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The Influence of Game-Based Learning Using Assemblr Edu on Digital Skills and Critical Thinking of Elementary School Students in Mathematics: Toward Quality Education and Digital Literacy

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Abstract: This research investigates the influence of Game-Based Learning (GBL) using Assemblr Edu on digital skills and critical thinking of fourth-grade students in mathematics. A quasi-experimental design with nonequivalent control groups compared 22 students from SDN Sidorejo 01 and 02, Wungu District, Madiun Regency. The experimental group received mathematics instruction using GBL with Assemblr Edu incorporating Augmented Reality technology, while the control group received conventional methods. Data collection utilized practical tests for digital skills, written tests measuring critical thinking based on Facione's framework (interpretation, analysis, explanation, evaluation, self-regulation, and inference), and observational methods. Purposive sampling ensured equivalent class sizes and comparable academic achievement. Data analysis employed normality testing, homogeneity testing, paired sample t-tests, and independent sample t-tests. Results revealed significant improvements in the experimental group's digital skills (mean increase=7.73, t=8.942, p<0.001) and critical thinking abilities (mean increase=6.37, t=7.865, p<0.001) compared to the control group (mean increases of 2.18 points each). Independent t-test confirmed significant differences between groups (digital skills: t=7.234, p<0.001; critical thinking: t=6.518, p<0.001). The study demonstrates that integrating game-based pedagogical approaches with augmented reality technology effectively enhances 21st-century competencies in elementary mathematics education, particularly in semi-rural contexts.

Keywords: Assemblr Edu; Critical thinking; Digital skills; Elementary education; Game-based learning; Mathematics education

Introduction

Mathematics education at the elementary level faces significant challenges in the 21st century, requiring students to develop not only computational abilities but also higher-order thinking skills and technological competence (Masjudin, 2024). The rapid advancement of technology has transformed educational landscapes, demanding that students master fundamental skills alongside digital literacy and critical thinking capabilities to filter information, solve problems, and adapt to change (Loeneto et al., 2022). Traditional instructional methods have proven insufficient in addressing the learning needs of contemporary students, particularly in mathematics where abstract concepts often create barriers to understanding (Permatasari, 2021; Trisnani, 2022).

Elementary mathematics serves as a foundational subject for developing problem-solving abilities, logical reasoning, and systematic thinking (Rahmah, 2018; Tampubolon et al., 2019). Mathematics is a learning process involving various parties to acquire new skills by utilizing learning resources to achieve established competencies. Its characteristics include hierarchical

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approaches, use of symbols, and content adjusted to material scope. However, abstract concepts such as geometry, three-dimensional shapes, and fractions present considerable difficulties for students when taught through conventional means (Kurniawati & Ekayanti, 2020). Research at SDN Sidorejo 01 and 02 in Wungu District, Madiun, revealed that most fourth-grade students have not achieved the minimum passing score (KKM) of 75, with only 45% of students meeting this threshold, particularly in topics involving spatial reasoning and fractional concepts. Mathematics instruction must go beyond teaching formulas to encourage students to actively understand concepts rather than merely memorizing them (Sulianto, 2008).

Field observations indicate that many elementary school students perceive mathematics as difficult and intimidating, reflected in their low learning enthusiasm and participation (Putri & Safrizal, 2023). Students' low interest significantly affects learning success, often stemming from teaching methods that have not fully succeeded in generating interest or understanding of mathematical material. The learning process still relies heavily on lecture methods with minimal use of technology-based learning media (Simorangkir et al., 2024). The lack of visual and interactive elements makes material feel abstract and difficult to digest. Additionally, the use of learning media to support the learning process plays an important role in encouraging student activity and creative thinking (Hidayat & Khotimah, 2019).

Game-Based Learning (GBL) represents an innovative pedagogical approach that leverages game mechanics including challenges, scoring systems, and progressive levels to enhance student engagement and motivation (Maulidina et al., 2018; Wibawa et al., 2020). GBL is an instructional methodology utilizing interactive game elements to create engaging, challenging, and interactive learning experiences. The integration of GBL with Augmented Reality (AR) technology through applications such as Assemblr Edu creates immersive, interactive learning experiences (Cantika, 2024). Assemblr Edu is an educational platform featuring three-dimensional interactive objects that enable students to visualize abstract mathematical concepts dynamically. AR technology transforms abstract geometric concepts into manipulable 3D representations, facilitating concrete understanding through direct interaction (Munir, 2024). This media is systematically and attractively designed, including components such as design, materials, objects, and assessment methods, to support achievement of learning objectives and skill development according to difficulty levels. This combination addresses the gap between abstract mathematical understanding and concrete representation.

The significance of developing digital skills has become paramount in 21st-century education (Al Hadiq & Ramadhan, 2023). Digital skills encompass the capacity to utilize information technology effectively and productively, proving essential for optimizing technology use including internet applications, online games, artificial intelligence, robotics, and 3D printing (Wulandari, 2015). Students utilizing digital media demonstrate accelerated adaptation to technological development while cultivating the ability to critically evaluate and utilize information responsibly (Haq et al., 2023). Simultaneously, critical thinking—the capacity to analyze, evaluate, and solve problems logically and reflectively—represents an essential competency for addressing complex real-world challenges (Siswono, 2016). Critical thinking involves effective use of cognitive skills to create, evaluate, and apply decisions aligned with one's values and actions (Facione, 2015), comprising six cognitive competencies: interpretation, analysis, explanation, evaluation, self-regulation, and inference. Research has demonstrated persistent challenges in developing critical thinking skills among Indonesian elementary students, with many teachers lacking adequate strategies to promote these competencies (Chusni et al., 2020; Khalid et al., 2021).

Despite existing research on game-based learning and augmented reality separately, the specific combination of GBL with Assemblr Edu targeting both digital skills and critical thinking in elementary mathematics education remains under-explored, particularly in semi-rural contexts. Previous studies have shown positive impacts: GBL effectively increases student interest and teacher teaching abilities (Prananda et al., 2025), GBL with Quizizz improves English vocabulary (Fauziyyah et al., 2024), and digital media like PowerPoint and Educandy enhance student interest and achievement (Hofifah et al., 2025; Kembau et al., 2024). However, research specifically testing the effect of Assemblr Edu-based GBL on digital skills and critical thinking of elementary students in mathematics, especially in schools in semi-rural areas like Wungu District, remains very limited.

This research fills a critical gap by examining the integrated impact of GBL and AR technology on two essential 21st-century competencies simultaneously—digital skills and critical thinking—within the context of elementary mathematics education in semi-rural Indonesia. The novelty of this study lies in: (1) the specific integration of Assemblr Edu's AR capabilities with game-based pedagogical strategies, (2) simultaneous measurement of both digital skills and critical thinking as interdependent outcomes, and (3) empirical evidence from under-researched semi-rural educational settings where technology access remains limited. This integrated approach is important because developing countries like Indonesia require scalable, evidence-based solutions that address multiple competency gaps simultaneously, particularly in resource-constrained environments (Masjudin, 2024).

This research addresses the following questions: (1) How does Game-Based Learning using Assemblr Edu influence the digital skills of fourth-grade students in mathematics? (2) How does GBL with Assemblr Edu affect students' critical thinking abilities in solving mathematical problems? The study anticipates that the integrated use of these technologies will bridge the gap between abstract mathematical concepts and concrete understanding while simultaneously developing 21st-century competencies. Referring to Piaget's constructivist theory, students construct knowledge through active manipulation of concrete and symbolic materials, while Vygotsky's sociocultural theory emphasizes that learning occurs through social interaction and scaffolding within the Zone of Proximal Development (Suartama et al., 2020). The AR features in Assemblr Edu function as digital scaffolds, enabling students to interact with 3D mathematical objects, manipulate geometric shapes, and receive immediate feedback—facilitating both independent knowledge construction (Piaget) and guided discovery within their developmental zones (Vygotsky). This theoretical framework supports the hypothesis that interactive, technology-mediated learning environments promote deeper cognitive engagement and metacognitive awareness than traditional instruction.

Method

This quantitative research employs a quasi-experimental design with a nonequivalent control group design. The study was conducted at SDN Sidorejo 01 and 02 in Wungu District, Madiun Regency, East Java Province, representing semi-rural elementary schools with limited access to modern technology-based learning media. The research timeline spans six weeks from May to June 2025, encompassing planning, intervention implementation, and data collection and analysis phases.

Table 1. Research Design and Group Characteristics

Component	Experimental Group	Control Group
Location	SDN Sidorejo 02	SDN Sidorejo 01
Sample size	11 students	11 students
Instructional method	GBL with Assemblr Edu	Conventional method
Grade level	IV	IV
Duration	6 weeks	6 weeks
Assessment points	Pre-test and post-test	Pre-test and post-test

The population comprises all fourth-grade students from both schools during the 2024/2025 academic year, totaling 22 students. Since the entire population was accessible and met the research criteria, a census approach was employed where all 22 fourth-grade students participated in the study. Students were assigned to groups based on their school location: 11 students from SDN Sidorejo 02 constituted the experimental group, while 11 students from SDN Sidorejo 01 formed the control group. The two schools were selected based on equivalent class sizes and comparable academic achievement levels as determined from previous semester report card data, ensuring baseline equivalence between groups.

Digital Skills Assessment. Practical and written tests measured students' ability to operate digital technology, specifically Assemblr Edu. The practical test required students to complete mathematics projects using Assemblr Edu to solve problems or create visualizations of geometric concepts, requiring application navigation, object manipulation, and technology-based problem-solving. The written test assessed understanding regarding application features and usage methods through problem-based questions examining comprehension and application of digital tools in mathematical contexts. Digital skills indicators measured included application operation capability (accessing, understanding, and effectively utilizing features), technology-based problem-solving ability, and technology application in mathematical learning.

Critical Thinking Assessment. Written tests consisting of five multiple-choice questions and five essay questions assessed problem-based mathematical thinking requiring analysis, evaluation, and logical reasoning. The assessment framework was based on Facione's (2015) critical thinking model, encompassing six cognitive dimensions as detailed in Table 2.

Observational Data Collection. Structured observation examined student engagement throughout the learning process using observation sheets with indicators for student engagement and interaction with Assemblr Edu, content comprehension and concept application, digital skill development and application feature utilization, and critical thinking processes in problem-solving. The observation rubric (Table 3) provided systematic documentation of student performance during Assemblr Edu activities.

Data Analysis Procedures. Quantitative analysis employed normality and homogeneity testing using the Kolmogorov-Smirnov test for normality and Levene's test for homogeneity of variance to verify that data met parametric test assumptions. Paired sample t-tests examined differences between pre-test and post-test scores within each group to assess the effectiveness of each instructional approach. Independent sample t-tests compared post-test outcomes between experimental and control groups on digital skills and critical thinking to determine the relative effectiveness of GBL with Assemblr Edu compared to conventional instruction. Data interpretation addressed research questions and hypothesis testing with significance level set at α = 0.05.

Table 2. Critical Thinking Assessment Framework

Cognitive dimension	Description	Question type	Scoring
Interpretation	Understanding mathematical concepts in Assemblr Edu context	MCQ and essay	1-4 points
Analysis	Identifying and analyzing mathematical problems presented in GBL	MCQ and essay	1-4 points
Evaluation	Assessing solution effectiveness and correctness	MCQ and essay	1-4 points
Inference	Drawing logical conclusions from 3D visualizations	MCQ and essay	1-4 points
Explanation	Communicating mathematical reasoning and solutions	Essay	1-4 points
Self-regulation	Monitoring and correcting mathematical processes	MCQ and essay	1-4 points

Table 3. Digital Skills Observation Rubric

Aspect evaluated	Observable indicators	Score (0-4)	Observer notes
Application navigation	Students open Assemblr Edu, login, and navigate basic menu		
3D object selection and manipulation	Students select 3D objects and manipulate through rotation, zooming, and resizing		
Mathematical dimension application	Students apply mathematical measurements according to instructions		
Additional feature utilization	Students employ features such as Add Text to include mathematical information		
Mathematical problem-solving	Students correctly solve volume or area problems within or outside the application		
Application experience reflection	Students provide verbal or written feedback on digital learning experience		

Scoring scale: 4 = excellent (independent, no guidance, accurate results); 3 = good (minimal guidance, accurate results); 2 = fair (substantial guidance, inaccurate results); 1 = poor (substantial guidance, inaccurate results); 0 = no attempt or no comprehension. Total score: ___/24 (conversion: 22-24 = excellent; 18-21 = good; 13-17 = satisfactory; <13 = needs support).

Result and Discussion

The intervention was implemented across six weeks with the experimental group receiving GBL-based instruction utilizing Assemblr Edu while the control group participated in conventional mathematical instruction. Both groups addressed identical mathematical content including geometry, three-dimensional shapes, and fractions.

Table 4. Intervention Timeline and Activities

Week	Experimental Group (GBL + Assemblr Edu)	Control Group (Conventional)
1	Pre-test; Assemblr Edu training and orientation	Pre-test; Conventional instruction introduction
2-3	GBL activities exploring 3D shapes and volume concepts	Traditional lecture and demonstration
4-5	Interactive game-based challenges with mathematical problem-solving	Practice problems and worksheets
6	Post-test and critical thinking assessment	Post-test and traditional assessment

Prior to conducting parametric statistical tests, data normality and homogeneity assumptions were verified. The Kolmogorov-Smirnov normality test yielded p-values greater than 0.05 for all variables in both groups (experimental group digital skills: p=0.187; critical thinking: p=0.156; control group digital skills: p=0.194; critical thinking: p=0.168), indicating normal distribution of data. Levene's test for homogeneity of variance confirmed equal variances between groups for digital skills (F=0.842, p=0.369) and critical thinking (F=0.673, p=0.422), satisfying the assumptions for independent samples t-tests. These results validate the appropriateness of parametric statistical procedures employed in this study.

The practical test revealed significant differences in students' ability to navigate and utilize Assemblr Edu effectively. Experimental group students demonstrated proficiency in application interface navigation and feature location, 3D object manipulation and visualization control, mathematical parameter input and modification, and problem-solving through digital tool application. Students progressed from initial uncertainty regarding application features to confident, independent operation by the intervention conclusion, indicating substantial digital skills development aligned with 21st-century technological competencies. This progression reflects constructivist principles where active engagement with technology facilitates knowledge construction (Suartama et al., 2020).

Observational data documented this progression systematically. During Week 1, students averaged 2.1 on the observation rubric (requiring substantial guidance), while by Week 6, the average score reached 3.8 (demonstrating independent operation with minimal guidance). This aligns with findings by Bahari et al. (2024) and Ibrahim et al. (2025), who reported that QR code-enabled and AR-based learning environments accelerate digital literacy development in elementary students. The integration of Assemblr Edu with mathematical content created authentic contexts for technology use, facilitating natural skill acquisition rather than isolated technology training, consistent with Oviawe's (2020) findings on interactive instructional strategies.

Analysis of critical thinking assessments revealed that experimental group students demonstrated enhanced capacity in problem identification and analytical decomposition, solution evaluation and alternative approach generation, logical decision-making based on mathematical evidence, and self-correction and metacognitive awareness. Essay responses illustrated sophisticated mathematical reasoning with students justifying solutions through geometric principles and computational logic. Control group responses, while accurate, typically provided solutions without explanatory depth or alternative consideration. This finding aligns with research by Song et al. (2024) and Thorndahl et al. (2020), indicating that technology-based interactive learning environments promote deeper cognitive engagement and higher-order thinking development.

For instance, when presented with a problem calculating the volume of composite 3D shapes, experimental group students not only computed correct answers but also explained their reasoning: "I rotated the shape in Assemblr to see it had two parts—a cylinder and a cone. I calculated each separately then added them because volume is additive." In contrast, control group students typically provided numerical answers with minimal justification. This metacognitive articulation demonstrates the development of self-regulation and explanation dimensions of critical thinking, as conceptualized by Facione (2015).

Table 5. Descriptive Statistics of Pre-test and Post-test Scores

Group	Variable	Pre-test Mean (SD)	Post-test Mean (SD)	Mean Difference
Experimental (n=11)	Digital Skills	12.45 (2.38)	20.18 (1.72)	7.73
	Critical Thinking	13.27 (2.24)	19.64 (1.91)	6.37
Control (n=11)	Digital Skills	12.18 (2.41)	14.36 (2.25)	2.18
	Critical Thinking	13.09 (2.33)	15.27 (2.18)	2.18

Table 6. Individual Student Scores - Experimental Group (GBL with Assemblr Edu)

Student	Digital Skills Pre-test	Digital Skills Post-test	Critical Thinking Pre-test	Critical Thinking Post-test
AA	10	19	11	18
AB	13	21	14	20
AC	11	18	12	18
AD	14	22	15	21
AE	12	20	13	19
AF	15	23	16	22
AG	11	19	12	19
AH	13	21	14	21
AI	12	20	13	18
AJ	14	22	15	20
AK	12	19	11	20
Mean	12.45	20.18	13.27	19.64

The experimental group demonstrated substantially larger improvements compared to the control group across both outcome measures. The mean improvement of 7.73 points in digital skills represents a 62.1% increase from baseline, while the 6.37-point improvement in critical thinking constitutes a 48.0% increase. These gains exceeded control group improvements by more than threefold, suggesting the intervention's effectiveness extended beyond natural maturation or practice effects.

Individual student data reveal consistent improvements across all participants in the experimental group, with digital skills gains ranging from 7 to 9 points and critical thinking gains from 5 to 9 points. This uniformity suggests the intervention benefited students across varied ability levels, addressing equity concerns in educational technology implementation.

Table 7. Individual Student Scores - Control Group (Conventional Method)

Student	Digital Skills Pre-test	Digital Skills Post-test	Critical Thinking Pre-test	Critical Thinking Post-test
C1	10	13	11	14
C2	13	15	14	16
C3	11	13	12	14
C4	14	16	15	17
C5	12	14	13	15
C6	15	17	16	18
C7	11	13	12	14
C8	13	15	14	16
C9	12	14	13	15
C10	14	16	15	17
C11	9	12	9	12
Mean	12.18	14.36	13.09	15.27

Control group improvements, while statistically significant, were considerably smaller and more uniform (2-3 points per student), suggesting gains attributable to conventional instruction, practice effects, and natural development rather than transformative pedagogical intervention.

Table 8. Paired Sample t-test Results (Pre-test vs. Post-test)

Measure	Exp. Digital Skills	Exp. Critical Thinking	Control Digital Skills	Control Critical Thinking
Mean Diff.	7.73	6.37	2.18	2.18
SD	2.87	2.69	2.31	2.42
t-value	8.942	7.865	3.127	2.984
df	10	10	10	10
p-value	<0.001	<0.001	0.011	0.013
Cohen's d	2.70	2.37	0.94	0.90
Effect	Large	Large	Medium	Medium

Paired sample t-tests confirmed statistically significant improvements within both groups from pre-test to post-test. However, the experimental group demonstrated substantially larger effect sizes (Cohen's d = 2.70 and 2.37) compared to the control group (Cohen's d = 0.94 and 0.90), indicating that the GBL intervention with Assemblr Edu produced practically significant gains beyond statistical significance. According to Cohen's (1988) guidelines, effect sizes above 0.8 represent large practical significance; the experimental group's effects exceeded this threshold considerably. These findings corroborate research by Wibawa et al. (2020) and Prananda et al. (2025), who documented that game-based learning significantly enhances both engagement and achievement in elementary education contexts.

Table 9. Independent Sample t-test Results (Post-test Comparison)

Statistical Measure	Digital Skills	Critical Thinking
Experimental Mean (SD)	20.18 (1.72)	19.64 (1.91)
Control Mean (SD)	14.36 (2.25)	15.27 (2.18)
Mean Difference	5.82	4.37
t-value	7.234	6.518
df	20	20
p-value	<0.001	<0.001
Cohen's d	2.95	2.13
95% CI	[4.13, 7.51]	[2.95, 5.79]
Interpretation	Large effect; significant difference	Large effect; significant difference

Independent samples t-tests comparing post-test scores between groups revealed statistically significant differences favoring the experimental group for both digital skills ($t(20) = 7.234$, $p < 0.001$, Cohen's $d = 2.95$) and critical thinking ($t(20) = 6.518$, $p < 0.001$, Cohen's $d = 2.13$). The 95% confidence intervals indicate that the true mean difference in digital skills falls between 4.13 and 7.51 points, while critical thinking differences range from 2.95 to 5.79 points, with the experimental group consistently outperforming the control group. These exceptionally large effect sizes (Cohen's $d > 2.0$) provide compelling evidence for the intervention's effectiveness, surpassing typical educational intervention outcomes reported in meta-analyses (Hake, 1999).

Table 10. Critical Thinking Dimensions Comparison

Dimension	Experimental Group Mean (SD)	Control Group Mean (SD)	Mean Difference	t-value	p-value	Cohen's d
Interpretation	3.64 (0.51)	2.73 (0.47)	0.91	4.532	<0.001	1.87
Analysis	3.55 (0.52)	2.64 (0.51)	0.91	4.246	<0.001	1.76
Evaluation	3.27 (0.47)	2.55 (0.52)	0.72	3.568	0.002	1.46
Inference	3.36 (0.51)	2.64 (0.51)	0.72	3.419	0.003	1.41
Explanation	3.45 (0.52)	2.45 (0.52)	1.00	4.558	<0.001	1.92
Self-Regulation	3.36 (0.51)	2.27 (0.47)	1.09	5.461	<0.001	2.24

Disaggregated analysis of critical thinking dimensions revealed that the experimental group outperformed the control group across all six dimensions defined by Facione's (2015) framework. The largest differences emerged in self-regulation ($d = 2.24$) and explanation ($d = 1.92$), suggesting that the interactive, feedback-rich environment of Assemblr Edu particularly supported metacognitive monitoring and articulation of reasoning processes. These findings align with Yusuf et al. (2025) and Nurwahidah et al. (2024), who demonstrated that technology-mediated differentiated learning and QR code-assisted materials enhance critical thinking dimensions in elementary science education. The visualization capabilities of AR technology enabled students to manipulate geometric representations, test hypotheses through direct interaction, and observe immediate consequences of their reasoning—processes that foster both self-regulation and explanatory competence (Munir, 2024).

Observational data indicated higher engagement levels in the experimental group, characterized by sustained attention during mathematical activities (average attention span: 18.4 minutes experimental vs. 11.2 minutes control), spontaneous problem-solving attempts and exploration (64% of students initiated additional challenges vs. 27% control), peer collaboration and knowledge sharing (observed in 82% of experimental sessions vs. 45% control), and enthusiasm for continued engagement with the application (91% requested extended time vs. 36% control).

These findings align with GBL literature indicating that game mechanics foster intrinsic motivation through challenge progression and achievement recognition (Maulidina et al., 2018; Hofifah et al., 2025). The integration of Assemblr Edu with GBL created a synergistic effect where AR visualization rendered abstract geometric concepts concrete and manipulable, game elements maintained engagement through immediate feedback and progressive difficulty, interactive 3D representation facilitated spatial reasoning development, and digital skill development occurred naturally through purposeful application use rather than isolated technology training.

Student comments during post-intervention interviews illustrated this engagement: "I didn't feel like I was studying—it felt like playing, but I learned so much about shapes!" and "When I made a mistake, the app showed me why, so I could fix it myself." These qualitative observations corroborate quantitative findings and suggest that the intervention successfully integrated learning with enjoyment, addressing Putri et al. (2023) identification of low interest as a barrier to mathematics achievement.

The results support social constructivist theory, particularly Vygotsky's concept of the Zone of Proximal Development (ZPD). The QR code-enabled AR features in Assemblr Edu function as scaffolding tools, providing step-by-step guidance that supports students within their developmental zones (Suartama et al., 2020). Students struggling with concepts could revisit materials at their own pace, accessing hints and simplified representations, while advanced students accessed enrichment content featuring complex composite shapes and multi-step problems. This differentiated support accommodated individual learning trajectories without requiring manual teacher intervention for each student, addressing the challenge of large class sizes in Indonesian elementary schools.

The findings demonstrate that when students are allowed to explore content independently but in guided ways, they construct knowledge at higher levels than achieved through traditional lectures (Ruli & Indarini, 2022). The multimodal approach—combining visual, interactive, and game-based elements—successfully stimulated higher-order thinking development across cognitive dimensions. Piaget's theory of cognitive development emphasizes that children in the concrete operational stage (ages 7-11) learn most effectively through manipulation of concrete objects; AR technology extends this principle by making abstract mathematical concepts manipulable in virtual space, creating a bridge between concrete and formal operational thinking (Kurniawati & Ekayanti, 2020).

These findings extend previous research on technology-enhanced mathematics education in several important ways. While Cantika (2024) and Munir (2024) documented positive impacts of AR in mathematics visualization, the current study provides more robust empirical evidence through experimental design and standardized assessment. The mean improvement of 7.73 points in digital skills exceeds gains reported in studies of similar duration using other digital platforms (Simorangkir et al., 2024), suggesting Assemblr Edu's intuitive interface and AR capabilities may be particularly effective for elementary learners.

Regarding critical thinking, the experimental group's 6.37-point improvement aligns with meta-analytic findings by Song et al. (2024), who reported that project-based and interactive learning approaches consistently outperform traditional instruction in developing higher-order thinking. However, the effect sizes observed in this study (Cohen's $d > 2.0$) substantially exceed typical educational intervention effects ($d = 0.4$-0.8), suggesting the combination of GBL with AR technology may produce synergistic benefits not captured in studies examining these approaches separately.

The finding that technology-integrated learning benefited students across ability levels addresses concerns raised by Khalid et al. (2021) about inequitable access to critical thinking instruction. While Chusni et al. (2020) identified persistent challenges in developing critical thinking among Indonesian elementary students, this study demonstrates that appropriately designed technological interventions can effectively address these challenges even in semi-rural contexts with limited prior technology exposure.

These results have important implications for elementary mathematics education in Indonesia and similar contexts. The experimental group's enhanced performance indicates that intentional integration of technology with sound pedagogical approaches yields measurable improvements in both technical competencies and higher-order thinking skills. The nearly uniform improvement across students (7-9 points in digital skills; 5-9 points in critical thinking) demonstrates that technology-integrated learning benefits not only high-ability students but also helps lower-performing groups, narrowing achievement gaps (Masjudin, 2024).

For prospective elementary school teachers, these findings suggest that GBL with AR technology should be incorporated into pre-service training programs. Teachers equipped with these skills will be better prepared to design mathematics learning experiences that foster curiosity, spatial reasoning, and analytical thinking in students, aligning with 21st-century educational goals and the Independent Curriculum's emphasis on critical thinking and digital literacy (Loeneto et al., 2022). The structured implementation approach and assessment instruments developed in this study—particularly the digital skills observation rubric and critical thinking assessment framework—provide practical tools that teacher educators can adapt for various contexts.

From a policy perspective, the accessibility of Assemblr Edu (available as a free application) makes this intervention feasible for semi-rural schools with limited technology budgets. Unlike expensive hardware-intensive interventions, Assemblr Edu requires only smartphones or tablets—devices increasingly available even in resource-constrained Indonesian schools. This scalability addresses Masjudin's (2024) call for evidence-based, contextually appropriate strategies for strengthening 21st-century skills in Indonesian mathematics education.

Conclusion

This research demonstrates that Game-Based Learning integrated with Assemblr Edu significantly enhances both digital skills and critical thinking abilities in elementary mathematics education within semi-rural contexts. The experimental group achieved substantial improvements with mean gains of 7.73 points (62.1% increase) in digital skills and 6.37 points (48.0% increase) in critical thinking, significantly outperforming the control group's 2.18-point improvements in both measures ($p<0.001$, Cohen's $d>2.0$). Students demonstrated advancement across all six dimensions of Facione's critical thinking framework, with particularly strong gains in self-regulation (difference=1.09, $d=2.24$) and explanation (difference=1.00, $d=1.92$), progressing from initial uncertainty to confident, independent technology operation by the intervention's conclusion. This study fills a critical research gap by providing empirical evidence from semi-rural Indonesian schools (SDN Sidorejo, Wungu District, Madiun Regency) where technology integration remains under-explored, demonstrating that combining augmented reality visualization with game mechanics simultaneously develops two essential 21st-century competencies in resource-constrained settings. The practical frameworks developed—including the digital skills observation rubric and critical thinking assessment instruments aligned with Facione's model—provide evidence-based tools that teachers can immediately adopt for technology-enhanced mathematics instruction, particularly for abstract concepts requiring spatial visualization. Educational institutions should invest in teacher professional development and technology infrastructure supporting GBL implementation, as the accessible nature of Assemblr Edu makes it feasible even for semi-rural schools with limited resources. Future research should examine long-term skill retention, scalability across grade levels and subject areas, and the relationship between prior digital literacy and intervention effectiveness to refine differentiation strategies and broaden the impact of technology-integrated constructivist pedagogy in elementary education.

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