Plagiarism Report

07 ___99-119 ___Sri Endang Pravita Sari 3065.pdf

Document Details

Submission ID
6ae6a254a8fca42d17ceb544

File Size
685.9 KB

File Name
07 ___99-119 ___Sri Endang Pravita Sari 3065.pdf

Total Pages
20 Page

Account Name
ITentix Plagiarism

Tota Words
9,956 Words

Submission Date
1 Nov 2026, 09:22 GMT+7

Tota Characters
84,519 Characters

Release Date
1 Nov 2026, 09:24 GMT+7

Filter Options

Filter settings used in this submission report.

- Exclude Bibliography

7%
Similarity

69
Matched Sources

Match Group

0% Internet sources
7% Publications
0% Submitted works (Student papers)

Top Sources

The sources with the highest number of matches within the submission.

1	Publication	<1%
siducat.org		
2	Publication	<1%
www.journalijar.com		
3	Publication	<1%
jppipa.unram.ac.id		
4	Publication	<1%
jpfis.unram.ac.id		
5	Publication	<1%
pnojournalarchive4.files.wordpress.com		
6	Publication	<1%
etdci.org		
7	Publication	<1%
jppipa.unram.ac.id		
8	Publication	<1%
journal-center.litpam.com		
9	Publication	<1%
siducat.org		
10	Publication	<1%
repository.usd.ac.id		
11	Publication	<1%
journal.unnes.ac.id		

12	Publication	<1%
ejournal.unib.ac.id		
13	Publication	<1%
publikasi.teknokrat.ac.id		
14	Publication	<1%
journals.plos.org		
15	Publication	<1%
jppipa.unram.ac.id		
16	Publication	<1%
jpcp.uswr.ac.ir		
17	Publication	<1%
siducat.org		
18	Publication	<1%
researchmgt.monash.edu		
19	Publication	<1%
siducat.org		
20	Publication	<1%
jurnal.unived.ac.id		
21	Publication	<1%
e-journal.hamzanwadi.ac.id		
22	Publication	<1%
journal.uii.ac.id		
23	Publication	<1%
jurnalfuda.iainkediri.ac.id		
24	Publication	<1%
www.nature.com		
25	Publication	<1%
www.cambridge.org		

26	Publication	<1%
dinastirev.org		
27	Publication	<1%
journal-center.litpam.com		
28	Publication	<1%
www.cambridge.org		
29	Publication	<1%
ejournal.uinsaizu.ac.id		
30	Publication	<1%
journal.uny.ac.id		
31	Publication	<1%
doras.dcu.ie		
32	Publication	<1%
eprints.soton.ac.uk		
33	Publication	<1%
jurnal.uns.ac.id		
34	Publication	<1%
ijsrem.com		
35	Publication	<1%
link.springer.com		
36	Publication	<1%
translational-medicine.biomedcentral.com		
37	Publication	<1%
ejournal.unesa.ac.id		
38	Publication	<1%
jurnal.radenfatah.ac.id		
39	Publication	<1%
jurnalfkip.unram.ac.id		

40	Publication	<1%
www.psychiatryinvestigation.org		
41	Publication	<1%
lipidworld.biomedcentral.com		
42	Publication	<1%
escholarship.org		
43	Publication	<1%
epub.uni-bayreuth.de		
44	Publication	<1%
jurnal.fh.unila.ac.id		
45	Publication	<1%
kups.ub.uni-koeln.de		
46	Publication	<1%
open.metu.edu.tr		
47	Publication	<1%
wnj.westscience-press.com		
48	Publication	<1%
open.metu.edu.tr		
49	Publication	<1%
journal.uinsgd.ac.id		
50	Publication	<1%
publikasiilmiah.unwahas.ac.id		
51	Publication	<1%
eprints.unm.ac.id		
52	Publication	<1%
www.theseus.fi		
53	Publication	<1%
eprints.bournemouth.ac.uk		

54	Publication	<1%
jurnal.uns.ac.id		
55	Publication	<1%
repository.uin-suska.ac.id		
56	Publication	<1%
link.springer.com		
57	Publication	<1%
journal.ikipsiliwangi.ac.id		
58	Publication	<1%
www.frontiersin.org		
59	Publication	<1%
journal.uny.ac.id		
60	Publication	<1%
jurnalfkip.unram.ac.id		
61	Publication	<1%
jeccr.biomedcentral.com		
62	Publication	<1%
www.frontiersin.org		
63	Publication	<1%
www.dovepress.com		
64	Publication	<1%
public-pages-files-2025.frontiersin.org		
65	Publication	<1%
bmcophthalmol.biomedcentral.com		
66	Publication	<1%
www.termedia.pl		
67	Publication	<1%
www.ijiet.org		

68 Publication

theses.hal.science

<1%

69 Publication

journals.plos.org

<1%

ISEJ Indonesian Science Education Journal

ISSN Online: 2716-3350
https://siducat.org/index.php/isej/
Published by Yayasan Darussalam Bengkulu
This article licensed under CC BY 4.0 International
OPEN ACCESS ARTICLE

Effects of a PBL-Assisted AR-Based Book Supporting SDG 4 on Conceptual Understanding and Critical Thinking

Sri Endang Pravita Sari[1], Joko Sulianto[2], and Ngatmini[3]
Master of Elementary Education Program, Graduate School, Universitas PGRI Semarang, Indonesia[123]
E-mail Corresponding: pravita90.vp@gmail.com

Received: June 16, 2026 | Revised: September 18, 2026 | Accepted: October 23, 2026

Abstract

This study examined differences in sixth-grade students' conceptual understanding and critical thinking between Problem-Based Learning (PBL) supported by an Augmented Reality (AR)-Based Book and conventional instruction in Solar System learning. A quantitative quasi-experimental study employing a nonequivalent pretest–posttest control group design involved 35 students from two elementary schools in Blora, Indonesia, comprising 17 experimental and 18 control participants. The intervention was implemented across three instructional sessions. Data were collected using validated essay-based assessments and analyzed through analysis of covariance (ANCOVA) and multivariate analysis of covariance (MANCOVA), controlling for pretest performance. The experimental group achieved higher posttest means in conceptual understanding (86.71 vs. 72.67) and critical thinking (85.82 vs. 70.17). ANCOVA revealed significant adjusted between-group differences in conceptual understanding (mean difference = 13.87, 95% CI [11.45, 16.29], $p < .001$) and critical thinking (mean difference = 15.38, 95% CI [12.19, 18.57], $p < .001$). MANCOVA confirmed a significant multivariate difference (Pillai's Trace = .862, $F(2, 30) = 95.34$, $p < .001$). These findings suggest that integrating AR-supported visualization within structured problem-based inquiry may support conceptual learning and evidence-based reasoning. Nevertheless, the small sample, nonrandom allocation, and school- and teacher-level confounding preclude definitive causal conclusions. Larger multisite and factorial studies are recommended.

Keywords: Augmented Reality; Conceptual Understanding; Critical Thinking; Elementary Science Education; Problem-Based Learning; Sustainable Development Goal 4.

INTRODUCTION

Quality science education in primary schools cannot be reduced to the acquisition of isolated factual knowledge; rather, it requires the development of conceptual understanding, scientific reasoning, critical thinking, and the ability to apply knowledge to complex real-world situations. These competencies are increasingly recognized as essential components of meaningful learning and sustainable educational development, particularly within the framework of Sustainable Development Goal 4 (SDG 4), which emphasizes inclusive, equitable, and quality education. Contemporary educational discourse has consequently shifted from predominantly transmission-oriented instruction toward pedagogical approaches that encourage inquiry, active participation, collaborative problem-solving, and evidence-based reasoning. Nevertheless, international assessments continue to reveal substantial disparities in students' scientific literacy and higher-order cognitive competencies, suggesting that improvements in educational access and technological infrastructure do not necessarily translate into meaningful learning outcomes. The OECD (2023) highlights the persistent need to strengthen students' capacity to interpret evidence, solve unfamiliar problems, and apply scientific knowledge in authentic contexts. Similarly, Sailer et al. (2021) emphasize that the educational value of digital technologies depends fundamentally on pedagogical

implementation rather than technological availability alone. Recent educational research further indicates that sustainable improvements in learning require coherent instructional design, appropriate technological integration, and systematic attention to learners' cognitive development (Chiu & Li, 2023; Koç & Kanadlı, 2025; Febriani et al., 2026). Accordingly, identifying instructional approaches that simultaneously strengthen conceptual understanding and critical thinking remains an important priority in elementary science education.

Conceptual understanding and critical thinking represent closely interconnected but theoretically distinguishable dimensions of cognitive development. Conceptual understanding refers to learners' capacity to recognize essential scientific principles, explain relationships among concepts, interpret phenomena, and apply acquired knowledge across different contexts. Critical thinking, conversely, involves the systematic analysis of information, evaluation of evidence, identification of logical relationships, examination of alternative explanations, and formulation of justified conclusions. Although conceptual knowledge provides the intellectual foundation for analytical reasoning, the acquisition of scientific concepts does not automatically ensure the development of critical-thinking competencies. García-Carmona (2025) distinguishes scientific thinking from critical thinking while emphasizing their mutually reinforcing relationship within science education. Similarly, Simonovic et al. (2023) demonstrate the importance of explicit reasoning activities in strengthening analytical thinking, argumentation, and metacognitive awareness. Meta-analytical evidence further suggests that collaborative problem-solving activities can promote critical-thinking development when learners are required to negotiate interpretations and justify their decisions (Xu et al., 2023). These findings indicate that elementary science instruction should not exclusively prioritize factual comprehension but should also create opportunities for students to evaluate scientific information, examine competing explanations, and construct logically defensible arguments.

The Solar System constitutes a particularly challenging instructional topic because its fundamental concepts involve astronomical scales, planetary motion, spatial relationships, orbital characteristics, and phenomena that cannot be directly observed in their entirety within conventional classrooms. Elementary students are frequently required to construct mental representations of objects and processes that extend beyond their immediate perceptual experiences. Consequently, explanations relying predominantly on verbal descriptions, textbook illustrations, or static diagrams may provide insufficient support for understanding three-dimensional astronomical relationships. Research investigating immersive educational technologies suggests that interactive visualization can facilitate the exploration of complex scientific phenomena by enabling learners to examine otherwise inaccessible structures and relationships. Önal and Önal (2021) found that augmented reality supported astronomy-related achievement and interest among gifted learners, while Cai et al. (2022) demonstrated the potential of AR-supported inquiry activities for elementary science learning. More recently, research comparing virtual and augmented reality in primary-level Solar System instruction has further examined the relationship between immersive visualization and learning performance (Limpinan et al., 2026). Nevertheless, the instructional effectiveness of visualization depends not merely on the sophistication of the representations but also on the extent to which students use them to investigate scientific relationships, construct explanations, and evaluate evidence (Wen et al., 2024; Gonnermann-Müller & Krüger, 2025; Wang et al., 2026).

Within the Indonesian educational context, these concerns are particularly relevant to Integrated Science and Social Studies (*Ilmu Pengetahuan Alam dan Sosial*, IPAS), which requires elementary students to develop scientific knowledge alongside contextual understanding and inquiry competencies. The implementation of the Merdeka Curriculum places increasing emphasis on active learning, conceptual exploration, and the application of knowledge to meaningful situations. However, translating these expectations into effective classroom practices remains

challenging when instruction depends heavily on teacher explanations, conventional textbooks, and limited opportunities for interactive investigation. The preliminary investigation conducted at SDN 1 Bangsri and SDN 2 Bangsri in Blora Regency, Central Java, identified difficulties among sixth-grade students in explaining Solar System concepts, connecting scientific evidence with observed phenomena, and developing logically justified explanations. A diagnostic assessment involving 35 students produced an overall mean score of 22.40 out of 40 points, equivalent to 56.00% of the maximum possible score. The experimental and control classes obtained descriptive diagnostic means of 22.59 and 22.22, respectively, indicating relatively similar initial performance without establishing statistical equivalence. Classroom observations and teacher interviews additionally suggested that learning activities were predominantly teacher-directed and that interactive technological resources were insufficiently integrated into scientific inquiry. Although these findings are specific to the participating schools, they reflect instructional concerns addressed in related Indonesian studies examining interactive science materials, problem-oriented instruction, and elementary students' reasoning competencies (Nofitri et al., 2024; Sapira & Ansori, 2024; Muspiroh et al., 2025).

Problem-Based Learning (PBL) provides a theoretically relevant pedagogical framework for addressing these instructional challenges. Grounded in constructivist and inquiry-oriented perspectives, PBL positions learners as active participants who develop understanding through investigating meaningful problems, identifying relevant information, examining evidence, and constructing explanations collaboratively. Rather than treating scientific concepts as information to be memorized, PBL encourages students to interpret problems, formulate questions, investigate possible solutions, and evaluate conclusions through interaction and reflection. A second-order meta-analysis conducted by Koçoğlu and Kanadlı (2025) provides evidence that PBL can support cognitive and affective learning outcomes, although the magnitude of its effectiveness varies according to research and implementation characteristics. Xu et al. (2023) similarly identify collaborative problem-solving as a productive instructional condition for strengthening critical-thinking competencies. Indonesian research also demonstrates the potential of PBL to support science learning, student participation, and cognitive development, although outcomes may differ across educational levels, instructional environments, and assessment approaches (Samsudin et al., 2023; Yudiana et al., 2023; Judijanto et al., 2024). Therefore, the pedagogical contribution of PBL should be understood through the quality of inquiry opportunities, collaborative interactions, and instructional guidance it provides rather than through assumptions of universal effectiveness.

The relevance of PBL extends beyond natural science education to other disciplinary contexts in which learners must analyze authentic problems and construct defensible interpretations. Erlina et al. (2025), in a study coauthored by Muhammad Sufian, investigated the integration of PBL into Arabic-language instruction incorporating religious moderation values. Their classroom action research indicated improvements in student engagement, linguistic performance, and reasoning-oriented classroom participation through contextual problem analysis, structured discussion, and reflective instructional refinement. Although the disciplinary context differs substantially from elementary science, the study provides complementary evidence concerning the instructional importance of authentic problems, collaborative dialogue, and guided reasoning. Related Indonesian research examining integrated learning emphasizes the importance of connecting subject content with students' experiences and meaningful instructional activities. Al Khansa et al. (2024), also involving Muhammad Sufian, reported that contextualized integrated instruction in Islamic education supported student engagement and understanding of learning content. These findings reinforce the broader pedagogical argument that active learning requires carefully organized interactions between instructional objectives, relevant learning materials, and opportunities for student participation. However, neither study directly establishes the effectiveness of AR-supported PBL in elementary astronomy education, making their contribution primarily conceptual and

pedagogical rather than direct empirical evidence for the present intervention.

Despite its instructional potential, PBL may encounter limitations when learners investigate scientific phenomena that are difficult to observe or represent through conventional instructional materials. Students examining planetary movement, relative astronomical positions, or spatial relationships require representations that support accurate observation and conceptual interpretation. Augmented Reality (AR) offers a potentially valuable solution by integrating digitally generated objects into the physical learning environment, allowing students to examine three-dimensional representations through interactive devices. Unlike static textbook illustrations, AR-based visualization can provide opportunities to rotate, observe, and compare virtual objects from different perspectives. A meta-analysis by Lin and Yu (2023) reported generally positive learning outcomes associated with AR-supported interactive environments, although substantial variation was evident across instructional conditions. Lu et al. (2025) further identified positive effects of AR on higher-order thinking, while emphasizing differences associated with visualization features, learning activities, and the cognitive competencies being assessed. Similarly, Hidayat et al. (2026) synthesized evidence concerning AR applications in science, technology, engineering, and mathematics education. These investigations collectively suggest that AR may support conceptual exploration and higher-order learning, but its contribution is contingent on instructional design, learning objectives, and the cognitive demands of the associated activities.

The theoretical value of AR can be understood through constructivist learning principles and the pedagogical role of multimodal representations. From a constructivist perspective, learners develop scientific understanding by actively interpreting information, relating new experiences to existing conceptual frameworks, and revising explanations through inquiry and reflection. AR-supported representations may facilitate this process by making abstract scientific objects accessible for observation and comparison. However, additional visual information does not necessarily produce deeper learning. Poorly structured interaction, excessive visual complexity, or insufficient instructional guidance may increase cognitive demands without improving understanding. Gonnermann-Müller and Krüger (2025) emphasize the importance of cognitive-load considerations when designing AR learning environments. Similarly, Koç and Kanadlı (2025), through network meta-analysis, demonstrate that different interactive learning environments produce varying educational outcomes, making it inappropriate to assume the inherent superiority of any particular technological modality. Research on primary science inquiry also indicates that teacher guidance influences how students interpret AR representations and participate in investigative activities (Wen et al., 2024; Wang et al., 2026). Accordingly, AR should be conceptualized as an instructional resource that supports specific cognitive processes rather than as an independent mechanism capable of automatically improving learning performance.

The integration of AR into learning materials further requires careful consideration of accessibility, instructional sequencing, and alignment between visual content and educational objectives. Printed learning resources supplemented by interactive digital representations may provide a bridge between familiar classroom materials and technology-mediated exploration. Research on digital instructional material development supports the importance of systematic design, learner accessibility, content relevance, and interaction quality. Koderi et al. (2023), in research involving Muhammad Sufian, developed an instructional film incorporating Lampung local wisdom to support Arabic communication skills among madrasah students. Similarly, Pribowo et al. (2024), also involving Muhammad Sufian, developed an interactive flipbook-based Islamic education e-module and evaluated its instructional feasibility and learning outcomes. Although these studies did not investigate AR-based science education, their findings illustrate the potential contribution of contextualized digital materials when multimedia resources are systematically aligned with instructional needs. Related investigations of interactive teaching resources and digitally supported instruction further emphasize the importance of combining technological content with active

learning rather than treating multimedia exposure as sufficient for conceptual development (Sailer et al., 2021; Nevrelova et al., 2024; Nikou, 2024).

The present study adopts this pedagogical orientation by integrating an AR-Based Book into the instructional phases of PBL rather than employing AR as an isolated visualization activity. The learning resource contains printed markers that students scan to access three-dimensional representations of Solar System objects. These representations are embedded within five instructional phases: problem orientation, organization of learning activities, guided investigation, presentation of findings, and reflection. During problem orientation, students encounter contextual questions concerning astronomical phenomena. During investigation, the AR-Based Book provides visual representations through which students can explore planetary characteristics, compare spatial relationships, and gather information relevant to the problems being examined. Subsequent collaborative discussions and presentations require students to articulate explanations, justify conclusions, and evaluate alternative interpretations. This integration is consistent with the argument that technology-supported visualization becomes more educationally meaningful when combined with explicit inquiry activities and opportunities for evidence-based reasoning (Cai et al., 2022; Wen et al., 2024; Wang et al., 2026). Research concerning AR-supported instructional design further indicates that learning outcomes should be examined in relation to the organization of learning activities, teacher mediation, and student interactions rather than attributed exclusively to technological features (Chen et al., 2026; Nevrelova et al., 2024; Geng et al., 2026).

Collaborative learning constitutes another important component of the proposed instructional framework because conceptual explanation and critical thinking develop through opportunities to articulate, compare, and revise ideas. Students who discuss scientific problems with peers are encouraged to make their reasoning explicit, confront alternative interpretations, and evaluate the adequacy of supporting evidence. Such interaction is particularly valuable when learners are investigating complex phenomena that require the coordination of multiple scientific concepts. Xu et al. (2023) demonstrate the relevance of collaborative problem-solving to critical-thinking development, while Simonovic et al. (2023) emphasize the contribution of explicit argumentation and analytical reflection. Indonesian educational research also provides related evidence concerning collaborative and visually supported instructional strategies. Afifurrahman et al. (2025), in a study coauthored by Muhammad Sufian, examined picture-word inductive instruction and group investigation in elementary Arabic writing education. Although its outcome measures and subject matter differ from those of the present study, the research contributes to the broader understanding of visual instructional resources and organized group learning. These findings suggest that collaborative investigation may complement interactive visualization by providing opportunities for learners to transform observations into articulated explanations. Nevertheless, the specific contributions of collaboration, PBL, and AR must be distinguished conceptually because an integrated intervention does not permit their independent effects to be identified without additional experimental comparisons.

Recent international scholarship increasingly emphasizes the importance of investigating how AR-supported instructional activities influence specific cognitive outcomes rather than relying exclusively on general achievement measures. Lu et al. (2025) identify differences in the relationship between AR and distinct dimensions of higher-order thinking, suggesting that cognitive outcomes should not be treated as interchangeable. García-Carmona (2025) similarly argues for clearer conceptual distinctions between scientific thinking and critical thinking, while Wang et al. (2026) demonstrates the relevance of teacher support within AR-enhanced inquiry learning in primary classrooms. Research on AR-based learning design also indicates that instructional effectiveness depends on the interaction between visual representations, task structures, and learners' cognitive engagement (Gonnermann-Müller & Krüger, 2025; Koç & Kanadlı, 2025; Hidayat et al., 2026). Consequently, an evaluation focusing solely on general learning achievement may overlook

meaningful distinctions between students' understanding of scientific concepts and their ability to analyze evidence, evaluate explanations, and justify conclusions. Simultaneously examining these competencies offers a more differentiated account of cognitive outcomes associated with technology-supported problem-based instruction.

Within Indonesian elementary education, the integration of PBL and AR has already received scholarly attention. Sapira and Ansori (2024) developed an AR-based science learning book integrated with PBL to improve elementary students' learning outcomes. Rachmayani and Setyasto (2025) subsequently examined AR-assisted PBL in elementary instruction concerning the forms and changes of matter. These studies demonstrate that combining PBL with AR is not a previously unexplored instructional approach. Other Indonesian investigations have addressed interactive science materials and PBL-oriented learning resources, highlighting their potential relevance to scientific understanding and critical-thinking development (Nofitri et al., 2024; Muspiroh et al., 2025; Mahfud et al., 2026). Nevertheless, previous studies vary substantially in instructional topics, participant characteristics, technological configurations, assessment instruments, and research designs. Accordingly, the contribution of the present research must be established through the specific instructional integration being examined, the characteristics of the targeted cognitive outcomes, and the methodological strategy used to evaluate them rather than through an unsupported claim that PBL and AR have never been combined.

A complementary perspective emerges from contemporary research examining digital learning within broader educational and developmental contexts. Handoko et al. (2026), writing in *Digital Learning, Social Science, and Life-course Studies*, investigated digital learning trajectories in biology education and emphasized the significance of contextual transitions and meaning-making processes. Damanik and Remtula (2026) likewise examined metacognitive readiness in digital learning and its relationship with lifelong learning pathways, while Hariandini et al. (2026) explored digital integrated learning through school-based classroom practices. Although these investigations differ from a short-term quasi-experimental intervention involving elementary science students, they underscore the importance of understanding digital learning as a pedagogically situated process rather than a purely technological activity. From a sustainability perspective, Febriani et al. (2026) examined the relationship between educational development and the Sustainable Development Goals in Indonesia and Australia. These studies provide a broader contextual foundation for positioning technology-supported science instruction within the aspiration of SDG 4. Nevertheless, alignment with SDG 4 should be interpreted as a contribution to quality-oriented instructional practice rather than direct evidence that an individual intervention achieves national or global sustainability targets (OECD, 2023; Sailer et al., 2021; Febriani et al., 2026).

Despite the expanding literature, several important research gaps remain. First, although PBL and AR have been examined independently and in combination, existing investigations employ diverse instructional configurations, making it necessary to clarify how specific AR resources are functionally integrated into successive phases of problem-based investigation. Second, assessments emphasizing technology feasibility, engagement, or general achievement may provide limited insight into the simultaneous development of conceptual understanding and critical thinking as distinguishable cognitive outcomes. Third, empirical evidence remains context-dependent, particularly in elementary astronomy instruction, where abstract spatial relationships create instructional demands that differ from those encountered in other science topics. Fourth, the interpretation of findings from quasi-experimental investigations requires explicit attention to baseline performance, selection processes, and potential institutional or teacher-level confounding. Although previous meta-analyses establish a strong rationale for investigating AR-supported and problem-oriented learning, variation in research designs and instructional contexts limits the direct generalization of their findings to the present setting (Koçoğlu & Kanadlı, 2025; Lu et al., 2025; Koç & Kanadlı, 2025). These gaps justify further context-specific investigation using clearly defined

cognitive constructs, transparent intervention procedures, and appropriate baseline-adjusted statistical analyses.

The principal novelty of the present study lies in the functional integration of an AR-Based Book into the structured phases of PBL for Grade VI Solar System instruction within Indonesian IPAS education, combined with the simultaneous examination of conceptual understanding and critical thinking. Unlike approaches treating AR primarily as a supplementary visualization tool, this investigation positions the AR-Based Book as a resource supporting problem investigation, observation, evidence interpretation, collaborative explanation, and reflection. Furthermore, the study operationalizes conceptual understanding and critical thinking through separate essay-based assessments and evaluates between-group differences using both univariate and multivariate analyses adjusted for initial performance. This approach provides a more differentiated description of cognitive outcomes associated with the integrated instructional condition. Nevertheless, its contribution should not be interpreted as establishing the independent effectiveness of PBL or AR, given that the intervention combines multiple pedagogical components and compares students from different schools. Rather, the study offers contextual empirical evidence concerning the implementation and associated learning outcomes of a pedagogically integrated PBL–AR-Based Book approach, extending prior Indonesian research while maintaining appropriate methodological caution (Sapira & Ansori, 2024; Rachmayani & Setyasto, 2025; Lu et al., 2025).

Accordingly, this study aims to examine whether sixth-grade students participating in Problem-Based Learning supported by an Augmented Reality-Based Book demonstrate statistically significant differences in conceptual understanding and critical thinking compared with students receiving conventional instruction on Solar System concepts. Specifically, the study investigates between-group differences in conceptual understanding after controlling for pretest performance, examines corresponding differences in critical thinking, and evaluates whether instructional condition is associated with a significant multivariate difference across both cognitive outcomes. By integrating interactive astronomical representations into structured problem-based investigation and employing baseline-adjusted statistical analyses, the study seeks to contribute empirical evidence to the development of pedagogically informed digital science instruction in Indonesian elementary schools. Because the investigation employs a nonequivalent quasi-experimental design involving intact classes from two different schools, its findings are interpreted as contextual between-group differences rather than definitive causal effects. The resulting evidence is expected to inform future instructional development and provide a basis for larger, more rigorously controlled investigations of PBL–AR integration in elementary science education.

METHODS

Research Design and Participants

This study employed a quantitative quasi-experimental nonequivalent pretest–posttest control group design. The study was conducted from February to May 2026 at SDN 1 Bangsri and SDN 2 Bangsri, Blora Regency, Central Java, Indonesia. The participants were 35 sixth-grade students, comprising 17 students in the experimental group and 18 students in the control group. The schools and classes were selected purposively based on the following inclusion criteria: (1) Grade VI students implementing the Merdeka Curriculum; (2) the same IPAS Solar System topic; (3) comparable learning needs identified through preliminary observation and teacher interviews; (4) availability of the required learning facilities; and (5) willingness of the school, teacher, students, and parents/guardians to participate. Classes were excluded if they did not meet the Grade VI IPAS curriculum requirements or could not complete the planned instructional and assessment procedures (Fraenkel et al., 2023).

Because intact classes from different schools were used, school membership and instructional condition were inherently confounded (Alim et al., 2024). Therefore, the findings were interpreted

as contextual between-group differences rather than definitive causal effects. Baseline performance was controlled statistically through ANCOVA and MANCOVA (Ahmad & Wilkins, 2025).

Table 1. School and Group Comparability

Characteristic	Experimental: SDN 1 Bangsri	Control: SDN 2 Bangsri
Students	17	18
Grade/Curriculum	VI / Merdeka	VI / Merdeka
Prior learning topic	Solar System	Solar System
Teacher qualification	S.Pd., Elementary School Teacher Education	S.Pd., Elementary School Teacher Education
Teaching experience	12 years	10 years
IPAS teaching experience	8 years	7 years
Instructional time	3 × 105 minutes	3 × 105 minutes
Basic facilities	Whiteboard, desks, electricity, projector	Whiteboard, desks, electricity, projector
Digital resources	Laptop, projector, smartphone, internet	Laptop, projector, smartphone, internet
Learning resources	Textbook, worksheets, projector materials, interactive digital media	Textbook, worksheets, printed visual materials
Teacher	Different teacher	Different teacher

Both schools had comparable basic facilities, curriculum, topic, and instructional duration; however, the learning resources differed. The experimental school used the intervention-supported interactive media, whereas the control school relied on conventional resources. These differences, together with teacher characteristics, were treated as potential sources of selection and treatment confounding (Hair et al., 2023).

Research Procedure and Intervention

Both groups completed pretests of conceptual understanding and critical thinking before instruction. The experimental group received PBL integrated with an AR-Based Book through five phases: problem orientation, problem organization, guided investigation, presentation of findings, and reflection. Students used the AR-Based Book to scan markers, observe three-dimensional planetary models, investigate Solar System phenomena, discuss evidence, and construct explanations. The control group received conventional instruction through teacher explanations, question-and-answer activities, textbooks, and individual exercises. Both groups addressed the same content and learning objectives for three meetings of 105 minutes each.

Implementation fidelity was monitored through a structured non-participant observation checklist containing 12 indicators covering PBL phases, AR-Based Book use, teacher activities, and student participation (Rachmayani & Setyasto, 2025; Sapira & Ansori, 2024). The observation data were used as supporting evidence of treatment fidelity and were not included as primary outcome data.

Teacher Effect

The experimental and control groups were taught by different teachers. Both teachers held an S.Pd. degree in Elementary School Teacher Education; the experimental teacher had 12 years of teaching experience, including approximately eight years teaching elementary IPAS, while the control teacher had 10 years of experience, including approximately seven years teaching IPAS. Both had experience implementing the Merdeka Curriculum and received the same information concerning learning objectives, content, instructional duration, assessment, and research procedures. Nevertheless, teacher characteristics and classroom practices could not be completely separated from the instructional condition and were therefore treated as a serious design limitation (Yudiana et al., 2023; Judijanto et al., 2024).

Instruments, Construct Framework, and Validation

Conceptual understanding and critical thinking were measured using 10-item essay tests administered as pretests and posttests. Conceptual understanding covered explaining concepts, interpreting relationships, applying concepts, and explaining phenomena. Critical thinking indicators were derived from the analysis, interpretation, evaluation, reasoning, and evidence-based argumentation dimensions specified in the study's construct framework. Each response was scored from 0–4 using an analytic rubric based on accuracy, completeness, relevance, logical reasoning, and evidence (Mulyana & Desnita, 2023; Dirman & Mufit, 2022).

Table 2. Construct and Scoring Framework

Construct	Indicators	Scoring basis
Conceptual understanding	Explaining concepts; interpreting relationships; applying concepts; explaining phenomena	Accuracy, completeness, and relevance
Critical thinking	Analysis; interpretation; evaluation; reasoning; evidence-based argumentation	Analysis, logical justification, evaluation, and evidence use

Scoring: *4 = accurate, complete, logically reasoned, evidence-supported; 3 = substantially correct with minor limitations; 2 = partially correct with important limitations; 1 = minimal relevant response; 0 = incorrect/irrelevant/no response.*

Three experts in elementary science education, elementary education, and educational assessment reviewed the instruments for content relevance, construct alignment, clarity, language, and learning-objective alignment. The overall validation score was 89.40%. A pilot test involving 30 sixth-grade students from SDN 3 Bangsri was conducted. Item-total correlations, difficulty, discrimination, and Cronbach's alpha were examined; α = .87. Because essay scores require judgment, two raters independently scored pilot responses after rubric training, producing an ICC of .89. Thus, Pearson correlation and Cronbach's alpha were treated as supporting evidence rather than the sole basis for validity; content and construct validity were established through the construct framework and expert judgment, while ICC provided evidence of scoring consistency.

Data Collection and Analysis

Preliminary observations and semi-structured teacher interviews were conducted to identify learning needs and select the research setting. Primary data were obtained from validated pretests and posttests of conceptual understanding and critical thinking.

Descriptive statistics, Shapiro–Wilk, and Levene's tests were first conducted. Because the groups were nonequivalent, ANCOVA was used separately for conceptual understanding and critical thinking, with posttest scores as dependent variables, instructional condition as the independent variable, and corresponding pretest scores as covariates. Assumptions of linearity, homogeneity of regression slopes, normality, and homogeneity of variance were examined (Amiruddin et al., 2024; Sriwahyuni et al., 2025). MANCOVA was subsequently used to examine the two posttest outcomes simultaneously while controlling for baseline scores. Wilks' Lambda, partial eta squared, and 95% confidence intervals were reported. N-Gain was retained only as descriptive supplementary information and was not used as the primary basis for causal claims. Statistical significance was set at α = .05.

Ethical Considerations

The study received ethical approval from Universitas PGRI Semarang (UPGRIS), Approval No. 012/KEP-ETIK/UPGRIS/IX/2026, dated 15 September 2026, and permission was obtained from SDN 1 Bangsri and SDN 2 Bangsri. Written informed consent was obtained from parents/guardians and assent from participating students. Participation was voluntary and did not affect students' academic evaluation. Participant identities were replaced with codes, data were securely stored, and results were reported in aggregate form. During AR activities, students received age-appropriate instructions and were supervised by the teacher and researcher; device use was restricted to instructional purposes and paused when discomfort occurred.

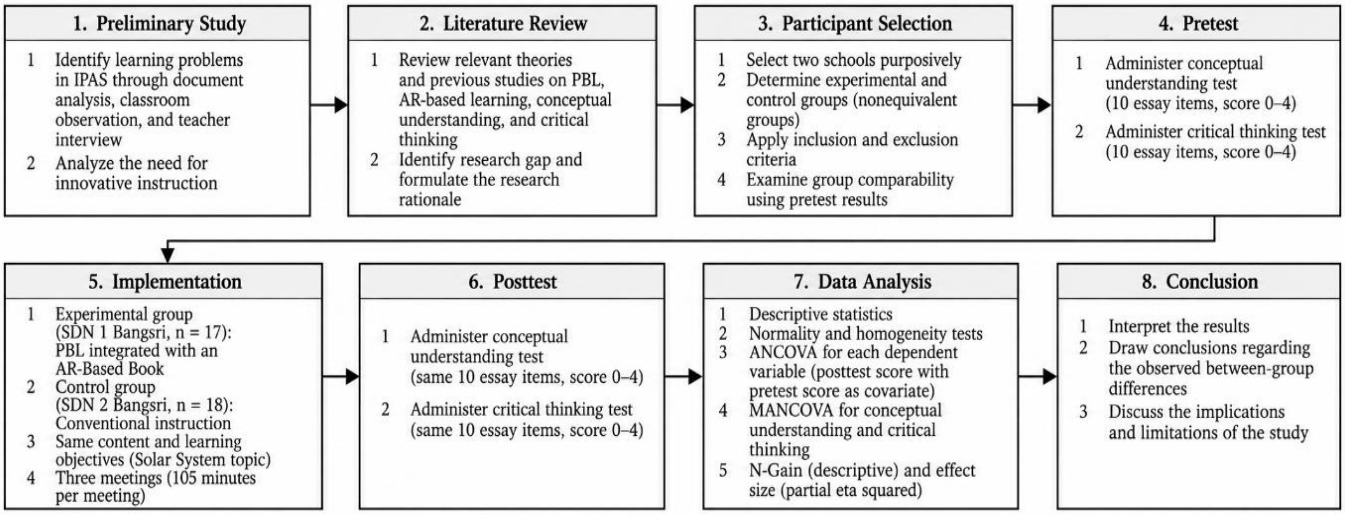


Figure 2. Research Procedure of the Nonequivalent Quasi-Experimental Study

RESULT AND DISCUSSION

Preliminary Analysis

Preliminary analyses were conducted to examine baseline performance and the assumptions for the primary inferential analyses. Descriptive statistics are presented in Table 3. At baseline, the experimental and control groups showed similar mean scores for conceptual understanding (47.53 vs. 46.72) and critical thinking (45.24 vs. 44.50). However, descriptive similarity alone was not considered evidence of baseline equivalence. Because the groups were non-randomly assigned and drawn from different schools, standardized mean differences and formal baseline comparisons were also considered.

For conceptual understanding, the standardized mean difference at pretest was Cohen's d = 0.28, indicating a small baseline difference. The corresponding mean difference was 0.81 points, 95% CI [−1.18, 2.80], with no statistically significant difference (p = .412). For critical thinking, the standardized mean difference was Cohen's d = 0.30, also indicating a small baseline difference. The mean difference was 0.74 points, 95% CI [−0.99, 2.47], and was not statistically significant (p = .387).

These results indicate that the groups had relatively similar initial performance, but they do not establish equivalence because the study used a nonequivalent, cross-school design. Accordingly, pretest scores were retained as covariates in the primary ANCOVA models regardless of the baseline significance tests.

Table 3. Descriptive Statistics of Conceptual Understanding and Critical Thinking

Outcome	Group	N	Pretest Mean	SD	SMD (Cohen's d)	Mean Difference	95% CI	p
Conceptual understanding	Experimental	17	47.53	3.22	0.28	0.81	−1.18 to 2.80	0.43
	Control	18	46.72	2.47	—	—	—	—
Critical thinking	Experimental	17	45.24	2.91	0.30	0.74	−0.99 to 2.47	0.38
	Control	18	44.50	1.95	—	—	—	—

Table 3 presents baseline comparability between groups. Pretest means were similar for conceptual understanding (47.53 vs. 46.72) and critical thinking (45.24 vs. 44.50), with small standardized mean differences (d = 0.28 and 0.30, respectively). Baseline comparisons were nonsignificant (p = .43 and .38). Nevertheless, because the groups were non-randomly assigned across different schools, pretest scores were retained as covariates in the primary ANCOVA models.

Posttest score distributions were subsequently examined to assess the magnitude and

variability of the observed between-group differences. As shown in Table 4, the experimental group obtained higher posttest means than the control group for conceptual understanding (86.71 vs. 72.67) and critical thinking (85.82 vs. 70.17). The mean differences were 14.04 points for conceptual understanding (95% CI = 11.89–16.19) and 15.65 points for critical thinking (95% CI = 13.36–17.95). The posttest standard deviations ranged from 2.68 to 3.91, indicating relatively restricted within-group variability. The reported minimum and maximum scores provide additional information about the score distributions and are considered when interpreting the magnitude of the observed group differences. Given the relatively restricted posttest variance, the effect estimates were interpreted cautiously, with consideration of potential score compression and the study's nonequivalent cross-school design.

Table 4. Results of Normality and Homogeneity Tests

Outcome	Group	N	Mean	SD	Minimum	Maximum	Mean Difference	95% CI
Conceptual understanding	Experimental	17	86.71	3.31	80.00	92.00	14.04	11.89–16.19
	Control	18	72.67	2.95	67.00	78.00	—	—
Critical thinking	Experimental	17	85.82	3.91	77.00	92.00	15.65	13.36–17.95
	Control	18	70.17	2.68	65.00	75.00	—	—

Normality and homogeneity assumptions were examined before the baseline-adjusted analyses. Shapiro–Wilk tests indicated normality (p > .05), while Levene's tests indicated homogeneous variances (p = .70 and .10). Box's M was F = 2.50, p = .06. Given the small, unequal groups, Pillai's Trace was used as the primary multivariate statistic for greater robustness.

Posttest Descriptive Statistics and Score Distribution

Following the intervention, the experimental group obtained higher posttest means than the control group for both conceptual understanding (86.71 vs. 72.67) and critical thinking (85.82 vs. 70.17). The corresponding mean differences were 14.04 points for conceptual understanding and 15.65 points for critical thinking.

For conceptual understanding, the 95% CI for the unadjusted mean difference was 11.88–16.20 points, while for critical thinking it was 13.32–17.98 points. The standardized mean differences were also large, with Cohen's d = 4.49 for conceptual understanding and Cohen's d = 4.70 for critical thinking.

Although the posttest distributions showed relatively small within-group variability (SD = 2.95–3.91), these large standardized differences should be interpreted cautiously. The restricted variance may magnify standardized effect estimates. Therefore, the results were examined in conjunction with the observed score ranges, score distributions, rubric-based scoring procedures, and inter-rater reliability rather than relying solely on group means and standard deviations. The present summary data, however, do not contain the individual score ranges required to report the minimum and maximum values; these should be added from the raw posttest dataset.

Table 5. ANCOVA Results for Posttest Outcomes Controlling for Pretest Scores

Dependent Variable	Covariate	F	df	p	Partial η^2	Adjusted Mean Difference	95% CI
Conceptual understanding	Pretest	118.64	1, 32	< .001	.787	13.87	11.45–16.29
Critical thinking	Pretest	96.72	1, 32	< .001	.751	15.38	12.19–18.57

Baseline-Adjusted Effects of the Intervention

Because the study used a nonequivalent pretest–posttest design, ANCOVA was used as the primary analysis, with pretest scores as covariates. The adjusted group effect was significant for conceptual understanding, $F(1, 32) = 118.64$, $p < .001$, partial $\eta^2 = .787$, with an adjusted mean difference of 13.87 points (95% CI [11.45, 16.29]). For critical thinking, the adjusted group effect was also significant, $F(1, 32) = 96.72$, $p < .001$, partial $\eta^2 = .751$, with an adjusted mean difference of 15.38 points (95% CI [12.19, 18.57]). These ANCOVA results were treated as the primary inferential evidence. Given the cross-school design and different teachers, however, the effects are interpreted as contextual between-group differences rather than definitive causal effects.

Table 6. MANCOVA Results Using Pillai's Trace

Effect	Pillai's Trace	F	Hypothesis df	Error df	p	Partial η^2
Group	0.862	95.34	2	30	< .001	.862

A MANCOVA was conducted to examine the multivariate effect of instructional condition on posttest outcomes while controlling for pretest scores. Pillai's Trace was selected because of its robustness for relatively small samples. The analysis showed a significant multivariate effect, Pillai's Trace = .862, $F(2, 30) = 95.34$, $p < .001$, partial $\eta^2 = .862$. This result indicates a significant adjusted multivariate between-group difference, which was interpreted together with the univariate ANCOVA results for each outcome.

Multivariate Analysis

A MANCOVA was conducted after checking the assumptions. Shapiro–Wilk tests indicated acceptable normality, Levene's tests showed homogeneous variances ($p = .70$ and .10), and Box's M was $F = 2.50$, $p = .06$. Given the small, unequal groups, Pillai's Trace was selected for its robustness. The analysis showed a significant multivariate group effect, Pillai's Trace = .862, $F(2, 30) = 95.34$, $p < .001$, partial $\eta^2 = .862$. Follow-up ANCOVAs showed significant adjusted differences for conceptual understanding, $F(1, 32) = 118.64$, $p < .001$, partial $\eta^2 = .787$, adjusted mean difference = 13.87 (95% CI [11.45, 16.29]), and critical thinking, $F(1, 32) = 96.72$, $p < .001$, partial $\eta^2 = .751$, adjusted mean difference = 15.38 (95% CI [12.19, 18.57]).

Table 6. MANCOVA Results Using Pillai's Trace

Effect	Pillai's Trace	F	Hypothesis df	Error df	p	Partial η^2
Group	0.862	95.34	2	30	< .001	0.862

Table 7. N-Gain Descriptive Results

Outcome	Group	N	Mean N-Gain	SD	Category
Conceptual understanding	Experimental	17	0.74	0.04	High
	Control	18	0.48	0.03	Moderate
Critical thinking	Experimental	17	0.74	0.05	High
	Control	18	0.46	0.03	Moderate

As an additional descriptive analysis, normalized gain (N-Gain) was calculated to describe the relative improvement from pretest to posttest. For conceptual understanding, the experimental group obtained a mean N-Gain of 0.74 (SD = 0.04), which was categorized as high, whereas the control group obtained a mean N-Gain of 0.48 (SD = 0.03), which was categorized as moderate. For critical thinking, the experimental group also obtained a mean N-Gain of 0.74 (SD = 0.05), categorized as high, while the control group obtained a mean N-Gain of 0.46 (SD = 0.03), categorized as moderate.

These N-Gain values provide a descriptive indication of the relative improvement observed in the two groups. However, N-Gain was not used as the primary inferential analysis because the study employed a nonequivalent pretest–posttest design. The primary inference was based on ANCOVA and MANCOVA models that adjusted for baseline performance.



Figure 3. Collaborative Investigation Using the AR-Based Book in PBL Learning



Figure 4. Students' Guided Exploration Using the AR-Based Book

Learning Improvement and Effect Size

Further evidence was provided by the N-Gain results in Table 8. The experimental group showed higher N-Gain values for conceptual understanding (0.74) and critical thinking (0.74), both categorized as high, compared with the control group (0.48 and 0.46), categorized as moderate. These results indicate greater observed learning gains in the experimental group, although they should be interpreted cautiously given the nonequivalent design, small sample, and differences in school contexts.

Table 8. Descriptive Statistics of N-Gain Scores

Variable	Group	N	Mean	SD	Category
Conceptual understanding	Experimental	17	0.74	0.04	High
	Control	18	0.48	0.03	Moderate
Critical thinking	Experimental	17	0.74	0.05	High
	Control	18	0.46	0.03	Moderate

Beyond the observed learning gains, the magnitude of the differences between the experimental and control groups was further examined using partial η^2 as a measure of practical effect. The results of the effect-size analysis for conceptual understanding and critical thinking are presented in Table 9.

Table 9. Practical Effect of the Intervention

Learning outcome	Partial η^2	Interpretation
Conceptual understanding	0.84	Large
Critical thinking	0.85	Large


KURIKULUM MERDEKA
GALAKSI

Figure 5. Teacher-Guided Presentation of Solar System Learning Using the AR-Based Book

The partial η^2 values were .84 for conceptual understanding and .85 for critical thinking, indicating large effects within the present sample. Figure 5 illustrates the integration of the AR-Based Book into teacher-guided PBL activities through visual exploration, discussion, and explanation. However, these effects should be interpreted cautiously given the nonequivalent design, small sample, and differences in school contexts.

Discussion

The findings demonstrate substantial differences in conceptual understanding and critical thinking between sixth-grade students receiving Problem-Based Learning (PBL) supported by an Augmented Reality (AR)-Based Book and those receiving conventional instruction. The experimental group achieved higher posttest scores in conceptual understanding (86.71 versus 72.67) and critical thinking (85.82 versus 70.17). After controlling for baseline performance, ANCOVA revealed significant adjusted mean differences of 13.87 points for conceptual understanding, $F(1, 32) = 118.64$, $p < .001$, partial $\eta^2 = .787$, and 15.38 points for critical thinking, $F(1, 32) = 96.72$, $p < .001$, partial $\eta^2 = .751$. MANCOVA further identified a significant multivariate group difference, Pillai's Trace = .862, $F(2, 30) = 95.34$, $p < .001$. These results address the study's objectives by demonstrating that both cognitive outcomes differed significantly between instructional conditions. Nevertheless, because the intervention was implemented in different schools by different teachers, the findings indicate associations with the integrated instructional condition rather than definitive causal effects.

The higher conceptual understanding observed in the experimental group is consistent with international research highlighting the educational potential of interactive scientific visualization. Cai et al. (2022) demonstrated the relevance of AR-supported inquiry activities for primary science learning, while Önal and Önal (2021) reported improvements in astronomy achievement through AR-assisted instruction. More recently, Limpinan et al. (2026) found that both AR and virtual reality supported Solar System learning among primary students, although their comparative design and assessment procedures differed from those employed in the present investigation. Similarly, Aldeeb et al. (2024) demonstrated that mobile AR-supported concept-association activities could facilitate knowledge acquisition among younger learners. These findings suggest that interactive representations can make abstract scientific relationships more accessible. However, the present study extends this discussion by situating three-dimensional astronomical visualization within structured problem investigation, collaborative explanation, and reflection rather than relying exclusively on technological presentation.

The improvement in critical-thinking performance also corresponds with international evidence concerning problem-oriented and technology-supported learning. Koçoğlu and Kanadlı (2025), through a second-order meta-analysis, identified positive contributions of PBL to cognitive and affective outcomes, although the magnitude of these relationships varied across studies. Lu et al. (2025) similarly reported a positive overall association between AR-supported instruction and higher-order thinking, with substantial variation according to visualization characteristics and cognitive dimensions. Xu et al. (2023) further demonstrated the importance of collaborative problem-solving for critical-thinking development. In the present investigation, students examined problems, interpreted visual information, discussed alternative explanations, and justified scientific conclusions. Such activities may have provided opportunities for analytical reasoning beyond factual recall. Nevertheless, the extent to which each activity contributed to the observed outcomes remains undetermined because problem-solving, collaboration, teacher guidance, and AR visualization were implemented simultaneously.

An important interpretive issue concerns the relationship between technological representation and cognitive processing. The AR-Based Book enabled students to examine three-dimensional astronomical objects, while the PBL sequence required them to use these representations within meaningful investigative activities. This instructional configuration is compatible with constructivist learning principles, which emphasize active knowledge

construction through experience, interaction, and reflection. However, interactive visualization does not necessarily produce deeper understanding without appropriate guidance. Gonnermann-Müller and Krüger (2025) identified considerable variation in the cognitive demands associated with different AR design features, whereas Chen et al. (2026) emphasized the importance of integrating instructional circumstances, learning activities, and interaction within AR-supported scientific inquiry. Furthermore, Wang et al. (2026) demonstrated the importance of teacher support in primary AR-based science learning. Consequently, the present findings are theoretically compatible with guided knowledge construction, but cognitive-load reduction, enhanced spatial processing, and specific knowledge-construction mechanisms were not directly measured and cannot be established empirically.

The Indonesian educational literature provides complementary evidence while revealing important differences in intervention design. Sapira and Ansori (2024) developed an AR-Based Book integrated with PBL for elementary science learning and reported improvements in learning outcomes. Rachmayani and Setyasto (2025) similarly investigated AR-supported PBL in elementary instruction concerning changes in the states of matter. Nofitri et al. (2024) emphasized the contribution of interactive instructional materials and PBL to elementary students' critical thinking. More directly, Krisnawati et al. (2026) compared AR-assisted PBL with PBL without AR among 62 elementary students and reported higher critical-thinking performance in the AR-supported group. Unlike that investigation, the present study compared an integrated PBL–AR instructional package with conventional instruction. Therefore, the current findings support the relevance of combining inquiry and visualization but cannot determine whether the observed differences originated primarily from PBL, AR, or their interaction. The variation across instructional topics and comparison conditions also prevents direct equivalence between reported effect magnitudes.

Broader Indonesian investigations reinforce the importance of contextualized instructional design and active student participation. Suharti et al. (2024) examined an AR-integrated educational game employing PBL and reported improvements in critical-thinking outcomes. Research involving Muhammad Sufian provides additional pedagogical perspectives across different disciplinary contexts. Erlina et al. (2025) investigated PBL within Arabic-language education, illustrating the relevance of contextual problems and reflective instructional activities, while Koderi et al. (2023) developed culturally contextualized digital learning media. Although these investigations cannot serve as direct empirical confirmation of AR-assisted elementary science instruction, they support the broader importance of pedagogical alignment, contextual relevance, and purposeful multimedia development. The present study adds science-specific evidence from Indonesian elementary classrooms, where abstract astronomical concepts require representational support and opportunities for evidence-based explanation.

Research published in *Digital Learning, Social Science, and Life-course Studies* provides further contextual insight. Hariandini et al. (2026) found that classroom technology integration frequently remained oriented toward information presentation rather than higher-order inquiry, demonstrating the importance of pedagogical organization. Sidik et al. (2025), through a review of PBL and project-based learning in programming education, highlighted the relevance of problem-oriented learning for analytical competencies, although their disciplinary focus differs from elementary science. Damanik and Remtula (2026) further emphasized metacognitive readiness as a resource within digital learning, suggesting a potential direction for investigating learners' reflective competencies. These studies collectively support examining how digital resources are incorporated into learning activities rather than assuming that technological availability independently improves achievement. However, because the present research did not directly assess metacognition, digital competence, or long-term learning trajectories, their relationships with the observed cognitive outcomes remain propositions for future investigation.

The magnitude of the observed differences requires particular scrutiny. Although the ANCOVA and MANCOVA results indicate large statistical effects within the sample, the restricted

posttest variability and small group sizes may produce unusually large standardized estimates. International syntheses consistently identify variation in the educational effects of AR according to learning context, intervention design, learner characteristics, and instructional modality (Lin & Yu, 2023; Hidayat et al., 2026; Koç & Kanadlı, 2025). Jiang et al. (2025) additionally document implementation challenges related to technical competence, infrastructure, distraction, and learner accessibility in K–12 immersive education. Differences in teacher expertise, school resources, and instructional familiarity may therefore contribute to variation between studies. Furthermore, the present investigation involved only three instructional meetings, preventing conclusions concerning sustained conceptual understanding or the transfer of critical-thinking abilities. The comparatively large effects should consequently be interpreted as context-specific statistical differences rather than evidence that the intervention is categorically superior to other PBL–AR approaches.

From a theoretical, pedagogical, and policy perspective, the findings offer several interconnected implications. Theoretically, they are compatible with the proposition that scientific understanding and reasoning may be supported when interactive representations are embedded within guided, problem-oriented inquiry; nevertheless, the underlying mechanisms require direct examination. Pedagogically, teachers may integrate AR-Based Books into structured tasks involving observation, evidence comparison, discussion, explanation, and reflection, rather than employing AR merely to increase visual attractiveness. Appropriate teacher facilitation, accessible interfaces, and manageable cognitive demands should remain central considerations, as supported by research on instructional guidance, digital literacy, and technology adoption (Nikou, 2024; Nevrelova et al., 2024; Wang et al., 2026). At the policy level, school leaders may consider professional development, equitable access to digital resources, appropriate device supervision, and protection of students' data within technology-supported science instruction. Such priorities are consistent with broader discussions of educational quality and sustainability, including the comparative SDG policy analysis presented by Febriani et al. (2026). However, the present study did not assess emotional well-being, media literacy, online identity, social media behavior, or mental health; therefore, no direct empirical conclusions concerning these outcomes or related regulatory interventions are warranted.

The principal contribution of this study lies in examining an AR-Based Book functionally integrated throughout the instructional phases of PBL for elementary Solar System learning while simultaneously evaluating conceptual understanding and critical thinking. Its novelty is not the unprecedented combination of PBL and AR, which previous investigations have already explored, but the explicit positioning of AR-supported astronomical representations as resources for investigation, evidence interpretation, collaborative explanation, and reflection. The simultaneous assessment of two distinguishable cognitive outcomes, accompanied by baseline-adjusted ANCOVA and MANCOVA, provides a more differentiated account of performance differences than general achievement scores alone. This contribution extends existing research by connecting the instructional organization of PBL–AR learning with multiple cognitive outcomes in the Indonesian IPAS context. Nevertheless, the study offers evidence concerning an integrated instructional condition rather than establishing a separately identifiable or synergistic effect of its individual components.

Several limitations constrain the interpretation and generalizability of these findings. The sample comprised only 35 students from two elementary schools, with purposive selection and no random assignment. Because each instructional condition corresponded to a different school and teacher, school-level characteristics and teacher effects were completely confounded with treatment assignment. Although baseline-adjusted analyses accounted for measured pretest performance, they could not eliminate unmeasured contextual differences or establish causal attribution. Restricted posttest variability, essay-based scoring, potential assessment familiarity, and the short intervention period further require consideration. The study also did not measure cognitive load, spatial reasoning, motivational mechanisms, sustained retention, or transfer to other scientific topics. Future investigations should involve larger multisite samples, multiple

classes per condition, stronger randomization or matching procedures, and appropriate consideration of clustered educational data. Factorial or dismantling designs comparing conventional instruction, PBL alone, AR alone, and integrated PBL–AR would help distinguish component-specific contributions. Longer-term studies incorporating delayed assessments, process measures, and qualitative classroom evidence could further clarify the cognitive mechanisms, instructional conditions, and sustainability of observed learning differences.

CONCLUSION

Higher conceptual understanding and critical thinking were observed among students receiving the integrated Problem-Based Learning (PBL) and Augmented Reality (AR)-Based Book instruction in elementary IPAS learning on the Solar System. The experimental group obtained an N-Gain score of 0.74 for conceptual understanding, compared with 0.48 in the control group. A similar pattern was found for critical thinking, with an N-Gain score of 0.74 in the experimental group and 0.46 in the control group. The baseline-adjusted ANCOVA results also showed significant between-group differences in conceptual understanding and critical thinking, with partial η^2 values of .787 and .751, respectively. The MANCOVA further indicated a significant multivariate difference across both cognitive outcomes, with Pillai's Trace = .862, $F(2, 30) = 95.34$, $p < .001$, partial $\eta^2 = .862$. Collectively, the empirical findings indicate substantial between-group differences associated with the integrated PBL–AR instructional condition in the present Solar System learning context.

Several limitations should be considered when interpreting the findings. The study involved only 35 sixth-grade students from two elementary schools, with 17 students in the experimental group and 18 students in the control group. The experimental and control groups were also located in different schools and taught by different teachers, so school- and teacher-level influences cannot be completely separated from the instructional condition. In addition, the intervention combined PBL, AR, teacher guidance, and collaborative learning, preventing independent attribution of the observed differences to PBL or AR alone. The study also examined only the Solar System topic, so the findings do not provide evidence of transfer to other science topics. Future research should involve larger samples, more schools, stronger matching or randomization where feasible, and factorial designs that can examine the separate and combined contributions of PBL and AR.

REFERENCE

Afifurrahman, M., Erlina, E., Ghazi, F., Koderi, K., & Sufian, M. (2025). Efektivitas penerapan model induktif kata bergambar dan investigasi kelompok terhadap hasil belajar kitabah siswa sekolah dasar. *Pendas: Jurnal Ilmiah Pendidikan Dasar, 10*(1), 231–247. https://doi.org/10.23969/jp.v10i01.23507

Ahmad, M., & Wilkins, S. (2025). Purposive sampling in qualitative research: A framework for the entire journey. *Quality & Quantity, 59*(2), 1461–1479. https://doi.org/10.1007/s11135-024-02022-5

Aldeeb, F. H., Sallabi, O. M., Elaish, M. M., & Hwang, G.-J. (2024). Enhancing students' learning achievements, self-efficacy, and motivation using mobile augmented reality. *Journal of Computer Assisted Learning, 40*(4), 1823–1837. https://doi.org/10.1111/jcal.12989

Alim, J. A., Oktaviani, C., & Wijaya, T. T. (2024). Enhancing mathematical reasoning through the integration of realistic geometry with interactive multimedia learning application. *Jurnal Pendidikan Progresif, 14*(3), 1533–1547. https://doi.org/10.23960/jpp.v14.i3.2024105

Al Khansa, E., Pahrudin, A., Jatmiko, A., Sufian, M., & Azad, I. (2024). The integrated learning model in Islamic religious education in junior high school. *Southeast Asian Journal of Islamic Education, 7*(2), 69–85. https://doi.org/10.21093/sajie.v7i2.9356

Amiruddin, A., Surahman, E., & Rochman, C. (2024). The application of a multimedia-assisted problem-based learning model based on Android to enhance students' critical thinking skills. *Jurnal Penelitian Pendidikan IPA, 9*(2), 88–98. https://doi.org/10.26740/jppipa.v9n2.p88-98

Cai, S., Liu, Z., Liu, C., Zhou, H., & Li, J. (2022). Effects of a BCI-based AR inquiring tool on primary students' science learning: A quasi-experimental field study. *Journal of Science Education and Technology, 31*(6), 767–782. https://doi.org/10.1007/s10956-022-09991-y

Chen, G., Zhou, Y., Wang, H., Oubibi, M., & Li, Y. (2026). "CAI-AR" instructional model: An ACT-R theory-based investigation of how students conduct scientific inquiry through augmented reality technology. *Education and Information Technologies, 31*, 301–334. https://doi.org/10.1007/s10639-025-13815-y

Chiu, T. K. F., & Li, Y. (2023). How can emerging technologies impact STEM education? *Journal for STEM Education Research, 6*(3), 375–384. https://doi.org/10.1007/s41979-023-00113-w

Damanik, F. H. S., & Remtula, J. N. (2026). Metacognitive readiness in digital learning and its role in lifelong learning pathways. *Digital Learning, Social Science, and Life-course Studies, 2*(1), 57–71. https://doi.org/10.70211/disolife.v1i2.349

Dirman, H. M., & Mufit, F. (2022). Design and validity of five-tier-multiple choice test e-instruments using iSpring Quiz Maker as an assessment of student science literacy in 21st century learning. *Jurnal Penelitian Pendidikan IPA, 8*(6), 3170–3179. https://doi.org/10.29303/jppipa.v8i6.2300

Erlina, E., Hijriyah, U., Ghazi, F., Syahril, S., & Sufian, M. (2025). Arabic problem-based learning for religious moderation: Classroom action research in Islamic education. *JPI: Jurnal Pustaka Indonesia, 5*(3), 13–24. https://doi.org/10.62159/jpi.v5i3.1806

Febriani, E., Woods, R., Madkur, A., & Hasanah, U. (2026). Implementation of the Sustainable Development Goals (SDGs) in the education and environmental sectors: A comparative study of Indonesia and Australia. *Gender, Islamic Law, and Sustainability, 1*(2), 102–116. https://doi.org/10.70211/gils.v1i2.547

Fraenkel, J. R., Wallen, N. E., & Hyun, H. H. (2023). *How to design and evaluate research in education* (11th ed.). McGraw Hill.

García-Carmona, A. (2025). Scientific thinking and critical thinking in science education: Two distinct but symbiotically related intellectual processes. *Science & Education, 34*, 227–245. https://doi.org/10.1007/s11191-023-00460-5

Geng, G., Green, K., Telford, A., & Zhu, Y. (2026). Engaging young minds: How smart augmented reality glasses transform learning experiences in AR smart glasses immersive virtual learning environments (AR smart glasses IVLE). *Journal of Science Education and Technology, 35*, 1058–1077. https://doi.org/10.1007/s10956-026-10299-4

Gonnermann-Müller, J., & Krüger, J. M. (2025). Unlocking augmented reality learning design based on evidence from empirical cognitive load studies—A systematic literature review. *Journal of Computer Assisted Learning, 41*(1), Article e13095. https://doi.org/10.1111/jcal.13095

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2023). *Multivariate data analysis* (9th ed.). Cengage.

Handoko, A., Philip, D., & HuongVu. (2026). Tracing digital learning trajectories in biology education across the life course: A qualitative study of learners' transitions and meaning making. *Digital Learning, Social Science, and Life-course Studies, 1*(2), 84–93. https://doi.org/10.70211/disolife.v1i2.336

Hariandini, Y., Yuda, I. B., & Ahmed, W. (2026). Implementing digital integrated learning in schools: Evidence from classroom practices. *Digital Learning, Social Science, and Life-course Studies, 2*(1), 46–56. https://doi.org/10.70211/disolife.v2i1.348

Hidayat, R., Samsudin, S., Wang, X., & Abd Rahman, S. N. (2026). Augmented reality in science, technology, engineering and mathematics education: A meta-analysis. *Journal of Computer Assisted Learning, 42*(1), Article e70164. https://doi.org/10.1002/jcal.70164

Jiang, H., Zhu, D., Chugh, R., Turnbull, D., & Jin, W. (2025). Virtual reality and augmented reality-supported K-12 STEM learning: Trends, advantages and challenges. *Education and Information Technologies, 30*, 12827–12863. https://doi.org/10.1007/s10639-024-13210-z

Judijanto, L., Fauzi, M. S., Hendrilia, Y., Kadir, D., Murnaka, N. P., & Fachruzzaki. (2024). The differences of students' learning outcomes using the discovery learning model and problem-based learning in science learning at primary schools. *Jurnal Penelitian Pendidikan IPA, 10*(10), 7354–7360. https://doi.org/10.29303/jppipa.v10i10.9046

Koç, A., & Kanadlı, S. (2025). Effect of interactive learning environments on learning outcomes in science education: A network meta-analysis. *Journal of Science Education and Technology, 34*, 681–703. https://doi.org/10.1007/s10956-025-10202-7

Koçoğlu, A., & Kanadlı, S. (2025). The effect of problem-based learning approach on learning outcomes: A second-order meta-analysis study. *Educational Research Review, 48*, Article 100690. https://doi.org/10.1016/j.edurev.2025.100690

Koderi, K., Sufian, M., & Erlina, E. (2023). Developing Lampung local wisdom film of Arabic communication skills for Madrasah Tsanawiyah students. *International Journal of Information and Education*

Technology, 13(12), 2004–2013. https://doi.org/10.18178/ijiet.2023.13.12.2015

Krisnawati, Y., Arhesa, S., Sibarani, H. A. R., Akbar, A., & Salido, A. (2026). Integrating augmented reality into problem-based learning: Effects on elementary school students' critical thinking in science. *Prisma Sains: Jurnal Pengkajian Ilmu dan Pembelajaran Matematika dan IPA IKIP Mataram, 14*(3), 1966–1982. https://doi.org/10.33394/j-ps.v14i3.20928

Limpinan, P., Pichetphon, W., Yuensook, T., & Jantakoon, T. (2026). An experimental comparative study of virtual reality and augmented reality for teaching solar system in primary education. *Journal of Technology and Science Education, 16*(1), 262–274. https://doi.org/10.3926/jotse.3684

Lin, Y., & Yu, Z. (2023). A meta-analysis of the effects of augmented reality technologies in interactive learning environments (2012–2022). *Computer Applications in Engineering Education, 31*(4), 1111–1131. https://doi.org/10.1002/cae.22628

Lu, Z., Chiu, M. M., Wang, S., Mao, W., & Lei, H. (2025). Effects of augmented reality on students' higher-order thinking: A meta-analysis. *Journal of Educational Computing Research, 63*(3), 728–747. https://doi.org/10.1177/07356331241309644

Mahfud, N. B. A., Indana, S., & Isnawati. (2026). Development of a problem-based learning science e-module integrating Ledre local wisdom to foster junior high school students' critical thinking skills. *JPI: Jurnal Pustaka Indonesia, 6*(2), 452–472. https://doi.org/10.62159/jpi.v6i2.2586

Mulyana, V., & Desnita. (2023). Development of a scientific literacy assessment instrument based on Tornado Physics Enrichment Book. *Jurnal Penelitian Pendidikan IPA, 9*(5), 3961–3967. https://doi.org/10.29303/jppipa.v9i5.3290

Muspiroh, N., Kurniawan, A., & Tabroni, I. (2025). Leveraging augmented reality (AR) and interactive media to enhance elementary students' mastery of scientific concepts: A cross-regional study in West Java, Indonesia. *EduBase: Journal of Basic Education, 6*(2), 215–225. https://doi.org/10.47453/edubase.v6i2.3530

Nevrelova, N., Korenova, L., Lavicza, Z., Bruzkova, N., & Schmid, A. (2024). Enhancing digital literacy in primary education through augmented reality. *Frontiers in Education, 9*, Article 1390491. https://doi.org/10.3389/feduc.2024.1390491

Nikou, S. A. (2024). Factors influencing student teachers' intention to use mobile augmented reality in primary science teaching. *Education and Information Technologies, 29*, 15353–15374. https://doi.org/10.1007/s10639-024-12481-w

Nofitri, F., Desyandri, Eriyanti, F., & Yerizon. (2024). Improving critical thinking skills of elementary students through science learning with interactive teaching materials and problem-based learning. *Jurnal Penelitian Pendidikan IPA, 10*(10), 7624–7633. https://doi.org/10.29303/jppipa.v10i10.7503

OECD. (2023). *PISA 2022 results (Volume I): The state of learning and equity in education*. OECD Publishing. https://doi.org/10.1787/53f23881-en

Önal, N. T., & Önal, N. (2021). The effect of augmented reality on the astronomy achievement and interest level of gifted students. *Education and Information Technologies, 26*(4), 4573–4599. https://doi.org/10.1007/s10639-021-10474-7

Pribowo, M. A., Hadiati, E., Koderi, K., & Sufian, M. (2024). Pengembangan e-modul Pendidikan Agama Islam interaktif berbasis flipbook untuk meningkatkan pembelajaran di sekolah menengah pertama. *Jurnal PAI Raden Fatah, 6*(4), 961–974. https://doi.org/10.19109/pairf.v6i4.24668

Rachmayani, I., & Setyasto, N. (2025). Effectiveness of learning outcomes through problem-based learning model utilizing augmented reality (AR) technology in Grade IV material on the form of matter and its changes in the Ki Hadjar Dewantara Group. *Jurnal Penelitian Pendidikan IPA, 11*(3), 408–419. https://doi.org/10.29303/jppipa.v11i3.10332

Sailer, M., Murböck, J., & Fischer, F. (2021). Digital learning in schools: What does it take beyond digital technology? *Teaching and Teacher Education, 103*, Article 103346. https://doi.org/10.1016/j.tate.2021.103346

Samsudin, A., Raharjo, T. J., & Widiasih. (2023). The effectiveness of contextual teaching learning (CTL) and problem-based learning (PBL) models in class VI science subjects on creativity and learning outcomes. *Jurnal Penelitian Pendidikan IPA, 9*(11), 9324–9331. https://doi.org/10.29303/jppipa.v9i11.5290

Sapira, & Ansori, I. (2024). Development of science learning media based on augmented reality book with problem-based learning model to improve learning outcomes of third grade students. *Jurnal Penelitian Pendidikan IPA, 10*(6), 3249–3260. https://doi.org/10.29303/jppipa.v10i6.7642

Sidik, R. M., Gunawan, I., Haqiqi, I. N., & Harnika, G. N. (2025). Learning strategies of problem-based

learning and project-based learning on students' programming skills: A bibliometric analysis and systematic literature review. *Digital Learning, Social Science, and Life-course Studies, 1*(2), 148–165. https://doi.org/10.70211/disolife.v1i2.155

Simonovic, B., Correa Vione, K., Stupple, E., & Doherty, A. (2023). It is not what you think it is how you think: A critical thinking intervention enhances argumentation, analytic thinking and metacognitive sensitivity. *Thinking Skills and Creativity, 49*, Article 101362. https://doi.org/10.1016/j.tsc.2023.101362

Sriwahyuni, D. R., Buchori, A., & Sulianto, J. (2025). Augmented reality book media based on a constructivist approach on improving students' cognitive abilities in the five senses material. *Jurnal Ilmiah Pendidikan Profesi Guru, 8*(3), 527–538. https://doi.org/10.23887/jippg.v8i3.104971

Suharti, P., Asyari, A., & Wikanta, W. (2024). Augmented reality integrated education game using problem-based learning model to improve critical thinking skills. *Research and Development in Education (RaDEn), 4*(1), 320–336. https://doi.org/10.22219/raden.v4i1.32026

Wang, Z., He, S., & Wen, Y. (2026). Teacher support in augmented reality-enhanced science inquiry learning in primary classrooms. *Journal of Research in Science Teaching, 63*(6), 500–513. https://doi.org/10.1002/tea.70053

Wen, Y., Lai, C., He, S., Cai, Y., Looi, C.-K., & Wu, L. (2024). Investigating primary school students' epistemic beliefs in augmented reality-based inquiry learning. *Interactive Learning Environments, 32*(9), 5355–5372. https://doi.org/10.1080/10494820.2023.2214182

Xu, E., Wang, W., & Wang, Q. (2023). The effectiveness of collaborative problem solving in promoting students' critical thinking: A meta-analysis based on empirical literature. *Humanities and Social Sciences Communications, 10*(1), Article 16. https://doi.org/10.1057/s41599-023-01508-1

Yudiana, K., Parmiti, D. P., & Putra, D. B. K. N. (2023). The effect of problem-based learning assisted by interactive media on elementary students' critical thinking skills. *Jurnal Ilmiah Pendidikan Profesi Guru, 6*(3), 566–576. https://doi.org/10.23887/jippg.v6i3.68576