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Virtual Reality and Artificial Intelligence: Challenges and Opportunities in its Implementation in Mathematics Learning

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ABSTRACT

Penelitian ini mengkaji tantangan dan peluang penerapan Virtual Reality (VR) dan Kecerdasan Buatan (AI) dalam pembelajaran matematika di sekolah menengah. Meskipun VR dan AI menawarkan potensi transformasional untuk meningkatkan pembelajaran melalui visualisasi konsep abstrak (misalnya, pemodelan geometri 3D) dan personalisasi instruksi, adopsinya menghadapi hambatan seperti biaya tinggi, infrastruktur tidak memadai, dan kurangnya pelatihan guru. Namun, dukungan dari pendidik dan siswa menunjukkan bahwa teknologi ini mampu menciptakan lingkungan belajar yang interaktif dan menarik. Pendekatan campuran (kualitatif-kuantitatif) yang menggabungkan wawancara, kuesioner, dan uji-t berpasangan mengungkapkan peningkatan signifikan pada motivasi dan pemahaman matematis siswa setelah penerapan VR ($t = -176.991$, $p < 0.001$). Rekomendasi mencakup dukungan finansial berbasis kebijakan, pengembangan konten lokal, dan program pelatihan guru yang terstruktur sesuai praktik global. Dengan mengatasi tantangan sistemik, VR dan AI dapat menjadi alat kunci dalam memajukan pendidikan matematika yang inklusif dan inovatif.

This study explored the challenges and opportunities of implementing Virtual Reality (VR) and Artificial Intelligence (AI) in mathematics education at secondary schools. While VR and AI offer transformative potential to enhance learning through immersive visualization of abstract concepts (e.g., 3D geometric modeling) and personalized adaptive instruction, their adoption faces barriers such as high costs, inadequate infrastructure, and insufficient teacher training. Nevertheless, stakeholder support from educators and students highlights their capacity to foster interactive and engaging learning environments. A mixed-methods approach combining interviews, questionnaires, and paired t-tests revealed significant improvements in student motivation and mathematical understanding post-VR implementation ($t = -176.991$, $p < 0.001$). Recommendations emphasize policy-driven financial support, localized content development, and scalable teacher training programs aligned with global best practices. By addressing systemic challenges, VR and AI can become pivotal tools for advancing equitable and innovative mathematics education.

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INTRODUCTION

The Industrial Revolution 4.0 has changed many aspects of life, including education (Dudhat & Ardi, 2023). Information and communication technology (I.C.T.) has excellent potential to improve the quality and effectiveness of education because it is increasingly integrated into the learning process. Today's most promising technologies are virtual reality (V.R.) and artificial intelligence (A.I.). With the ability to create immersive simulated environments, virtual reality (V.R.) offers a more interactive and engaging learning experience.

More adaptive and unique learning experiences can be generated by artificial intelligence, which includes the ability to process data and provide intelligent responses (Nalubega & Uwizeyimana, 2024a). Math learning, often considered an abstract and challenging subject for many students to understand, has much potential for change. V.R. allows students to visualize abstract mathematical concepts in three dimensions, making them easier to understand (Agbo et al., 2023; Buchori et al., 2024; Su et al., 2022). The potential to simulate math experiments through V.R. could provide a more realistic and engaging learning experience (Cheong et al., 2023). Meanwhile, A.I. can analyze student learning data and provide learning materials tailored to individual needs (Bucea-Manea-Ţoniş et al., 2022). A.I. can also provide quick and accurate feedback on students' work so they can correct mistakes more quickly (Nalubega & Uwizeyimana, 2024a; Wardat et al., 2024).

The utilization of technology, Virtual Reality (V.R.), and Artificial Intelligence (A.I.) in mathematics education has enormous potential to improve students' understanding of abstract concepts. A study by (Buchori et al., 2024) showed that students who learned geometry using V.R. increased scores with an average learning achievement of 84.53 in the experimental class compared to 70.33 in the control class. V.R. allows students to visualize three-dimensional objects interactively to more easily understand spatial relationships and geometric properties (Uriarte-Portillo et al., 2023).

Relevance to conditions in Indonesia

How ready are we to overhaul the traditional learning paradigm by adopting advanced technologies such as Virtual Reality (V.R.) and Artificial Intelligence (AI)? Amid the rapid development of information technology, Indonesia is struggling to integrate V.R. and A.I. into the education system. The main challenges are the digital divide and the lack of adequate infrastructure. As a developing country, Indonesia strives to improve the quality of education. Virtual Reality (V.R.) and Artificial Intelligence (A.I.) technologies are promising solutions to overcome complex educational problems.

Although Virtual Reality (V.R.) and Artificial Intelligence (AI) have enormous potential to be applied in education in Indonesia, there are still several obstacles, such as digital inequality and limited infrastructure (Dobrev & Garov, 2023). However, with the proper policy support, investment in human resource development, and collaboration between the government, the private sector, and educational institutions, this problem can be solved. The potential of virtual reality and artificial intelligence to improve the quality of education in Indonesia is very promising.

Implementing V.R. and A.I. in education is the government's responsibility and involves various parties such as educational institutions, technology companies, and civil society (Oliveira et al., 2023). Strong collaboration between all stakeholders is essential to ensure the successful implementation of this technology. By working together, we can create an innovative and inclusive education ecosystem.

Implementation Challenges

The government encourages the use of information technology (I.C.T.) in learning, but many challenges must be overcome. The digital divide, lack of infrastructure, and lack of high-quality human resources are some of these problems. Although virtual reality (V.R.) and artificial intelligence (A.I.) have great potential to improve the quality of education in Indonesia, they need to be supported by the right policies and sufficient investment. V.R. and A.I. hardware and software are still relatively expensive, so not all schools can afford them (Fransson et al., 2020). Stable internet access and adequate technological infrastructure are needed to support using VR and AI (Limbong et al., 2024). Today's teachers need solid technical competencies to take advantage of the potential of V.R. and A.I. in learning. Integrating this technology will open new opportunities to create more innovative and compelling learning experiences (Ahmad et al., 2024; Govender, 2023). There is a significant gap between the potential of V.R. and A.I. technologies and the availability of learning content that utilizes these

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technologies optimally. This is an obstacle to the widespread application of V.R. and AI-based learning (Lee & Kim, 2023). Applying new technology in learning often faces resistance from some students and teachers. Discomfort or doubt about using new technology is typical. Factors such as a lack of digital literacy, concerns about change, and a preference for traditional learning methods can be the leading causes of this resistance (Czerniewicz & Feldman, 2024).

This research is based on the theory of constructivism, which emphasizes the importance of direct experience in learning. By harnessing the potential of V.R. and A.I., this research aims to dig deeper into how technology can create a more interactive and meaningful learning experience for math students at the secondary level. The research will use qualitative and quantitative approaches, including surveys, in-depth interviews with teachers and students, and analysis of technology usage data. Through this research, it is hoped that a more comprehensive understanding of the challenges and opportunities of using V.R. and A.I. in mathematics learning can be obtained, as well as policy recommendations and best practices to improve learning effectiveness. The results of this research are expected to contribute to the development of technology-based mathematics curricula, teacher training, and the formulation of educational policies that support innovation in learning.

METHOD

This study uses a mixed method approach, using qualitative and quantitative techniques used simultaneously in the design of the research explanation to collect detailed data (Ratnasari & Sudradjat, 2023; Sugiyono, 2019; Viera, 2023). Once the quantitative data is collected and analyzed, the qualitative data is collected and re-analyzed to produce credible and valid conclusions. All ethical considerations required for data collection and analysis are met in this study. The primary respondents' voluntary consent is requested orally before the interview to guarantee the confidentiality and anonymity of the data during data collection through the interview.

Sampling

The study specifically targeted math teachers from various high schools who already had teaching certifications. Using purposive and snowball sampling techniques, the researchers successfully recruited ten teachers who deeply understood V.R. and A.I. technology. Qualitative data were collected through in-depth interviews to understand teachers' experiences and perspectives in integrating this technology into mathematics learning. In addition to teachers, the researcher also recruited 85 students from various educational institutions who have obtained more technology-based learning, especially using VR and AI in mathematics learning.

Research instruments

The study used in-depth interviews, classroom observations, and questionnaires to evaluate using V.R. and A.I. technology in math learning (Abdualiyeva et al., 2022; Allam, 2015). Interviews with teachers and students identify aspects such as effectiveness, user experience, and the challenges and opportunities of this technology. Class observation helps observe the application of technology and emerging challenges, while questionnaires collect participant demographic data. The research also analyzes related education policies to understand the support or barriers to technology integration. The data is analyzed thematically to identify key themes and provide practical recommendations for teachers, policymakers, and curriculum developers regarding using V.R. and A.I. technologies in secondary schools.

Data collection

The study involved interviews with ten teachers and a questionnaire to 85 students from several schools to explore the problems and opportunities of using V.R. and A.I. technology in math learning. All interviews were recorded with the participant's consent to maintain confidentiality. Participants were asked to explain their understanding of V.R. and A.I. to avoid misunderstandings. Record files are labeled and stored with two copies to prevent data corruption.

The research consisted of two stages of data collection: first, a questionnaire for students to measure their perceptions of the use of V.R. and A.I., including their convenience, enjoyment, and impact on learning motivation; second, analysis of student learning outcome data before and after the application of V.R. and A.I. technology by collecting test scores or related tests.

Data Analysis

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Data collected through literature studies, in-depth interviews, and questionnaires will be analyzed in stages. Qualitative data will be analyzed by reading interview transcripts repeatedly, doing open coding to find concepts and phrases, and grouping the code into more extensive subcategories. This process is iterative to find complex patterns and relationships. Quantitative data from the questionnaire will be processed using S.P.S.S. with descriptive analysis to describe variable characteristics and inferential analysis to test hypotheses. Quantitative data from pre- and post-intervention tests will be analyzed using a paired t-test to assess the impact of V.R. on mathematics performance. Validity and reliability of the questionnaire will be ensured through corrected item-total correlation analysis and Cronbach's Alpha testing (Fan, 2013), while qualitative data from interviews will undergo thematic coding to identify patterns in teacher and student perspectives (Buchori et al., 2024).

RESULTS AND DISCUSSION

Results of Interviews with Stakeholders

The results of interviews with teachers and students show diverse views on V.R. and A.I. technology in mathematics learning. Teachers identified vital challenges such as high costs, lack of infrastructure, and technical readiness. Interviews revealed that teachers emphasized the importance of intensive training and gradual integration as feasible steps. For example, one teacher noted, 'Gradual implementation allows us to adapt without overwhelming students.' This aligns with Wardat et al. (2024), who found that institutional support is critical for successful technology adoption. Teachers also acknowledge that this technology is changing their role to be more of a facilitator, requiring new technical skills. The students showed enthusiasm for V.R. and A.I. technology, feeling that V.R. facilitates understanding abstract concepts through immersive visualization and that A.I. offers personalized and adaptive learning (Dobrev & Garov, 2023). They feel this technology increases learning motivation and makes learning more engaging and interactive. However, significant obstacles exist, such as limited access and inadequate infrastructure.

The results of the analysis also show that most students and teachers agree that further training is urgently needed to maximize the benefits of V.R. and A.I. technologies. It emphasizes the importance of professional development for teachers and the provision of ongoing training (Nawas, 2023; Salloum et al., 2024; Wardat et al., 2024). Key recommendations include ongoing training, development of technology-based materials, and ongoing evaluation of the effectiveness of the use of technology. Implementing V.R. and A.I. technologies have great potential to improve math learning, but its success depends on adequate support from the entire education ecosystem. Teachers and students see great potential in this technology to improve the quality of math learning, but its success depends heavily on the readiness and support of the entire education ecosystem (Chapman, 2012; Walther et al., 2022)

Results of Paired Sample T-Test

The paired T-test will be used to analyze the quantitative data obtained from this study. This test allows us to compare the averages of two paired data groups, such as the pre-treatment and post-treatment scores of the same group of students. In other words, the paired t-test will test whether there is a statistically significant difference between the two values. The results of this test will provide empirical evidence regarding the effectiveness of learning using VR and A.I. Based on the constructivism learning theory, it is hoped that using VR in mathematics learning can increase students' motivation to learn. A pair test will be conducted on student learning motivation data before and after participating in VR-based learning to test this hypothesis. Thus, we can find out empirically whether there is a significant increase in students' learning motivation after being given this treatment.

Eighty-five students from various schools have been randomly selected as respondents in this study. The criteria for selecting respondents are students in grades 10 to 12 who have internet access and are willing to participate in the entire series of research activities. The diversity of the respondents' schools is expected to increase the generalisability of the research findings so that the results obtained can be more relevant to the conditions of mathematics learning in various schools. This sizable sample also allows for more in-depth statistical analysis to test research hypotheses.

Before the paired t-test, a normality test analysis will be done using *Kolmogorov-Smirnov* on the S.P.S.S. application. The test results show that the data is normally distributed if the significance value

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exceeds 0.05. The data is considered not generally distributed if the significance value is less than 0.05. The following table illustrates the results of the data normality test.

Table 1. *Kolmogorov-Smirnov normality test results*

Variable	Kolmogorov-Smirnov		
	Statistics	**df**	**Sig.**
Before	.089	85	.096
After	.088	85	.099

a. Lilliefors Significance Correction

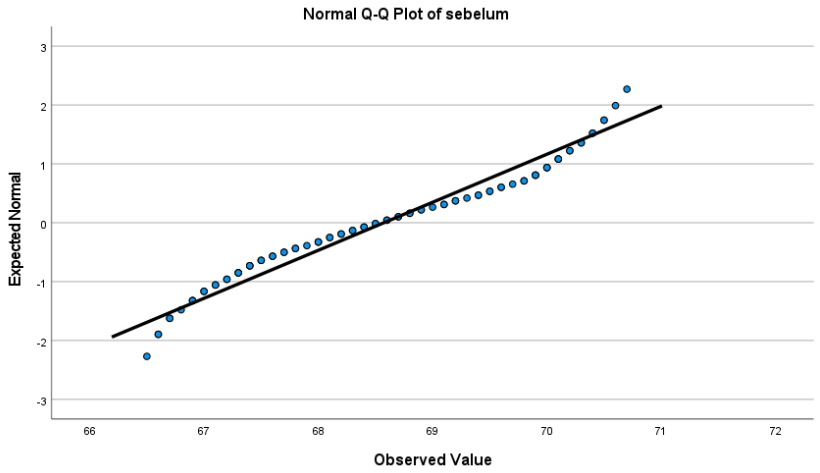

Figure 1. The results of the normality test using the Normal Q-Q diagram of the previous variable plot

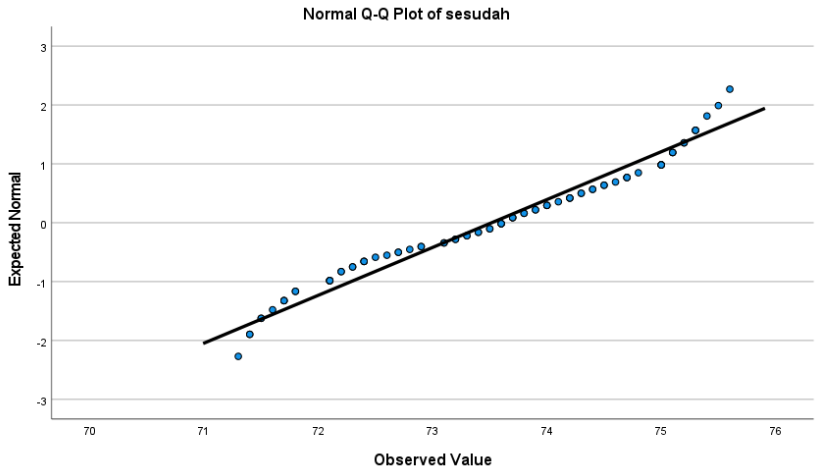

Figure 2. The results of the normality test using the Q-Q diagram of the variable plot after

The test results were obtained, and the data was expected. Then, the paired t-test was continued; the results of the paired t-test showed a statistically significant difference in the value of [variable] between before and after the treatment (t = [calculated t value], df = [degree of freedom], $p < 0.05$). This indicates that [explain the interpretation of the results by the hypothesis regarding using V.R. effectively improves students' understanding of mathematical concepts. The full results can be seen in the following table.

Table 2. Paired samples statistics

		Mean	**N**	**Std. Deviation**	**Std. Error Mean**
Pair 1	before	68.5729	85	1.22595	.13297
	after	73.5153	85	1.23032	.13345

Table 3. Paired samples correlations

		N	**Correlation**	**Sig.**
Pair 1	Before & After	85	.978	.000

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Table 4. Paired samples test

		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	Df	Sig. (2-tailed)
					Lower	Upper			
Pair 1	Before & After	-4.94235	.25745	.02792	-4.99788	-4.88682	-176.991	84	.000

The analysis showed that students' average mathematics learning score before learning using V.R. was 68.5729, while after using V.R., it was 73.5153, indicating an increase in the average learning outcomes. The standard deviation for the after value is 1.23032, with an average error standard of 0.13345, while the standard deviation for the previous value is 1.22595. The correlation between the before and after values was insignificant, with a coefficient of 0.978 and a significance value of 0.000.

The paired sample test showed an average difference of -4.94235 between the before-and-after values, with a 95% confidence interval between -4.99788 and -4.88682. The calculated t-value is -176.991, which is more significant than the t-value of table 1.9886 for df=84 and significant at 0.05/2. This shows a significant difference between learning outcomes before and after learning using V.R., indicating that using V.R. positively influences mathematics learning.

Validity and Reliability Results of the Questionnaire

The researcher will measure the level of students' learning motivation when using V.R. and AI-based learning. Eighty-five students will be tested using the *Corrected Item to Total Correlation method*. This method means correlating the score of each item with the total score and then making corrections to the value of the overestimated correlation coefficient, which is an estimate of a value greater than the actual value so that there is no overestimation of the total item coefficient.

The correlation value of the associated total item is also referred to as the r count in this validity test. The criterion for the level of motivation to learn is validity if r counts > t table and r calculates < r table. Using this S.P.S.S. tool, we only need to compare the known calculated r (*correlate item-total correlation column*) with the calculated r table at a significance of 0.05 or 5%, with a two-sided test and the number of respondents 85, df (freedom rate) formula df(n-2). df=85-2 = 83, see in the r distribution of the product moment table, for n=83 at a significance of 5%, the r-table is obtained of 0.2133.

Table 5 Output of the Validity Test of correlate item-total correlation

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
VR1	183.08	331.499	.537	.	.845
VR2	182.93	335.971	.463	.	.847
VR3	182.75	334.503	.453	.	.846
VR4	182.73	342.370	.257	.	.850
VR5	182.73	337.189	.406	.	.847
VR6	182.68	338.317	.406	.	.848
VR7	182.80	336.597	.432	.	.847
VR8	182.77	337.719	.421	.	.847
SUMVR	154.71	256.231	.621	.	.846
AI1	182.88	332.733	.564	.	.845
AI2	182.56	339.960	.440	.	.848
AI3	183.06	332.346	.483	.	.845
AI4	183.21	331.423	.473	.	.845
AI5	182.77	335.695	.429	.	.847
AI6	182.77	334.948	.551	.	.846
AI7	183.06	326.274	.577	.	.843
AI8	182.67	335.647	.481	.	.846
SUMAI	155.24	234.714	.697	.	.848
VI1	182.64	334.256	.606	.	.845
VI2	182.81	334.156	.466	.	.846
VI3	182.57	338.272	.488	.	.847

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	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
VI4	182.62	331.612	.652	.	.844
VI5	182.70	329.175	.704	.	.843
VI6	182.57	330.826	.651	.	.844
VI7	182.54	335.794	.522	.	.846
SUMVI	156.68	269.594	.553	.	.848

Table 6. Results of the Validity Test using the item correlate test- total correlation of student learning motivation

	r-count value	r-table values	Information
VR1	0.646	0.213	Valid
VR2	0.588	0.213	Valid
VR3	0.694	0.213	Valid
VR4	0.548	0.213	Valid
VR5	0.653	0.213	Valid
VR6	0.592	0.213	Valid
VR7	0.615	0.213	Valid
VR8	0.578	0.213	Valid
AI1	0.733	0.213	Valid
AI2	0.575	0.213	Valid
AI3	0.620	0.213	Valid
AI4	0.680	0.213	Valid
AI5	0.625	0.213	Valid
AI6	0.681	0.213	Valid
AI7	0.717	0.213	Valid
AI8	0.640	0.213	Valid
VI1	0.464	0.213	Valid
VI2	0.499	0.213	Valid
VI3	0.419	0.213	Valid
VI4	0.672	0.213	Valid
VI5	0.590	0.213	Valid
VI6	0.465	0.213	Valid
VI7	0.482	0.213	Valid

If Cronbach's Alpha value is more than 0.60 (Fan, 2013; Hopkins, 2000), the reliability test can be carried out from the S.P.S.S. output. Cronbach's Alpha value is compared to the table's r-value; if the alpha r value of the table is more significant than 0.60, then the questionnaire or questionnaire compiled is considered consistent or reliable. If the alpha t value of the table is lower than 0.60, then the questionnaire or questionnaire is considered inconsistent or unreliable.

Table 6. Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.851	0.911	26

Suppose the Cronbach's Alpha value of 0.851 is compared to the r-table of 0.2133, and the Cronbach's Alpha value of 0.851 is above 0.60. In that case, the instrument is considered reliable or consistent as a data collection tool in a study.

Validity and reliability tests should be carried out before data collection in the study to measure validity and reliability. From the validity test results, as many as 26 question instruments were given to 85 students from several schools surveyed regarding learning motivation when using V.R. and A.I. in mathematics learning. We use item-total correlation for validity tests to get invalid question item instruments declared valid. A reliability testing model can be seen using Cronbach's Alpha. A Cronbach's Alpha value of 0.851 or higher than 0.60 indicates that the instrument is reliable.

Case studies of V.R. and A.I. implementation in schools

The application of Virtual Reality (V.R.) in mathematics education has shown promising results in improving students' understanding of mathematical concepts compared to ordinary learning methods.

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Research shows that V.R. increases engagement and facilitates a deeper understanding of complex topics. Meanwhile, Artificial Intelligence (A.I.) in mathematics education has shown promising results in improving students' understanding of mathematical concepts compared to traditional methods. Research shows that A.I. can tailor learning experiences to individual needs, optimizing educational outcomes.

Improvement of Conceptual Understanding

A study using the Student Facilitator and Explanation (S.F.A.E.) approach in a V.R. environment showed significant improvements in students' mathematical representation abilities and conceptual comprehension compared to traditional methods (Suri et al., 2024). Another study found that V.R. technology improved students' data processing and graphic representation skills, with the experimental group achieving a 97% improvement in graphic representation abilities (Alzoubi, 2024).

Immersive Learning Experience

V.R. allows students to interact with 3D geometric shapes, making abstract concepts more tangible. A game-based V.R. platform shows that 83% of students find it easier to visualize geometric shapes (Sarma et al., 2023). Developing an immersive learning environment has been associated with improved user experience and a better understanding of mathematical concepts, as evidenced by various case studies (Shen et al., 2023).

Personalized Learning Experience

A.I. technology enables personalized learning, adapting content to meet students' specific needs, significantly improving their understanding of mathematical concepts (Tulak et al., 2024). A study found a strong positive correlation between A.I. use and student engagement, with high percentages of visual (88%) and mental (84.5%) indicators during learning activities (Efendi et al., 2024).

Improved Problem-Solving Skills

A.I. tools, such as ChatGPT, Gemini, Claude, and others, show high accuracy in solving mathematical problems, outperforming students in multiple-choice and short-answer formats, which shows that A.I. can effectively support conceptual understanding (Govender, 2023; Hidayatullah et al., 2024). Customized A.I. learning methods have improved math academic achievement and self-study abilities, especially in underserved areas (Whang & Lee, 2024).

Analysis of government policies in the development of educational technology

The government of Indonesia is actively working on regulations regarding the use of virtual reality (V.R.) and artificial intelligence (A.I.) in education, although the framework is still evolving. Although integrating this technology is beneficial, it poses challenges requiring comprehensive legal supervision.

Current Regulatory Landscape

Indonesia is a developing country and currently does not have a specific law regulating A.I. technology, instead relying on existing regulations such as Law No. 19 of 2016 concerning Electronic Information and Transactions, which does not adequately address the complexity of A.I. (Abidin, 2023). There are calls for updated regulations, including data protection, algorithm transparency, and A.I. education applications, ensuring responsible use in educational settings (Santoso et al., 2024).

Education Initiatives

Recent workshops have been conducted to improve teachers' understanding of A.I. and Augmented Reality (A.R.) tools, demonstrating the impetus to integrate these technologies in the classroom (Nisa et al., 2024). The evaluation of these programs shows a significant improvement in teacher skills, indicating a positive trend to adopt A.I. and A.R. in education. While the Indonesian government is making strides in integrating A.I. and V.R. into education, the regulatory framework is still not sufficiently developed, requiring further clarity and legal support to maximize the potential of these technologies.

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Curriculum Policies

In Indonesia, the current independent curriculum is used, one of the points of which is Independent Learning. The Freedom to Learn policy in Indonesia aims to improve the flexibility and quality of education, which has significantly impacted the adoption of V.R. and A.I. technology in schools. While it presents opportunities for innovative learning, challenges remain in its implementation. The Independent Curriculum allows teachers to design learning programs that combine VR and A.I., fostering creativity and critical thinking among students (Saa, 2024). Schools are encouraged to integrate technology into their curriculum, which can improve student engagement and learning outcomes (Suttrisno & Yulia, 2024). Despite its potential, the policy faces obstacles such as inadequate technological infrastructure and teacher training, hindering the effective integration of V.R. and A.I. (Adri et al., 2023; Saa, 2024). A study shows that school readiness is influenced by knowledge, attitudes, and institutional support, which are crucial for adopting new technologies (Rusdinal et al., 2024).

Discussion

The results of the questionnaire analysis showed that the instrument used to measure the level of student learning motivation was valid and reliable. This indicates that the instrument can accurately measure what it wants, namely the level of student learning motivation when using V.R. and AI-based learning. Thus, the data obtained from the questionnaire can be relied on to answer research questions. The paired t-test results revealed a statistically significant improvement in mathematics scores ($t = -176.991$, $p < 0.001$), indicating that VR-based learning significantly enhanced student performance. This aligns with Su et al. (2022), who reported a 14.2% increase in conceptual understanding when using immersive technologies. These findings indicate that using V.R. in mathematics learning positively influences student learning outcomes. This study's results align with several previous studies that show that using VR technology in learning can improve students' motivation and learning outcomes (Su et al., 2022).

Qualitative and quantitative data show that although most respondents support and can improve learning outcomes using V.R. and A.I. technologies, technical and financial constraints are the main obstacles. To address this, the study suggests a comprehensive implementation strategy, including ongoing training for teachers, the development of quality technology-based learning materials, and adequate policy and budget support from educational institutions and the government. Thus, the great potential of V.R. and A.I. technology in increasing the effectiveness and relevance of mathematics learning can be optimally realized (Wang, 2023). While students are generally enthusiastic about technology's personalization and visualization potential, teachers are more likely to highlight technical constraints and lack of support as significant barriers (Mallek et al., 2024; Nalubega & Uwizeyimana, 2024b). This difference in perception indicates the need to align expectations between the two groups and design more specific training programs to meet each other's needs.

The results show that the successful application of V.R. and A.I. in education highly depends on solid policy support. The government and educational institutions must allocate sufficient budgets for infrastructure development, teacher training, and procuring necessary hardware and software. In addition, there needs to be a policy that encourages technology integration into the curriculum and assessment (Chairani et al., 2022). Thus, the transformative potential of V.R. and A.I. technology can be maximized to improve Indonesia's education quality. While Indonesia does not have a specific law on A.I. technology, existing laws, such as Law Number 19 of 2016 and Government Regulation Number 71 of 2019, address issues related to electronic transactions and prohibit the use of deepfake technology (Abidin, 2023). The role of the government in providing legal protection through laws and particular institutions for using this technology is crucial to ensure legal certainty for users in Indonesia (Zuliarti et al., 2022). However, the challenges faced are also increasingly complex. Previous research has focused more on these technologies' technical and pedagogical potential, while recent research has given greater attention to social and organizational aspects. This trend shows that implementing technology in education involves technical aspects and requires broader cultural and organizational changes.

Overall, this discussion shows that while the challenges in implementing V.R. and A.I. technologies in math learning are significant, the potential benefits are enormous. With careful implementation strategies and ongoing support, this technology can effectively improve students' understanding of mathematical concepts and learning motivation. Strong support from schools,

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governments, and technology developers is essential to overcome obstacles and maximize the potential of V.R. and AI technology in education.

Opportunities for the use of V.R. and A.I. technology in mathematics learning

Mathematics learning is often a scourge for many students. However, with the advent of Virtual Reality (V.R.) and Artificial Intelligence (A.I.) technologies, the landscape of mathematics education is now undergoing a significant transformation. Imagine students exploring geometric concepts in a three-dimensional space using V.R. or getting a personal A.I. tutor who can adjust the difficulty level of the questions according to each student's abilities. Several strategies can be used to maximize the potential of virtual reality (V.R.) and artificial intelligence (A.I.) in creating personalized and effective math learning experiences. The technology can adapt to individual learning styles, increase engagement, and provide tailored feedback (Oliveira et al., 2023).

More Interactive Learning

V.R. allows students to experience math concepts directly and visually, increasing understanding and interest in learning. In contrast to traditional learning methods often fixated on textbooks and whiteboards, V.R. offers a more dynamic and engaging approach (Dobrev & Garov, 2023). With VR, students can be actively involved in learning, not just as passive recipients of information. This allows students to build a deeper and more meaningful understanding.

With this technology in math learning, students can explore geometric shapes in three-dimensional spaces, conduct mathematical experiments virtually, or even solve problems in a simulated environment (Sarma et al., 2023). This immersive and interactive learning experience makes the subject matter more engaging and helps students build a stronger connection between abstract concepts and the natural world (Su et al., 2022).

Personalization of Learning

A.I. can analyze student learning data and provide customized feedback, making learning more effective. A.I. can use machine learning algorithms to identify students' learning patterns, strengths, and weaknesses (Wardat et al., 2024). Based on this data analysis, A.I. can develop learning programs tailored to the specific needs of each student. For example, A.I. can provide additional exercises or more straightforward sample questions for students struggling to understand certain concepts. On the other hand, for students who already have a good grasp of the material, A.I. can provide a higher challenge to stimulate their potential (Bui & Alaei, 2022). AI-powered personalization of learning allows each student to learn at an appropriate pace and style, thereby improving overall learning motivation and effectiveness.

Accessibility

Virtual Reality (V.R.) and Artificial Intelligence (A.I.) technologies can significantly improve students' access to quality learning materials in remote areas. The technology offers an immersive and interactive educational experience that can bridge the gaps caused by geographical remoteness. A study found that 89% of students felt V.R. videos provided an appropriate learning experience despite discomfort during use (Wilkerson et al., 2022). AI-driven education systems can also assess and adapt to students' learning behaviors, increasing focus and immersion in virtual environments. This approach has shown promise in improving educational outcomes by delivering tailored content (Xu et al., 2020).

Integrating technology in education is essential, especially in remote areas where teacher quality is often compromised. Effective educational technology can mitigate these challenges and improve the quality of learning (Lee & Kim, 2023). While V.R. and A.I. present innovative solutions, challenges such as equipment cost and user experience must be addressed to maximize their potential in distance education.

21st Century Skill Enhancement

This technology can help students develop critical thinking, problem-solving, and creativity skills. By interacting with a dynamic and complex virtual environment, students are trained to analyze information, evaluate different solutions, and find new ways to overcome challenges. In addition, this technology also encourages students to think creatively and innovatively when finding solutions.

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Through technology-enabled learning, students not only master the subject matter but also develop 21st-century skills that are in demand in the future of work, such as adaptability to change, critical thinking, and teamwork (Dudhat & Ardi, 2023).

Studies show that V.R. can effectively improve critical thinking skills, with experimental groups showing significant advantages compared to traditional methods (Çakıroğlu et al., 2023). Students often use A.I. tools like ChatGPT and Canva to facilitate creative and collaborative learning (Fadli & Iskarim, 2024). The integration of V.R. and A.I. technology presents excellent benefits, and it is essential to balance technology with traditional learning methods to foster critical interpersonal skills and prevent over-reliance on technology (Balushi et al., 2024).

Innovation in Curriculum Development

V.R. and A.I. can drive the development of a more relevant and engaging curriculum for students. By harnessing the potential of these two technologies, educators can create a more immersive and interactive learning experience. The curriculum can be designed with learning modules tailored to each student's interests and learning styles. Students interested in history can explore essential events in virtual reality, or students who love math can solve complex problems through interactive simulations (Shen et al., 2023). The flexibility and personalization offered by V.R. and A.I. allow the curriculum to continuously adapt to students' times and needs, ensuring that education remains relevant.

Students can gain a deeper understanding of the subject matter through V.R. technology, which allows them to explore virtual environments that simulate real-world situations (Landers, 2018). Conversely, AI allows for real-time curriculum adjustments according to students' needs and understanding, making the learning experience more adaptive (Anekal et al., 2023). Combining these two technologies can create a dynamic and innovative learning environment where the curriculum focuses on student learning and developing students' critical skills and creativity. Thus, V.R. and A.I. play an essential role in presenting innovations in curriculum development that align with the demands of the times and the needs of students.

Potential for Research

Using V.R. and A.I. in education opens up opportunities for more in-depth research on the learning process. With this technology, researchers can collect richer and more complex data on how students interact with learning materials, solve problems, and collaborate with peers (Balushi et al., 2024). This data can be analyzed in depth to uncover learning patterns that were previously difficult to detect. Research that utilizes V.R. and A.I. can provide new insights into the factors that affect learning effectiveness, allowing for the development of more personalized and effective learning strategies (Mallek et al., 2024).

Using V.R., researchers can observe how students adapt to the simulated environment and how this affects information retention and problem-solving skills (Dobrev & Garov, 2023). Meanwhile, AI enables real-time data collection and analysis of various student interactions, providing more granular insights into the effectiveness of teaching methods and individual responses (Zuliarti et al., 2022). This combination of technologies can help identify factors that enhance or hinder learning, paving the way for pedagogical innovation and a more personalized approach to education. This potential makes V.R. and A.I. essential tools in educational research, which can enrich our understanding of how learning happens and how to improve future education quality.

Challenges of using V.R. and A.I. technology in mathematics learning

The implementation of V.R. and A.I. in mathematics learning offers enormous potential. However, the use of this technology still faces various challenges. In addition to the technical aspect, the readiness of educators, students, and school infrastructure is also a determining factor for success. The integration of this technology with the existing curriculum also requires careful consideration. The challenge is in the technical aspect and how this technology can be effectively integrated with the existing curriculum. In addition, more research is needed to evaluate its effectiveness comprehensively. It is essential to ensure that this technology is used responsibly and does not harm students.

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Budget Allocation and Financial Resources

V.R. and A.I. technology use in mathematics learning faces several challenges, especially budget allocation. An increase in the budget for developing technological infrastructure in schools, including providing stable internet access and adequate hardware, is a crucial step (Abdualiyeva et al., 2022). However, the cost of procurement of high-quality hardware, software, and learning content is often an obstacle for schools, especially private schools or schools in areas with limited budgets. Financial resources allocated for education and technology are also a determining factor. Countries with larger education budgets tend to adopt new technologies more quickly. This disparity in budget allocation has the potential to widen the gap in access to quality educational technology, thereby hindering the equitable distribution of education quality.

A strategic approach is essential to prioritize budget allocation for educational technology in Indonesia amid various educational needs. This involves assessing current challenges, stakeholder engagement, and aligning with national education goals. Limited infrastructure and uneven internet access hinder the practical application of educational technologies, especially in remote areas (Rabani et al., 2023). Inadequate training for educators affects technology integration in the classroom, requiring targeted professional development programs (Firdaus & Ritonga, 2024). Budget decisions are influenced by various levels of government, from national ministries to local education services, emphasizing the need for collaborative planning (Rukimin, 2024). Engaging local communities and stakeholders can increase the relevance and effectiveness of technology initiatives (Indah et al., 2024). Viewing education technology as a long-term investment can help prioritize funding in a way that meets immediate and future educational needs (Alfarizi & Sari, 2024). While prioritizing education technology funding, balancing this investment with other urgent educational needs is essential, ensuring a holistic approach to improving Indonesia's education system.

Government Policy

V.R. and A.I. technology use in mathematics learning also faces several regulations and policy-related challenges. There needs to be clear regulations regarding using student data in AI-based learning to protect data privacy and security. Government policies that support technological innovation in education are also very crucial. Developed countries often have more comprehensive policies compared to Indonesia. Despite several government initiatives, policies specifically supporting using V.R. and AI technologies in education are still not comprehensive (Lievianto & Erlyana, 2024). The lack of precise regulation could hinder the adoption of these technologies and raise concerns regarding ethics and safety. Developed countries tend to have more comprehensive regulations, providing a solid legal basis for using advanced technologies in education (Nisa et al., 2024). Despite several government initiatives in Indonesia to promote technological innovation, policies that specifically support the use of V.R. and A.I. in learning are still limited and less comprehensive. This regulatory ambiguity can significantly hinder integrating V.R. and A.I. technology into the math curriculum.

A collaborative and multi-faceted approach is essential to effectively engage various stakeholders in policies that support the use of V.R. and A.I. technologies in education in Indonesia. It involves governments, educational institutions, the tech industry, and civil society to create a robust framework for implementation. The Ministry of Education has implemented a community service program that trains teachers in using A.I. and V.R. technologies, significantly improving their pedagogical skills and understanding of interactive learning tools (Nisa et al., 2024). Hold workshops and training for teachers supported by the government. Programs that aim to improve teachers' competencies in A.I. and V.R. technologies can significantly improve their pedagogical skills, as demonstrated by community service initiatives that trained more than 100 teachers. A comprehensive legal framework is needed to address data privacy and accountability, ensuring that A.I. technology is applied responsibly while protecting individual rights (Intani & Annisa, 2024). Stakeholder engagement by holding Focus Group Discussions (F.G.D.s) can reveal insights on the balance between innovation and ethical considerations, guiding policy development (Wahyuningtyas & Singgalen, 2023). While collaborative approaches are promising, challenges such as different stakeholder priorities and the need for continued dialogue could hinder progress. Addressing these challenges is critical to successfully integrating V.R. and A.I. in Indonesia's education landscape. While these policies show hope in improving the quality of education, challenges remain in ensuring equitable access to technology and comprehensive training for all educators.

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Cultural Influence and Values

The use of V.R. and A.I. technology in mathematics learning is also influenced by cultural and content factors. People's culture and values play an essential role in accepting new technologies. In some countries, acceptance of technology may be higher compared to others. Developing V.R. and AI-based learning content relevant to Indonesia's educational curriculum is crucial. However, most V.R. and A.I. content available today is foreign. The lack of quality local content relevant to Indonesia's educational curriculum is an obstacle. This can hinder the effectiveness of technology utilization in mathematics learning, as students may have difficulty understanding content inappropriate for their cultural and linguistic contexts (Asmayawati et al., 2024a). The culture and values of society affect the extent to which new technologies can be accepted and integrated into the education system. In addition, the lack of VR and AI-based learning content in the national education curriculum is an obstacle (Sudipa et al., 2022). Therefore, developing quality local content in the educational curriculum in Indonesia is essential to ensure that this technology can be used effectively and positively impact mathematics learning.

To develop V.R. and AI-based learning content relevant to Indonesia's local culture and context, it is essential to integrate local cultural elements, utilize technology effectively, and ensure adaptability in educational practices. The following strategy can be used to incorporate local cultures. It is leveraging V.R. applications to promote local wisdom and sustainable tourism, as demonstrated by developing a Virtual Reality Destination Experience (V.R.D.E.) model that increases tourist engagement with local culture (Wismantoro et al., 2022). Create interactive content that showcases a wide variety of regions and customs of Indonesian people through augmented reality, preserving cultural heritage while engaging users in gamified learning experiences (Pranata et al., 2018). Use technology-assisted activities, such as drone-assisted virtual field trips, to facilitate intercultural learning and improve students' understanding of local traditions and cultures and can also solve math problems from them (Shadiev et al., 2023). While this strategy emphasizes the importance of local context, it is also essential to remain aware of the potential challenges of balancing technology integration with cultural authenticity, ensuring that content remains relevant and engaging to learners.

Lack of Human Resources and Teacher Training

Human resources also challenge using V.R. and AI technology in mathematics learning. While providing sufficient training for teachers to improve their abilities in using V.R. and A.I. technologies is essential, adequate training is often absent (Alfalah, 2018; Nalubega & Uwizeyimana, 2024b). One of the obstacles is the lack of human resources capable of handling technological problems. With VR and A.I., teachers must transform from conventional teachers to facilitators who can help students learn independently (King et al., 2022). This means that the teaching approach must be significantly changed. Strong support is needed in training and perspective change for teachers to carry out this new role well and support the successful use of technology in mathematics learning.

Based on recent research findings, several strategies can be implemented to improve teachers' access to quality training in utilizing V.R. and A.I. technology in education. Using and following training and some adequate technical support should be tailored to the specific needs of teachers, emphasizing the perceived usability of V.R. and A.I. tools. Research shows that teachers prioritize the benefits of technology over its complexity, suggesting that training should focus on practical applications that improve the quality of teaching (Chen & Zou, 2024). Integrating A.I. tools in classroom learning, the survey showed that while teachers are generally optimistic about A.I., only a quarter actively use A.I. tools. Training should incorporate a broader range of A.I. applications beyond popular tools like ChatGPT, ensuring educators can engage students effectively (Galindo-Domínguez et al., 2024). Using immersive VR environments for teacher training has increased engagement and acceptance, suggesting that the platform can become crucial in developing classroom management skills (Álvarez et al., 2024). Nonetheless, some teachers may refuse to use this technology because they are concerned about its complexity or whether it is relevant to their teaching context. Providing targeted support and demonstrating the benefits of V.R. and A.I. can help reduce barriers and create a more creative educational environment.

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Infrastructure Limitations and the Digital Divide

In mathematics learning, virtual reality (V.R.) and A.I. technologies rely heavily on adequate technological infrastructure—consistent internet access and sufficient hardware (Rompis, 2019). However, the main obstacle is uneven internet access, especially in rural areas. Hardware such as high-spec computers and V.R. headsets are also costly. The digital divide further exacerbates this challenge, as not all students have the same access to technology. This gap can potentially widen the academic achievement gap between students with access to technology and those without access (Asmayawati et al., 2024b). As a result, for V.R. and A.I. technologies to be used equally and effectively in learning, a serious effort must be made to address infrastructure issues and digital disparities.

Several strategies can be implemented to reduce the digital divide in Indonesia and ensure equitable access to V.R. and A.I. technologies for all students. This strategy focuses on increasing digital literacy, improving infrastructure, and developing A.I. literacy. Research shows that men have higher digital literacy than women, especially among the older generation. Bridging this gap requires targeted education programs and access to technology for women and marginalized groups (Long et al., 2023). Increased investment in digital infrastructure, especially in rural areas, is critical to providing all students with the tools they need to learn (Rompis, 2019). Implementing school A.I. literacy programs can help students understand and utilize A.I. tools effectively. A study shows that structured interventions can significantly improve A.I. literacy among elementary students (Relmasira et al., 2023). Recommendations for improving AI-based learning tools include improving features for local languages and contexts, ensuring that all students can benefit from this technology (Utami et al., 2023). While this strategy presents a path to reducing the digital divide, challenges such as resource allocation and different levels of community engagement must be addressed to ensure sustainable progress.

Data Security

The use of V.R. and AI technology in math learning also faces data security issues because A.I. requires vast data collection and analysis of student learning performance. This raises concerns about data privacy and information security. There are possibilities for data misuse, privacy breaches, and cyberattacks (Al-Zahrani, 2024). Therefore, it is crucial to ensure strict regulations and robust procedures are in place to protect data when using this technology (Rahayu et al., 2024). For the use of AI to be done safely and responsibly in math learning, student privacy must be prioritized.

Teachers, schools, and government agencies must work together to protect student data in Indonesia from misuse in the context of V.R. and A.I. technology. Each plays a vital role in ensuring ethical standards and protecting privacy. Teachers are responsible for instilling digital citizenship in their students by emphasizing the responsible use of technology and awareness of privacy issues (Ananto & Ningsih, 2023). Schools must establish clear policies on the ethical use of technology and data privacy and comply with national laws (Sun, 2023). They can interact with policymakers and encourage better protection and transparency in data handling. Governments must be responsible for creating a robust legal framework to protect student data and address the uncertainties that exist in the law. It should drive awareness campaigns about the moral consequences of A.I. and V.R. technologies, which will help educators and educational institutions implement best practices (Arifin & Lennerfors, 2022). Collaborative frameworks are essential, but technological advancements are rapidly outpacing regulations, leaving students vulnerable to data misuse.

CONCLUSION

The study results indicate that although this technology has great potential to improve the quality of learning, several significant challenges remain, including high costs, limited infrastructure, and the technical readiness of teachers and students. Nevertheless, teachers and students generally support the use of this technology because it makes learning more interactive, engaging, and relevant to current developments. Students perceive that virtual reality helps visualize abstract concepts, while artificial intelligence enables more personalized and adaptive learning. However, the success of implementing this technology strongly depends on the readiness and support of the entire education ecosystem. Effective implementation of virtual reality and artificial intelligence in education requires strong support from multiple stakeholders, including governments, schools, and technology developers. A comprehensive implementation strategy, supported by appropriate policies and adequate funding, is

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necessary to overcome these challenges. With proper planning, this technology can effectively enhance students' motivation and understanding of mathematical concepts.

Furthermore, researchers recommend continuous teacher training, the development of technology-based learning materials, and ongoing evaluation. Financial and technical support from governments and educational institutions is also essential to address cost and infrastructure constraints. With careful implementation strategies and sustained support, virtual reality and artificial intelligence technologies have strong potential to positively transform mathematics learning at the high school level.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author Contribution

CIAF: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft, Data Curation, Investigation

YMC: Supervision, Project Administration, Funding Acquisition,

MS: Validation, Visualization, Review & Editing.

MME: Validation, Visualization, Review & Editing.

Conflict of Interest

The authors declare that there is no conflict of interest.

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