Hacıoğlu and Gülhan [28] confirmed that AR improves students' ability to analyze information and solve problems through interactive learning experiences, including fostering student learning engagement. Learning with AR allows students to connect theory to real-life situations through visual simulations, thereby enhancing conceptual understanding and metacognitive reflection [29]. Furthermore, studies by Barta et al. [30] and Marques et al. [45] show that AR-based learning modules improve students' analytical, problem-solving, and evaluative skills because 3D visual interactions stimulate higher cognitive engagement. This is in line with Sonia and Airlanda [32] opinion that selecting an effective learning model can help improve students' critical thinking skills, which are essential in facing the challenges of the globalization era. Likewise, this reinforces Vygotsky's theory of social constructivism, which states that effective learning occurs when students actively construct their knowledge through social and contextual interactions [21], [46].

The analysis of the various studies mentioned above shows that the use of AR in developing learning materials significantly contributes to improving students' critical thinking skills. Through interactive learning experiences, AR connects theory with real-world practice, enabling students to not only understand concepts abstractly but also see their application in more concrete contexts. This encourages students to more actively analyze information, solve problems, and engage in metacognitive reflection, strengthening their conceptual understanding. Furthermore, the 3D visual interactions offered by AR have been shown to stimulate higher cognitive engagement. Students are encouraged to explore, compare, and evaluate information in greater depth, consistently developing their analytical, problem-solving, and evaluative skills. Therefore, it can be asserted that the application of AR in learning not only increases student motivation and engagement but also strengthens the foundation of

critical thinking skills, which are essential in facing the challenges of the globalization era. AR acts as a bridge between theory and practice, as well as a tool that supports the creation of a reflective, collaborative, and meaningful learning process.

Radu [47] in his meta-analysis confirmed that the effects of AR on improving critical thinking are consistent across disciplines. The synthesis of these results showed that students learning using AR experienced an average 25–30% increase in higher-order thinking skills compared to the control group. Similar research by Pabara et al. [33] showed similar results in the Indonesian educational context, where local AR media proved effective in strengthening students' conceptual understanding at the junior high school level. Wang and Chen [34] explained that AR-based collaborative learning creates a learning environment that encourages argumentation, reasoning, and group reflection. This technological integration stimulates students to critically discuss phenomena visualized in augmented form, ultimately strengthening analytical skills [38]. Thus, AR-based digital collaboration not only enriches the learning experience but also expands critical thinking capacity in a social context.

The results of studies by Abdulla et al. [35] and Li et al. [36] show that the use of AR in science and biology learning helps students understand abstract concepts more concretely through spatial visualization. 3D visualization facilitates logical analysis and the ability to evaluate relationships between variables in scientific phenomena. This is in line with the dual coding theory [48] which emphasizes that the combination of verbal and visual information strengthens critical thinking processes. In the context of the Independent Curriculum, research by Dishinta and Hadi [25] shows that AR teaching materials support differentiated learning that adapts to students' needs and interests. Students who used AR modules showed significant improvements in aspects of reflection and logical reasoning, in line with the characteristics of the Pancasila Student Profile. These findings emphasize the relevance of AR technology in supporting student-centered and experiential learning. Overall, these findings confirm that the integration of AR in education is highly relevant in creating more meaningful, contextual, and experiential learning experiences. AR plays an important role in shaping a generation that is critical, reflective, and adaptive to global challenges, while also supporting the transformation of education towards more innovative and humanistic learning.

Research by Bacca et al. [37] found that AR-based learning significantly improves Higher-Order Thinking Skills (HOTS), including critical, creative, and reflective thinking. These results are consistent with research by Supriyono et al. [39], who developed an interactive AR module based on constructivist theory. Students who learned using the module showed significant improvements in their analytical and idea synthesis skills. Han and Park [40] emphasized that AR-based digital textbooks have great potential in developing scientific reasoning. The integration of AR into textbooks provides a real-world context that helps

students form connections between abstract concepts and their practical applications. These findings support the principle of reflective learning, where students understand not only what to learn, but also why and how to learn [49].

Yuliana and Andini [41] highlighted the role of AR pedagogy in strengthening argumentative analysis skills. Through AR-based problem-based learning, students are required to identify problems, formulate hypotheses, and evaluate solutions with integrated visual evidence. AR serves as a scaffolding tool that helps students achieve a deeper understanding [42], [50]. A study by Nguyen et al. [42] also found that AR gamification increases students' intrinsic motivation and curiosity. Game elements combined with the AR learning environment encourage students to think critically in solving logic-based challenges and reflecting on them. This aligns with Deci and Ryan [51], self-determination theory, which states that intrinsic motivation arises when students feel autonomous, competent, and socially connected. Research by Arifin and Sari [43] shows that project-based AR media can improve students' self-reflection skills through exploratory and collaborative activities. Students are not only required to understand concepts but also to apply knowledge concretely in a project context. This approach facilitates higher-order critical thinking skills such as evaluation and decision-making.

Chen and Zhou [44] suggest that immersive learning experiences through AR encourage students to think critically about phenomena they experience virtually. Students become better able to analyze cause and effect and develop inferences based on visual data. These results indicate that interactivity and immersion are key to the success of AR-based learning. In an affective context, AR has also been shown to increase students' emotional engagement with learning materials. According to research by Bacca et al. [37], this emotional engagement plays a crucial role in triggering deep cognitive reflection and awareness. Emotional engagement in learning enables a personal connection between students and the material [31]. In addition to the cognitive and affective aspects, the social dimension of AR learning is also significant. Studies by Wang and Chen [34] and Lee and Kim [38] show that AR strengthens interactions between students through virtual collaboration and visual-based discussions. AR-based learning environments create peer learning situations that enrich argumentation and critical reasoning. Based on the analysis of these findings, it can be concluded that AR-based learning offers comprehensive strengths in the cognitive, affective, and social domains. Cognitively, AR encourages students to think critically through immersive experiences that allow them to analyze cause and effect and draw inferences based on visual data. Affectively, the emotional engagement created through interaction with learning

materials strengthens reflection and cognitive awareness, while creating a deeper personal connection between students and the knowledge they acquire.

However, several studies have noted challenges in AR implementation, particularly in terms of teacher readiness and infrastructure [25], [52]. Teachers need to understand AR's pedagogical design so that learning is not merely visual but remains oriented towards developing critical thinking skills. Without proper guidance, AR can become a mere entertainment tool [44]. Methodologically, most studies used quasi-experimental designs with a control group. This indicates a strong trend towards empirical evidence supporting the effectiveness of AR. Radu [47] found that meta-analysis corroborates the finding that improvements in students' critical thinking achieve moderate to large effects (Cohen's d = 0.55–0.75), demonstrating empirical consistency across various educational contexts.

Overall, the implementation of AR in education has been proven to have a consistent positive impact on improving students' critical thinking skills. Various studies have shown that AR can provide immersive, interactive, and contextual learning experiences, encouraging students to analyze, evaluate, and reflect on knowledge more deeply. However, the effectiveness of AR is highly dependent on teacher readiness and infrastructure support. Without proper pedagogical understanding, AR risks becoming merely a medium for entertainment without making a significant contribution to learning outcomes. Therefore, AR integration needs to be accompanied by teacher training and thorough learning design planning to truly optimize its benefits. Supported by strong empirical evidence, including meta-analyses showing moderate to large effects on improving critical thinking, AR can be viewed as a strategic innovation in education. This technology has the potential to strengthen the transformation of learning towards a more reflective, critical model that is in line with the demands of the 21st century.

One important aspect emerging from the SLR results is the role of instructional design in the success of AR-based learning materials. Research by Supriyono et al. [39] emphasized the importance of integrating cognitive, visual, and reflective elements in AR modules. Designs that balance visualization and conceptual scaffolding proved most effective in enhancing critical thinking skills. Recent research by Nguyen et al. [42] and Chen and Zhou [44] also showed that the use of AR in flexible learning environments (blended or mobile learning) expands students' access to reflective learning experiences. AR allows students to learn independently with the support of a digital context that remains cognitively challenging. Overall, the SLR results demonstrate that developing AR-based learning materials is an effective strategy for fostering critical thinking skills, especially when applied with the principles of constructivism, collaborative learning, and self-reflection. These findings support

the policy direction of the Independent Curriculum, which emphasizes differentiated and contextualized technology-based learning.

Conclusion

The results of this systematic review indicate that the development of AR-based learning materials has a significant positive impact on improving students' critical thinking skills. AR has been shown to strengthen students' abilities in analysis, evaluation, and reflection through immersive and interactive learning experiences. The integration of AR with constructivism and problem-based learning theories creates a contextual, collaborative learning environment and encourages students' simultaneous cognitive and emotional engagement. Furthermore, the effectiveness of AR-based teaching materials is highly dependent on pedagogical design, teacher readiness, and infrastructure support. The success of AR implementation is determined not only by technological aspects but also by the extent to which teachers are able to facilitate and direct digital experiences into reflective and meaningful thinking processes. Thus, the integration of AR into teaching materials aligns with the spirit of creating students with future character, namely shaping students who are intelligent, great, critical thinkers, creative, and adaptive to global challenges in the digital era.

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Conflict of Interest

The authors declare no conflict of interest.

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