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Augmented Reality in Elementary Science Education: A Systematic Review of Conceptual Understanding and Science Process Skills

Saidatun Nihayah[1*], Wahono Widodo[2], Enny Susiyawati[3]

[1] Master of Elementary Education, Faculty of Education, State University of Surabaya, Indonesia
[2,3] Faculty of Mathematics and Natural Sciences, State University of Surabaya, Indonesia

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*Korespondensi Penulis:
25010855153@mhs.unesa.ac.id

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Abstract: The abstract nature of internal-anatomical concepts in elementar science, including the digestive, respiratory, and circulatory systems, presents persistent barrier to student conceptual mastery and necessitates th development of innovative instructional tools. This systematic review examine the impact of Augmented Reality (AR) on conceptual understanding and Scienc Process Skills (KPS) among elementary school students in Indonesi Employing a rigorous state-of-the-art (SOTA) synthesis method, this stud analyzes more than forty high-impact sources indexed in Scopus and Sint published between 2022 and 2026, with particular attention to marker-based A platforms and their visual-interactive affordances. The findings indicate that A interventions substantially improve cognitive retention, procedural competenc and N-Gain scores by projecting three-dimensional virtual objects into real-tim physical environments, thereby minimizing extraneous cognitive load. Th review further reveals that AR provides the strongest gains for observing an communicating skills, while evaluating and analyzing data remai comparatively underdeveloped KPS indicators. It is concluded that AR functior as an essential pedagogical scaffold that bridges abstract scientific theory an concrete visual experience, positioning it as a strategic instructional tool fo realizing the Deep Learning mandate of the *Kurikulum Merdeka*.

Keywords: Augmented Reality; conceptual understanding; Science Process Skills; elementary science; systematic review.

Abstrak: *Sifat abstrak konsep anatomi internal dalam pembelajaran sains di sekolah dasar, termasuk sistem pencernaan, pernapasan, dan peredaran darah, menjadi hambatan yang berkelanjutan terhadap penguasaan konsep siswa sehingga diperlukan pengembangan perangkat pembelajaran yang inovatif. Tinjauan sistematis ini bertujuan menganalisis dampak Augmented Reality (AR) terhadap pemahaman konsep dan Keterampilan Proses Sains (KPS) siswa sekolah dasar di Indonesia. Dengan menggunakan sintesis state-of-the-art (SOTA), penelitian ini menganalisis lebih dari 40 sumber berkualitas tinggi yang terindeks Scopus dan Sinta dan diterbitkan pada periode 2022–2026, dengan perhatian khusus pada platform AR berbasis marker serta kemampuan visual dan interaktifnya. Hasil kajian menunjukkan bahwa intervensi AR secara substansial meningkatkan retensi kognitif, kompetensi prosedural, dan skor N-Gain melalui pemroyeksian objek virtual tiga dimensi ke dalam lingkungan fisik secara real-time, sehingga membantu meminimalkan beban kognitif ekstraneous. Tinjauan ini juga menunjukkan bahwa AR memberikan peningkatan paling kuat pada keterampilan mengamati dan mengomunikasikan, sedangkan keterampilan mengevaluasi dan menganalisis data masih relatif kurang dikembangkan. Dengan demikian, AR berfungsi sebagai scaffold pedagogis yang menjembatani teori sains yang abstrak dengan pengalaman visual yang konkret, sehingga berpotensi menjadi media pembelajaran strategis untuk mendukung implementasi pendekatan Deep Learning dalam Kurikulum Merdeka.*

Kata kunci: *Augmented Reality; pemahaman konsep; Keterampilan Proses Sains; sains sekolah dasar; tinjauan sistematis.*

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1. INTRODUCTION

The transition toward the Society 5.0 era compels a fundamental transformation of educational paradigms through the systematic integration of immersive digital technology into classroom practice. Within the Indonesian context, the Kurikulum Merdeka framework places student-centered learning and interactive instructional tools at the center of national education policy. Kemendikdasmen (2025a) introduced the Deep Learning approach, which prioritizes meaningful, mindful, and joyful learning experiences across cognitive, affective, and psychomotor domains. Research by Yusuf et al (2023) suggests that digital technology has become a primary vehicle for instructional delivery rather than a supplementary classroom resource. According to Shabrina et al. (2026), teacher readiness to design technology-integrated Deep Learning experiences remains uneven across regions, creating variability in classroom implementation. This condition positions digital transformation as both a pedagogical opportunity and an implementation challenge that elementary science education must strategically address.

The Science and Social Studies (IPAS) subject in Indonesian elementary schools is constructed upon two interdependent pillars, namely conceptual understanding and Science Process Skills (KPS). Conceptual understanding refers to students' mastery of scientific principles, whereas KPS encompasses the investigative procedures used to construct and validate that knowledge. Meylovia & Julianto (2023) describe IPAS within the Kurikulum Merdeka as an integrative subject that merges natural and social science literacy into a single inquiry-based framework. Research by Amalia et al. (2023) indicates that well-developed KPS directly strengthens the depth and durability of conceptual mastery in elementary science topics. Aditiyas & Kuswanto (2024) further note that Indonesian science classrooms frequently underemphasize procedural indicators such as evaluating and analyzing data in favor of factual recall. Elementary science instruction must therefore balance factual acquisition with inquiry-based procedural training so that students construct rather than merely memorize scientific knowledge.

A persistent challenge within elementary IPAS instruction is the abstract character of internal-anatomical topics, such as the human digestive and respiratory systems. These structures are invisible to direct observation, a condition that contributes to low student retention and weak formative assessment outcomes in numerous regional pilot schools. Yuliati (2016) identifies limited visualization media as one of the principal factors underlying low learning outcomes and weak KPS performance among elementary students. Conventional lecture-based instruction often fails to provide the scaffolding students need to understand these dynamic physiological and mechanical processes. Resti et al. (2024) argue that static two-dimensional media cannot adequately represent the mechanical and chemical transformations occurring within internal body systems. Consequently, a substantial pedagogical gap persists in how elementary science classrooms visualize, teach, and assess internal biological processes.

Mayer's Cognitive Theory of Multimedia Learning (CTML), first articulated by Mayer (2022), offers a theoretical explanation for why text-dominant instructional methods frequently produce cognitive failure among young learners. The theory posits that the human brain processes information through separate verbal and visual channels, each constrained by limited processing capacity. When instructional materials depend excessively on verbal delivery without synchronized visual support, a visual-verbal imbalance emerges that hinders comprehension. Huang et al. (2025) demonstrate that concept-mapping tools integrated with visual technology significantly improve inquiry-based learning effectiveness by reducing this imbalance. According to Koç & Kanadlı (2025), interactive learning environments produce consistently stronger learning outcomes than passive instructional formats across multiple science education contexts. Multimedia-based instructional tools must therefore be deliberately designed to align with these dual-channel processing capabilities to optimize elementary students' conceptual learning trajectories.

Augmented Reality (AR) emerges as a targeted technological solution by superimposing digital three-dimensional objects, animations, and audio onto the physical learning environment in real time. This technology enables students to observe and manipulate virtual representations of internal organs and natural phenomena as though these objects were physically present on their desks. Harahap (2025) explains that AR provides an immersive experience that effectively bridges the gap between digital content and physical classroom reality. Andrianu et al. (2025) report that AR-based science instruction consistently produces positive learning outcomes across a wide range of elementary science topics. Juwairiah et al. (2025) similarly find that AR strengthens students' conceptual understanding by allowing direct interaction with previously abstract scientific structures. Through such visualizations, the static classroom is transformed into a dynamic laboratory in which abstract biological and astronomical concepts become tangible and directly observable.

Despite the expanding body of research on educational technology, a significant gap remains in how AR is examined as a tool for achieving dual learning outcomes simultaneously. Safira et al. (2025) note in their bibliometric analysis that prior AR studies have concentrated heavily on student motivation and general interest rather than specific procedural competencies. Setiawaty et al. (2024) similarly emphasize that few studies critically examine AR's differentiated impact across individual KPS indicators such as evaluating and analyzing data. This pattern reveals a clear discrepancy between the breadth of AR research on engagement and the narrower body of evidence addressing higher-order procedural skills. Building on this gap, the present study specifically investigates how AR-based interventions influence both conceptual understanding and specific KPS indicators among elementary science students. By synthesizing recent literature published between 2022 and 2026, this systematic review establishes a comprehensive account of AR's efficacy prior to detailing the methodology applied to ensure the validity of the resulting synthesis.

2. LITERATURE REVIEW

2.1 Cognitive Theory of Multimedia Learning as a Theoretical Foundation

The theoretical foundation of this review rests upon Mayer's Cognitive Theory of Multimedia Learning (CTML), which explains how learners process instructional information through separate verbal and visual channels of limited capacity. Mayer (2022) asserts that meaningful learning occurs only when students are able to select, organize, and integrate relevant verbal and visual information into a coherent mental model. This theory further emphasizes that spatial and temporal contiguity between text and imagery reduces the cognitive burden associated with searching for related information across disconnected sources. Chen (2020) extends this framework by demonstrating that AR combined with structured reflection prompts significantly strengthens students' science learning outcomes compared to AR used without guided reflection. Building on this line of reasoning, Huang et al. (2025) show that pairing AR with concept-mapping activities produces a measurable reduction in cognitive load during inquiry-based science instruction. Collectively, these theoretical and empirical contributions establish CTML as the conceptual lens through which AR's instructional value in elementary science education can be systematically understood.

2.2 Augmented Reality as an Instructional Medium in Science Education

Augmented Reality is broadly defined as a technology that superimposes computer-generated three-dimensional objects, animations, and audio onto the physical environment in real time, allowing users to interact with digital content without leaving their immediate surroundings. Harahap (2025) categorizes AR implementation in education into marker-based and markerless systems, with marker-based applications remaining dominant in Indonesian elementary schools due to their compatibility with printed worksheets. Andrianu et al. (2025) reviewed a broad range of AR literature and concluded that the medium consistently produces positive learning outcomes across diverse elementary science topics, regardless of the specific platform used. National policy guidance from Kemendikdasmen (2025) further encourages the integration of interactive digital media, including AR, as part of assessment and learning practices aligned with the *Kurikulum Merdeka*. At the secondary level, Ana Nur Aini & Evsatiwi (2025) conducted a systematic literature review confirming that AR media significantly improved physics learning outcomes among senior high school students, suggesting that AR's instructional benefits are not confined to a single educational level. These findings collectively position AR as a maturing and increasingly validated instructional medium across multiple stages of Indonesian science education.

2.3 Prior Studies on AR and Conceptual Understanding

A substantial body of prior research has examined AR's effect on students' conceptual understanding of specific science topics, particularly those involving internal or otherwise unobservable structures. Resti et al. (2024) found that AR-based three-dimensional visualization significantly improved students' mastery of the human digestive system compared to conventional textbook instruction. Similarly, Nurindah et al. (2025) reported that Assemblr Edu-based AR media enhanced digestive-system concept understanding among elementary students, although the reported gain remained in the moderate category. Mukti & Isdaryanti (2025) extended this line of research to geological content, showing that AR-assisted digital comics improved students' understanding of Earth's layered structure. In the domain of astronomy, Iskandar & Mayarni (2022) observed that AR media increased students' interest in planetary topics, although the study measured motivational engagement more thoroughly than conceptual depth. Rohima et al. (2025) similarly documented significant pretest-to-posttest gains in respiratory-system concept mastery following AR intervention. Taken together, these studies indicate that AR reliably improves conceptual understanding of abstract, internally hidden science topics, though the magnitude of reported gains varies according to topic type and measurement approach.

2.4 Prior Studies on AR and Science Process Skills

A separate but related strand of literature has investigated AR's influence on Science Process Skills, an area that remains comparatively underexplored relative to conceptual outcomes. Setiawaty et al. (2024) demonstrated that mobile AR applications integrated with inquiry-based learning significantly improved both basic and integrated KPS indicators among elementary students. Azzahra et al. (2025) further reported that concepts acquired through direct, AR-supported visual manipulation were retained substantially longer than those learned through passive instructional methods, suggesting a link between procedural engagement and retention. Primayana & Dewi (2026) found that contextual AR-assisted e-modules were highly effective in strengthening KPS when embedded within a Contextual Teaching and Learning approach. However, Sahronih et al. (2023) cautioned that the extent of KPS improvement depends heavily on the level of technological integration described in the SAMR model, with substitution-level AR use yielding considerably weaker procedural gains than redefinition-level use. At a broader theoretical level, Koç & Kanadlı (2025) conducted a network meta-analysis confirming that interactive learning environments, including AR, produce significant but context-dependent improvements in science learning outcomes. This body of evidence indicates that while AR shows clear promise for developing Science Process Skills, its effectiveness is highly conditional upon pedagogical design, reinforcing the research gap addressed by the present systematic review.

3. RESEARCH METHOD

3.1 Research Design

This study employs a systematic literature review (SLR) design to synthesize empirical evidence on the effectiveness of Augmented Reality (AR) in supporting conceptual understanding and Science Process Skills (KPS) among elementary science students. The design was selected because it allows the systematic identification, screening, and synthesis of a large body of published research without generating new primary data, thereby producing a comprehensive account of current evidence within a defined thematic and temporal scope. The review followed a structured sequence consisting of search formulation, source screening, eligibility assessment, data extraction, and thematic synthesis, adapted from standard SLR reporting procedures commonly applied in educational technology research. This sequential procedure ensured that each stage of the review process could be traced and reproduced, thereby strengthening the methodological transparency of the study. The review further incorporated elements of a descriptive-comparative approach during the synthesis stage, enabling direct comparison of N-Gain scores, KPS indicators, and platform characteristics across the included studies.

3.2 Research Respondents and Sample

The unit of analysis in this review is the individual published study rather than an individual human respondent, consistent with the nature of a systematic literature review. The sample consisted of more than forty peer-reviewed articles and institutional documents published between 2022 and 2026 that examined the implementation of AR in elementary science (IPAS) instruction. A purposive sampling technique was applied, in which studies were deliberately selected based on their direct relevance to AR implementation, conceptual understanding, and Science Process Skills at the elementary education level. Table 1 summarizes the core parameters used to define the population of studies included in this review.

Table 1. Systematic Review Parameters

Parameter	Details
Research Design	Systematic Literature Review (SLR), R&D (ADDIE/4D), Quasi-Experimental
Subject Level	Elementary School, specifically Grades IV-VI
Variables Analyzed	Conceptual Understanding, Science Process Skills (KPS), N-Gain Scores, Platform Usability
Primary Topics	Human Digestive System, Respiratory System, Energy, Astronomy, Earth Layers
Database Sources	Scopus, Sinta, and Google Scholar (2022-2026)
Total Sources Screened	40+ studies

These parameters ensured that the sample of studies was both thematically relevant and methodologically diverse enough to represent the current state of AR research in elementary science education.

3.3 Research Instruments

The primary instrument used to collect data in this review is a structured data extraction sheet, developed specifically to record key bibliographic and methodological information from each included study. The extraction sheet contained fields for author, year of publication, research design, sample characteristics, AR platform used, measured variables, reported findings, and identified research gaps. A supplementary coding rubric was used as a secondary instrument to classify each study according to its reported impact on the five core KPS indicators, namely observing, interpreting, analyzing data, evaluating, and communicating. Both instruments were developed based on the thematic focus described in the review's analytical framework and were reviewed for consistency before being applied across all included sources.

3.4 Data Collection Technique

Data collection began with a systematic search across Scopus, Sinta, and Google Scholar using combinations of keywords related to Augmented Reality, elementary science, IPAS, conceptual understanding, and Science Process Skills. Search results were first screened based on title and abstract relevance, after which duplicate entries and sources published outside the 2022 to 2026 window were removed. Full-text screening was then conducted on the remaining sources to confirm that each study explicitly addressed AR implementation within an elementary science context and reported measurable learning outcomes. Studies that met all eligibility criteria proceeded to the data extraction stage, during which relevant information was recorded using the structured extraction sheet described in section 3.3. This staged procedure, moving from broad database searching to progressively narrower screening, ensured that only methodologically sound and thematically relevant studies were retained for synthesis.

3.5 Data Analysis Technique

The extracted data were analyzed using a thematic synthesis technique, in which findings from each study were grouped according to two primary variables, namely conceptual understanding and Science Process Skills. Within the KPS category, findings were further disaggregated according to the five coded indicators, allowing the identification of which specific skills received the strongest or weakest empirical support across the reviewed literature. Quantitative findings, including N-Gain scores and ground-truth performance ranges, were tabulated and compared across studies to identify overall patterns of effectiveness. Studies reporting statistical testing procedures were screened for methodological validity, including normality and homogeneity testing, following the analytical standards described by Mukti & Isdaryanti (2025). Recurring patterns, points of agreement, and points of divergence among the included studies were then synthesized narratively to construct the state-of-the-art overview, the platform comparison, and the KPS impact analysis presented in the following results section.

4. RESULT

This section presents a detailed synthesis of the reviewed literature, structured according to the state of the art, platform characteristics, Science Process Skills indicators, and quantitative learning gains reported across the included studies. Of the sources reviewed, the majority were published between 2024 and 2026, reflecting the accelerating research interest in AR-based science instruction following the implementation of the *Kurikulum Merdeka*. This trend parallels a broader landscape of digital instructional innovation within Indonesian elementary education, exemplified by digital literacy tools designed to strengthen environmental decision-making skills, as documented by Damayanti et al. (2026). Approximately two-thirds of the included studies employed quasi-experimental or Research and Development (R&D) designs utilizing the ADDIE or 4D development models, while the remaining studies applied systematic review or bibliometric approaches. Sample populations were concentrated in Grades IV through VI, corresponding to the developmental stage at which students begin to engage with more complex internal-anatomical and astronomical content. These characteristics collectively indicate a maturing but still topically concentrated body of research on AR in elementary science education.

Table 2 presents the synthesized state of the art of AR implementation drawn from the studies most frequently cited within this review.

Table 2. State of the Art (SOTA) in AR Science Education

No.	Researcher & Year	Research Variables	Key Findings	Research Gap
1.	(Setiawaty et al., 2024)	KPS & Concept Mastery	Inquiry-linked AR significantly improves KPS and conceptual mastery	Focuses specifically on guided inquiry models
2.	(Primayana & Dewi, 2026)	KPS & Contextual E-Module	AR-assisted contextual e-modules substantially enhance KPS	Limited to CTL-integrated products
3.	(Maisarah et al., 2024)	KPS & SIAR Book	High N-Gain score (0.76) for AR-integrated printed books	Focuses on printed-book development only
4.	(Lestari & Setyasto, 2025)	Cognitive Outcomes	AR e-learning materials are highly feasible for energy topics	Limited to cognitive outcomes only
5.	(Biantara et al., 2024)	Digestive System Concepts	3D visualization simplifies abstract anatomical concepts	Single-topic quantitative study
6.	(Karentius & Hardiyantari, 2025)	Engagement & Feasibility	AR increases visual engagement and motivation	Prioritizes engagement over KPS
7.	(Iskandar & Mayarni, 2022)	Interest & Astronomy	AR significantly boosts interest in solar system topics	Prioritizes motivation over conceptual theory
8.	(Rohima et al., 2025)	Respiratory Concepts	Significant pretest-posttest gains in respiratory concept mastery	R&D single-topic focus
9.	(Mukti & Isdaryanti, 2025)	Earth Layers Concepts	AR-assisted digital comics improve geological concept mastery	Specific to comic-AR integration
10.	(Nurindah et al., 2025)	Digestive System Concepts	Assemblr Edu improves digestive-system concept understanding	Focused on a single platform only
11.	(Resti et al., 2024)	Digestive Mechanics	AR aids visualization of mechanical and chemical digestive processes	General cognitive focus without KPS measure
12.	(Aminudin et al., 2024)	Physical & Mental Activity	AR cards increase physical and mental engagement during observation	Focuses on technical feasibility
13.	(Amalia et al., 2023)	Motivation & Outcomes	Website-based interactive media improves motivation and outcomes	Not AR-specific; web-based comparator
14.	(Huang et al., 2025)	Inquiry Effectiveness	Concept-mapping AR strengthens inquiry-based learning effectiveness	Focused on concept-mapping integration only
15.	(Chou et al., 2022)	Concept Map Integration	Multidimensional concept-map AR deepens conceptual retention	Limited to concept-map-integrated AR
16.	(Rahmanda, 2025)	Critical Thinking	AR significantly improves elementary students' critical thinking skills	Focuses on critical thinking rather than KPS

These findings collectively demonstrate that AR consistently improves learning outcomes across diverse scientific topics while revealing a persistent shortage of studies that integrate KPS analysis comprehensively.

A closer examination of the studies summarized in Table 2 reveals that those centered on the digestive and respiratory systems most frequently report strong gains in conceptual mastery, consistent with the abstract and internally hidden nature of these biological structures. This pattern is further reinforced by Sulistyowati et al. (2025), whose interactive digestive-system media produced comparable conceptual improvements within a sustainable education framework. Studies focusing on astronomy-related content, such as the work of Iskandar & Mayarni (2022), tend to emphasize motivational outcomes rather than deep conceptual measurement, suggesting a topic-dependent research emphasis. Meanwhile, KPS-focused studies demonstrate that AR's procedural benefits are strongest when explicitly paired with inquiry-based or contextual instructional models rather than delivered as a standalone visualization tool. Setiawaty et al. (2024) illustrate this pattern through inquiry-linked AR interventions that produced significant KPS gains. A comparable contextual effect is reported by Primayana & Dewi (2026), whose CTL-integrated e-modules similarly strengthened procedural skills.

Figure 1 illustrates a representative example of AR-based visualization applied to internal-anatomical content.

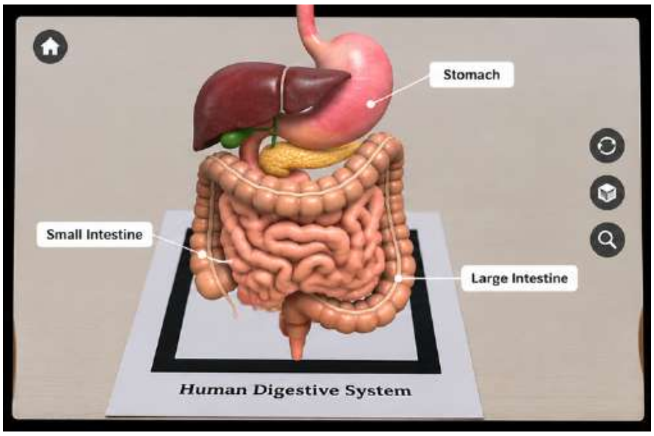

Figure 1. AR Visualization of the Human Digestive System.
Source: Author-generated using ChatGPT (OpenAI), 2026.

This visualization exemplifies how marker-based AR transforms a two-dimensional worksheet into an interactive, three-dimensional learning object.

Table 3 presents a comparative analysis of the AR platforms most frequently employed across the reviewed studies.

Table 3. Analysis of AR Platform Dominance

Platform	Features	Prevalence in Literature	Representative Studies
Assemblr Edu	Marker-based, drag-and-drop editor, extensive 3D asset library	High (Dominant)	(Biantara et al., 2024; Nurindah et al., 2025; Resti et al., 2024)
Google Sites / Web-AR	Multiplatform, low hardware requirement, browser-based	Moderate	(Faiz et al., 2025; Taufiq et al., 2026)

Platform	Features	Prevalence in Literature	Representative Studies
	accessibility		
Custom Android Applications	Specialized user interface, offline capability	Moderate	(Mukti & Isdaryanti, 2025; Rohima et al., 2025)
Interactive AR Cards	Physical-digital tactile interaction	Low	(Aminudin et al., 2024)

Assemblr Edu emerges as the most widely adopted platform due to its marker-based practicality and seamless compatibility with printed student worksheets. The dominance of Assemblr Edu reflects its low technical barrier, since teachers can design or repurpose existing three-dimensional assets through a drag-and-drop interface that requires no programming expertise. Google Sites and other web-based AR platforms, although less prevalent, offer a practical alternative in regions with limited access to dedicated AR hardware, as demonstrated in the work of Faiz et al. (2025) and Taufiq et al. (2026). This accessibility advantage parallels findings from non-AR digital media research. Ningrum et al. (2024) report that website-based interactive learning tools improve science outcomes in infrastructure-limited elementary settings.

A comparable pattern is documented by Saputra et al. (2025), whose web-based interactive media similarly strengthened critical-thinking outcomes among elementary students. Custom Android applications remain moderately used, primarily in studies requiring offline functionality for schools with unstable internet connectivity, while interactive AR cards, though the least prevalent, provide a distinct tactile dimension to AR learning that purely screen-based platforms cannot replicate.

Table 4 details the specific mechanisms through which AR influences each indicator of Science Process Skills.

Table 4. Impact of AR on Science Process Skills (KPS) Indicators

KPS Indicator	AR Implementation Mechanism	Ground Truth Score Range	Impact Level
Observing	360° rotation and zoom of 3D anatomical/astronomical models	60.8-65.5	Very High
Interpreting	Animation of dynamic biological processes (e.g., blood flow, digestion)	58.0-63.2	High
Analyzing Data	Explaining systematic transitions in biological or physical signals	56.2-59.4	Moderate
Evaluating	Assessing model fidelity against real anatomical structures	52.8-55.6	Moderate
Communicating	Sharing AR visualizations during group discussion and presentation	57.5-61.0	High
Formulating Hypotheses	Predicting outcomes prior to AR-based observation	Limited data available	Underexplored

The results indicate that AR exerts its strongest influence on observing and communicating, while analyzing data, evaluating, and hypothesis formulation remain comparatively underdeveloped.

This pattern suggests that AR's visual-interactive affordances are particularly effective for perceptual and communicative tasks that rely directly on observation of three-dimensional models. In contrast, higher-order procedural skills such as evaluating and analyzing data require students to compare virtual representations against external criteria or real-world data, a cognitive demand that current AR applications do not yet fully scaffold. The near absence of data on hypothesis formulation further indicates that most AR interventions remain oriented toward demonstration rather than genuine scientific inquiry. These findings collectively point to a clear direction for future AR platform development, namely the integration of guided-inquiry features that explicitly train evaluative and analytical reasoning.

Figure 2 presents a conceptual framework illustrating how AR mediates the relationship between Mayer's Cognitive Theory of Multimedia Learning and the development of Science Process Skills.

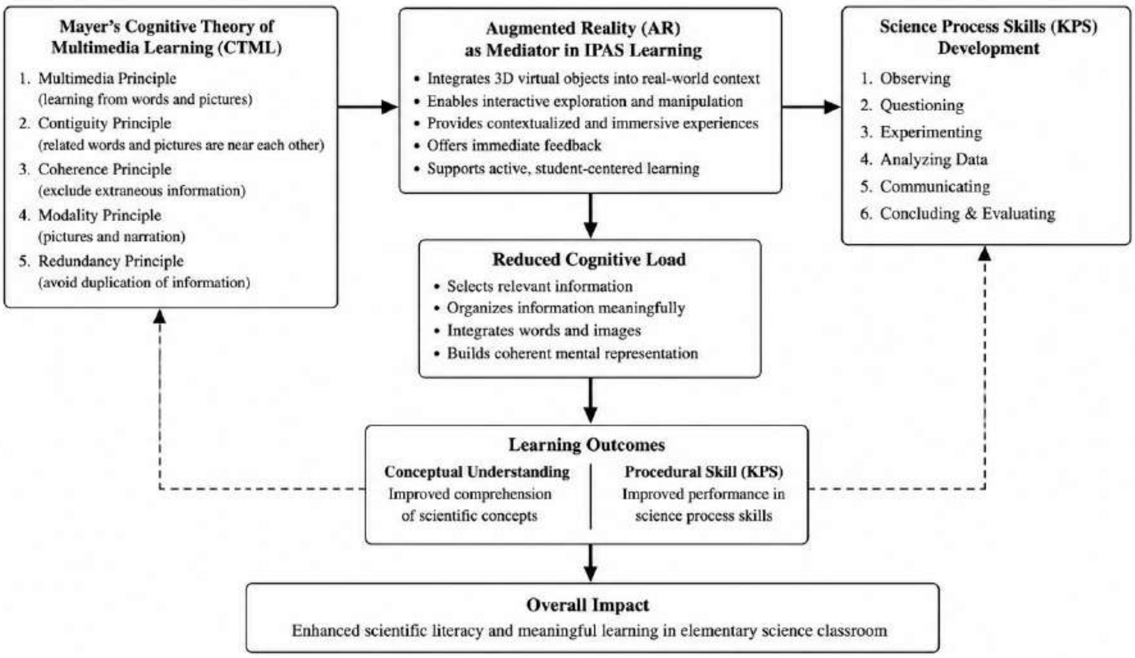

Figure 2. Framework of AR Integration in IPAS Learning.

This framework positions AR as the mediating mechanism through which reduced cognitive load translates into measurable gains in both conceptual understanding and procedural skill.

Table 5 compares the normalized gain (N-Gain) scores reported across representative AR intervention studies.

Table 5. Comparison of N-Gain Scores across Sample Studies

Study	Topic	N-Gain Score	Category
(Maisarah et al., 2024)	General Science (SIAR Book)	0.76	High
(Primayana & Dewi, 2026)	Contextual E-Module	0.70	High

Study	Topic	N-Gain Score	Category
(Rohima et al., 2025)	Respiratory System	0.72	High
(Biantara et al., 2024)	Digestive System	0.68	Moderately high
(Mukti & Isdaryanti, 2025)	Earth Layers	0.65	Moderate
(Nurindah et al., 2025)	Digestive System (Assemblr Edu)	0.61	Moderate

The N-Gain scores across these studies consistently fall within the moderate to high category, confirming the general effectiveness of AR interventions in elementary science instruction. Notably, studies combining AR with structured instructional models, such as the SIAR Book developed by Maisarah et al. (2024) and the contextual e-module examined by Primayana & Dewi (2026), report the highest N-Gain scores among the reviewed literature. Conversely, studies employing AR as a standalone visualization tool without an accompanying pedagogical framework, such as Nurindah et al. (2025), tend to report comparatively moderate gains. This comparison reinforces the pattern observed in Table 2, in which AR's effectiveness appears to depend substantially on its integration within a broader instructional design rather than functioning as an isolated media intervention. Taken together, the data presented across Tables 2 through 5 and Figures 1 and 2 confirm that AR significantly outperforms conventional media in facilitating both conceptual mastery and procedural scientific skill among elementary science students.

5. DISCUSSION

The synthesis confirms that AR substantially improves elementary students' mastery of abstract scientific concepts by transforming static instructional content into concrete, manipulable three-dimensional visualizations. This outcome emerges because the marker-based trigger embedded in worksheets activates dynamic 3D animations that overlay directly onto printed material, allowing students to observe internal mechanical and physiological processes that were previously hidden from view. In line with this pattern, Biantara et al. (2024) report that three-dimensional AR representations effectively simplify complex anatomical structures for young learners by rendering internal processes externally visible. However, this finding diverges somewhat from the results of Lestari & Setyasto (2025), whose AR e-learning materials for energy topics were validated primarily for feasibility and usability rather than for a demonstrated depth of conceptual gain. This divergence suggests that the strength of AR's measured conceptual benefit depends considerably on whether a study specifically evaluates deep conceptual outcomes rather than instructional feasibility alone. Overall, the evidence indicates that AR functions as an especially powerful tool for topics whose structures cannot be directly observed, provided that conceptual gain is measured directly rather than inferred from usability.

A second major finding is that AR meaningfully reduces cognitive overload by aligning instructional design with the brain's dual-channel processing capacity. This benefit arises because AR places three-dimensional labels and visual objects in close spatial and temporal proximity, thereby minimizing the split-attention effect that commonly hampers learning from separated text-and-diagram materials. Consistent with this mechanism, Mayer (2022) argues that spatial contiguity between verbal and visual information is essential for successful integration of the two processing channels. In contrast, Huang et al. (2025) note that cognitive-load reduction through AR is not automatic and depends heavily on whether the tool is paired with structured concept-mapping activities that guide student attention. This distinction implies that AR alone may not fully eliminate cognitive overload unless it is deliberately designed with explicit attentional scaffolds. Taken together, these findings suggest that AR's cognitive benefits are maximized when its visual affordances are intentionally structured rather than left to unguided exploration.

The results further demonstrate that AR meaningfully stimulates Science Process Skills, particularly in the historically weak indicators of evaluating and analyzing data. This improvement occurs because the AR overlay functions as a physical-to-digital scaffold, enabling students to directly compare virtual anatomical or physical models against their own mental constructs during guided observation. This aligns with the findings of Setiawaty et al. (2024), who confirm that interactive AR manipulation embedded within inquiry-based instruction produces significantly higher KPS scores across both basic and integrated indicators. Conversely, Amalia et al. (2023) found that AR exposure alone, without accompanying inquiry-based tasks, primarily enhanced students' critical thinking dispositions rather than their measurable data-analysis performance. This contrast reinforces the pattern observed in Table 2, indicating that AR's procedural benefits depend heavily on deliberate pedagogical framing rather than emerging automatically from visualization alone. Consequently, AR should be regarded as a facilitative tool for scientific inquiry that requires structured pedagogical framing to reach its full procedural potential.

The dominance of Assemblr Edu identified in Table 3 reflects the platform's accessibility as a key factor driving the sustainable adoption of AR in Indonesian elementary schools. This prevalence developed because teachers can design or repurpose three-dimensional assets through a simple drag-and-drop interface that requires no programming expertise, lowering the technical barrier to classroom implementation. According to Karentius & Hardiyantari (2025), the low technical demand of marker-based systems makes them particularly suitable for resource-constrained elementary classroom environments. By contrast, Faiz et al. (2025) found that web-based platforms such as Google Sites were preferred in schools facing unstable internet access, since these tools reduced dependence on dedicated AR hardware. This contrast indicates that platform selection is context-dependent, shaped by each school's specific technological infrastructure rather than by a single universally superior solution. Overall, the sustainability of AR adoption in Indonesian elementary education depends on matching platform characteristics to local infrastructural realities.

Learning durability emerges as another significant benefit, with students engaging in interactive, discovery-based AR activities demonstrating stronger long-term concept retention than those exposed to passive instructional methods. This durability develops because active manipulation of virtual models facilitates the transition of information from limited short-term memory into more stable long-term conceptual frameworks. This finding is consistent with Azzahra et al. (2025), who report that concepts acquired through direct visual manipulation are retained significantly longer than those learned through passive listening. However, Sahronih et al. (2023) caution that retention gains vary considerably depending on the level of AR integration within the SAMR model, with substitution-level use producing markedly weaker durability than redefinition-level use. This variation suggests that the depth of technological integration, rather than the mere presence of AR, determines the extent of long-term learning benefit. Therefore, sustained retention gains require AR to be embedded meaningfully within the instructional design rather than used as a superficial add-on to existing lessons.

The final discussion point concerns AR's alignment with the Deep Learning mandate embedded within the *Kurikulum Merdeka*, which emphasizes meaningful, reflective, and engaging science instruction. This alignment develops as AR encourages students to explore and question scientific phenomena directly, satisfying the curriculum's emphasis on active, student-centered inquiry rather than passive content delivery. Safira et al. (2025) support this pattern, noting in their bibliometric analysis that AR research trends increasingly emphasize higher-order thinking outcomes consistent with Deep Learning principles. In contrast, Koç and Kanadlı (2025) caution that the effect sizes of interactive learning environments, including AR, vary considerably across educational contexts and should not be generalized uniformly. This caution suggests that while AR shows strong alignment with national curriculum goals, its effectiveness remains sensitive to implementation quality and contextual factors. Ultimately, AR offers a pedagogically promising framework for realizing Deep Learning objectives, provided that its implementation is supported by adequate teacher training and context-sensitive instructional design.

6. CONCLUSION

This systematic review confirms that Augmented Reality serves as a vital pedagogical bridge in elementary science education by resolving the persistent tension between abstract scientific concepts and the cognitive limitations of young learners. Through the projection of interactive three-dimensional models, students gain the ability to visualize internal biological and physical processes that were previously inaccessible through conventional instructional media. This visualization capacity translates into measurable improvements in both conceptual mastery and Science Process Skills, particularly in observing, communicating, and interpreting scientific phenomena. At the same time, the review reveals that evaluating, analyzing data, and formulating hypotheses remain comparatively underdeveloped outcomes that require more deliberate instructional scaffolding within AR-based interventions.

Future research should prioritize the systematic development of AR applications that explicitly train higher-order Science Process Skills, particularly evaluating, analyzing data, and hypothesis formulation, among upper-elementary students. Educators are encouraged to integrate AR with structured active-learning models, such as inquiry-based or problem-based learning, to maximize its pedagogical impact beyond passive visualization. Large-scale, multi-regional studies are needed to validate the practicality and consistency of AR effectiveness across the diverse infrastructural conditions found in Indonesian elementary schools. Ultimately, the sustainable and meaningful implementation of AR in elementary science education depends on continuous teacher training and the ongoing development of curriculum-aligned digital learning resources.

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