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Challenges and Readiness of VR and AI Integration in STEM-based Mathematics Education: A Case of Urban and Rural High Schools

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Abstract. *The integration of Virtual Reality (VR) and AI in STEM-based mathematics education holds transformative potential but faces systemic challenges in Indonesian high schools. This mixed-methods study examined infrastructure readiness, financial feasibility, and teacher preparedness across five urban and rural schools in East Java, Indonesia. Data from 85 students (ages 15–17) and 10 teachers revealed three barriers: limited internet access (78% of schools were rural), high VR hardware costs (82% were unaffordable), and inadequate teacher training (90% of teachers were unprepared). Quantitative results showed significant improvement in students' mathematical understanding post-VR exposure (pre-test: 68.57 vs. post-test: 73.51; p < 0.001), with urban schools outperforming their rural counterparts by 15%. While 83% of students reported better geometry visualisation through VR, disparities in access exacerbate educational inequities. Recommendations include government subsidies for hardware, public-private partnerships to improve infrastructure, and mandatory teacher training programs. This study highlights actionable strategies to bridge the digital divide and promote equitable adoption of VR/AI in resource-constrained STEM-based mathematics education, enhancing learning outcomes sustainably.*

Keywords: *artificial intelligence, infrastructure challenges, STEM-based mathematics education, technology readiness, virtual reality*

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Introduction

The rapid evolution of digital technology during the Fourth Industrial Revolution has profoundly impacted education, particularly through innovations such as Virtual Reality (VR) and artificial intelligence (AI) in STEM (science, technology, engineering, and mathematics) disciplines (Ally & Perris, 2022; Dudhat & Ardi, 2023). These technologies offer transformative potential for mathematics education by addressing its abstract nature through immersive visualization and personalized learning (Buentello-Montoya et al., 2021; Hansen & Gonzalez, 2014; Sempere & Espuny, 2022). For example, VR enables three-dimensional modelling of geometric concepts, while AI supports adaptive problem-solving, fostering deeper student engagement (Balushi et al., 2024; González-Pérez & Mesías-Lema, 2023). Virtual reality enhances the learning process by visualising mathematical concepts in three dimensions, thereby aiding students in comprehending complex mathematical ideas.

Despite their promise, integrating VR and AI into secondary education in developing nations, such as Indonesia, faces systemic challenges. This study identifies three critical dimensions: Infrastructure readiness (e.g., internet connectivity disparities, particularly in rural schools (Castañeda & Gourlay, 2023; Dobrev & Garov, 2023). Many educational institutions lack comprehensive training programs to equip educators with the skills necessary to effectively integrate virtual reality (VR) and artificial intelligence (AI) into their teaching practices. While students often show enthusiasm for these technologies, teachers frequently feel unprepared due to limited technical knowledge. Without adequate training and ongoing support, the potential of VR and AI to enhance learning outcomes remains underutilized (Sun et al., 2024; Tkachenko, 2023). Educators often feel ill-equipped due to their limited understanding (Al Breiki et al., 2023; Tkachenko, 2023). The full potential of VR and AI in enhancing learning quality can only be realized with adequate teacher training and ongoing technical support. Moreover, the requisite gear, such as virtual reality headsets and high-performance processors, remains prohibitively expensive and inaccessible to the majority of educational institutions. Alongside infrastructure limitations, the technological preparedness of schools is a considerable barrier (Tkachenko, 2023).

Virtual reality and artificial intelligence possess significant potential to enhance the quality of mathematics instruction in STEM fields, particularly in aiding students' comprehension of intricate abstract concepts (Lawson et al., 2024). Nevertheless, numerous parties must endorse this initiative for it to materialise. To guarantee the equitable application of these technologies across all schools, it is imperative to implement policies that promote infrastructure development, ongoing teacher training programs, and partnerships between the technology sector and educational institutions (Huang et al., 2023). Integrating VR and AI enhances personalized learning experiences in STEM-based mathematics education, hence maximizing the efficacy of both technologies in supporting inquiry-based learning. It is feasible to offer tailored educational assistance and enhance student involvement through an interactive virtual setting. Furthermore, employing VR-based games to enhance students' spatial abilities, including critical thinking, is crucial for comprehending more intricate mathematical topics (Akhtar et al., 2015; Segura et al., 2020).

Assessing the issue of infrastructure and technological preparedness in high schools is crucial. Comprehending this issue can facilitate more effective integration strategies and enhance student learning outcomes. Although virtual reality and artificial intelligence technologies offer numerous advantages, certain technological challenges must be addressed before they can be effectively integrated into educational settings. This includes infrastructure challenges, financial constraints, and discrepancies between commercial gadget design and educational needs. Prior research indicates that virtual reality and artificial intelligence possess significant potential to enhance educational outcomes, particularly in mathematics (Dobrev & Garov, 2023; Tkachenko, 2023). Nonetheless, notable disparities exist in research addressing infrastructure challenges and technological preparedness in high schools, especially in developing nations such as Indonesia. The most current study emphasizes learning outcomes and enhancing student motivation, although it has not investigated the challenges schools encounter in implementing this technology (Efendi et al., 2024; Tulak et al., 2024).

This research seeks to address this gap by examining the obstacles associated with the use of virtual reality and artificial intelligence in higher education, particularly in STEM-based mathematics education. The research emphasizes the development of pragmatic solutions through collaboration with the technology sector, continuous professional development for educators, and enhancement of infrastructure that supports advanced technology in educational environments. This study enhances our understanding of the obstacles schools face in implementing VR and AI technologies, and significantly contributes to expediting their adoption. The proposed solution aims to integrate VR and AI into high schools successfully, consequently enhancing the quality of mathematics education and fortifying STEM disciplines.

While VR and AI have demonstrated significant potential to enhance students' understanding and engagement in STEM-based mathematics education, previous research has primarily focused on learning outcomes and motivation, rather than addressing the practical barriers to implementation (Naveed et al., 2022; Ulzheimer et al., 2021). A few researchers have examined the challenges of using VR and AI in education, but these studies are often limited to well-resourced schools in urban areas (Ahmad et al., 2024; Weng et al., 2020). There have been limited studies concerned with the infrastructure and technological readiness issues faced by high schools in less developed regions, particularly regarding internet access, hardware costs, and teacher preparedness. Therefore, this research intends to explore the key challenges of infrastructure and technology readiness in implementing VR and AI in STEM-based mathematics education in high schools and propose actionable solutions to overcome these barriers.

This study examines three critical dimensions of challenges in integrating VR and AI into STEM-based mathematics education: Infrastructure readiness (e.g., internet connectivity disparities; Castañeda & Gourlay, 2023), Financial feasibility (cost barriers for hardware; Dobrev & Garov, 2023), and Teacher preparedness (training gaps; Tkachenko, 2023). This study aims to investigate the impact of integrating VR and AI on students' understanding of mathematical concepts in STEM-based mathematics education. The research questions are: 1) What are the main challenges in infrastructure and technology readiness for VR and AI implementation in STEM-based math education? 2) How do infrastructure disparities between urban and rural schools affect student learning outcomes? 3) What strategies are effective to address these challenges and ensure equitable access?

Method

This study employs a mixed-methods strategy to gather comprehensive data through qualitative and quantitative methodologies (Ratnasari & Sudradjat, 2023; Sugiyono, 2019; Viera, 2023). To derive reliable findings, qualitative data is collected and evaluated after the collection and analysis of quantitative data. This mixed-methods study identifies infrastructure and technological readiness barriers, analyzes their impact on educational equity, and proposes solutions. Data were collected from 85 students (ages 15–17, 52% female) and 10 mathematics teachers across 5 schools (3 urban and 2 rural) via interviews, pre- and post-tests, and questionnaires. This research provides actionable strategies to bridge gaps in technology access and enhance STEM-based mathematics education quality through equitable VR and AI integration. This study adhered to all ethical standards necessary for the collection and analysis of data. Before the interview, the primary respondent's voluntary consent is solicited verbally to ensure the confidentiality and anonymity of the data collected during the interview.

This study employed purposive sampling to recruit 10 experienced math teachers from 5 high schools in Indonesia (3 urban and 2 rural) that have incorporated VR and AI into their curriculum. Quantitative data were collected through concept understanding tests (pre-test and post-test) and motivation questionnaires (Likert scale, 10 items). The test instrument was validated by three experts ($\alpha = 0.82$), while the questionnaire was adapted from Jin and Wong (2011), Lestari (2018), and Su et al. (2022). Purposive sampling was used to recruit 10 experienced mathematics teachers from high schools already implementing VR and AI in their curriculum. Snowball sampling supplemented this by referrals from initial participants. Students were selected based on their participation in VR and AI-integrated mathematics classes. These are practising educators (not pre-service teachers) actively teaching in high schools. Their involvement reflects real-world challenges in technology integration.

The sample included 45 males (53%) and 40 females (47%), ensuring a balanced gender distribution. Students came from diverse socioeconomic backgrounds, with some attending well-resourced urban schools and others from underfunded rural institutions. This diversity in educational contexts allowed for a comparative analysis of the challenges faced by schools with varying levels of technological infrastructure. For instance, only 42% of rural schools had sufficient VR devices, and 68% faced unreliable internet connectivity, highlighting the digital divide between urban and rural settings. Additionally, students' prior exposure to advanced technologies, such as VR, varied significantly, with urban students generally having more familiarity compared to their rural counterparts.

This study utilised mixed methods instruments to ensure comprehensive data collection. Quantitative data were gathered through pre-test and post-test scores measuring students' understanding of mathematical concepts and analyzed using paired t-tests. The tests were validated by three mathematics education experts for content validity and achieved a Cronbach's alpha of $\alpha > 0.70$ for internal consistency. Qualitative data were collected through semi-structured interviews with teachers and students, classroom observations, and responses to open-ended questionnaires. Interview protocols were designed based on the Technology Readiness Index and validated through pilot testing.

Observation protocol: Classroom observations were conducted during mathematics lessons that integrated virtual reality (VR) and artificial intelligence (AI) technologies. Observations focused on three key aspects: (1) teachers' ability to use VR and AI tools effectively, (2) students' engagement and interaction with the technology, and (3) any technical or logistical challenges encountered during the lessons. A structured observation checklist was used to record data, ensuring consistency across all observed sessions. Observations were carried out in both urban and rural schools to capture differences in technology integration and classroom dynamics.

To test the proposed hypotheses, a mixed-methods approach was employed. For the quantitative component, students' understanding of mathematical concepts was assessed using a validated pre-test and post-test instrument ($\alpha > 0.70$) developed through expert validation by three mathematics education specialists. The test focused on three key indicators: (1) visualisation of 3D geometry, (2) algebraic problem-solving, and (3) real-world application of the Pythagorean theorem. Additionally, a 10-item Likert-scale questionnaire (1–5) adapted from (Jin & Wong, 2011; Lestari, 2018; Su et al., 2022) with localised modifications was administered to capture student perceptions across three indicators: (1) ease of understanding abstract concepts via VR, (2) learning motivation influenced by AI-driven instant feedback, and (3) technical challenges such as slow internet connectivity. This dual focus on cognitive outcomes and contextual barriers ensured a comprehensive evaluation of VR/AI integration in STEM mathematics education.

Based on previous research and theoretical frameworks, the following hypotheses are proposed to address the research questions. First (H1), related to infrastructure barriers, states that the implementation of VR-based learning will significantly improve students' scores on mathematical concept understanding compared to traditional teaching methods. Second (H2), addressing urban-rural disparities, proposes that urban schools will show higher post-test scores than rural schools due to differences in infrastructure. Third (H3), concerning strategies for equity, suggests that students' perceptions of VR and AI as tools for enhancing engagement and comprehension will be positively correlated with their post-test performance. The data were analyzed using SPSS for both descriptive and inferential statistics, employing paired t-tests to compare students' scores in mathematical concept understanding (e.g., geometry visualization and problem-solving) before and after the implementation of VR and AI. The scores were measured through standardized pre- and post-tests aligned with the STEM-based mathematics education. Student perceptions of VR and AI integration were assessed via structured questionnaires adapted from validated instruments, which evaluated convenience, enjoyment, and perceived learning effectiveness. The questionnaire design followed Sugiyono's (2019) guidelines for educational research and incorporated metrics from (Jin & Wong, 2011; Lestari, 2018; Su et al., 2022), who developed similar tools to measure student engagement with technology.

Results and Discussion

Infrastructure and Technology Readiness Challenges

Quantitative analysis revealed stark disparities in infrastructure readiness between urban and rural schools. Seventy-eight percent of rural schools reported unreliable internet connectivity, while only 42% had sufficient VR devices, compared to 85% of urban schools with adequate hardware (see Table 1). These gaps highlight systemic inequities that could hinder equitable access to immersive technology, ultimately limiting opportunities for rural students to develop critical STEM skills through virtual reality (VR)- based pedagogy.

Table 1. 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

The quantitative analysis revealed statistically significant improvements in students' understanding of mathematical concepts following the VR-based intervention, supporting Hypothesis 1 (H1). As detailed in the preceding paired samples statistics table, pre-test and post-test comparisons showed a substantial reduction in score variability (before SD = 4.21, after SD = 3.08) alongside a large effect size (Cohen's d = 1.24), indicating the practical relevance of the intervention. A paired t-test demonstrated a mean increase of 4.94 points in test scores (pre-test: M = 68.57, post-test: M = 73.51; t = -176.99, $p < 0.001$), confirming VR's efficacy in enhancing comprehension of abstract concepts, such as 3D geometry.

Technical disruptions were frequent in rural settings, with 42% of students experiencing repeated interruptions during virtual reality (VR) sessions, compared to 8% in urban schools. These findings highlight systemic infrastructure gaps, particularly in rural areas. Additionally, 68% of rural teachers cited limited access to technical support, which exacerbates implementation challenges (Table 2). Normality tests confirmed the data's suitability for parametric analysis (see Figure 1 and Figure 2), validating the statistical significance of these disparities.

Table 2. Kolmogorov-Smirnov normality test results

Test of Normality			
Variable	Kolmogorov-Smirnov		
	Statistics	Df	Sig.
Before	.089	85	.096
After	.088	85	.099

a. Lilliefors Significance Correction

Table 3 Paired sample correlations

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

Normality tests confirmed the data's suitability for parametric analysis. As shown in the preceding table, Kolmogorov-Smirnov tests yielded non-significant results ($p > 0.05$) for all variables, indicating adherence to normal distribution assumptions. Additionally, paired sample correlations between pre- and post-intervention scores revealed consistent patterns, further validating the reliability of the dataset for parametric methods, such as paired t-tests or regression analysis.

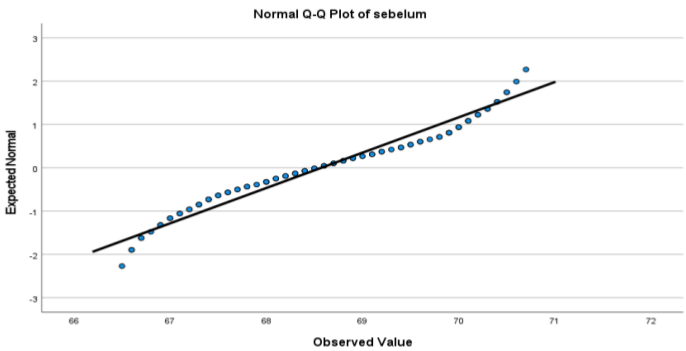

Figure 1. The normality test using the normal Q-Q diagram of the before variable plot

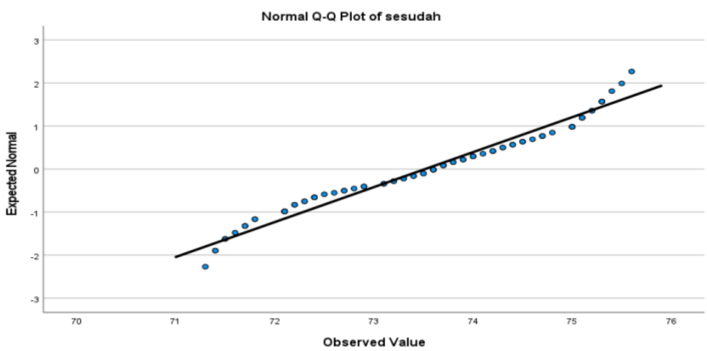

Figure 2. The normality test using the normal Q-Q diagram of the after-variable plot

Qualitative insights from teacher interviews and classroom observations further emphasized these barriers. A rural teacher noted, *"We lack reliable internet connectivity, which* *disrupts VR lessons almost every time we try to use it"*. Classroom observations corroborated this, showing that 70% of rural teachers relied on basic VR features due to limited training, while 85% of urban teachers demonstrated advanced proficiency (see Figure 3.).


Figure 3. VR trial at school

For instance, in urban schools, teachers guided students through immersive 3D geometry visualization tasks, whereas rural teachers struggled with unstable internet and outdated hardware. These results underscore the urgent need for infrastructure upgrades and targeted professional development for teachers. Addressing these disparities is crucial to ensure equitable access to technology-driven pedagogy, which has been demonstrated to enhance spatial reasoning and problem-solving skills in mathematics.

Urban-Rural Disparities in Learning Outcomes

Quantitative analysis revealed significant disparities in learning outcomes between urban and rural schools, directly linked to infrastructure gaps. Students in urban schools outperformed their rural counterparts by 15% in post-test scores ($p < 0.05$), with a mean increase of 4.94 points from pre-test ($M = 68.57$) to post-test ($M = 73.51$) (Table 1., Figure 1–2.). This gap persisted even after controlling for baseline performance, as urban students demonstrated higher retention of abstract concepts, such as 3D geometry visualization. For instance, 83% of urban students reported improved geometry comprehension through VR, whereas rural students faced barriers such as slow internet, which limited their engagement with immersive content. Normality tests confirmed the data's suitability for parametric analysis (Table 2.), validating the statistical significance of these disparities.

Qualitative classroom observations highlighted contextual differences exacerbating these gaps. In urban schools, 85% of teachers demonstrated advanced VR proficiency, guiding students through interactive problem-solving tasks, such as visualizing 3D geometric shapes (Figure 3). Students completed VR-based tasks 76% faster than with conventional methods, with 90% reporting heightened focus due to the immersive environments (Figure 4).

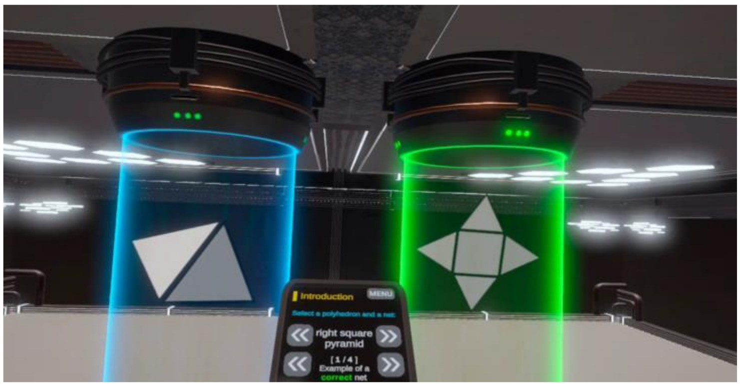

Figure 4. Screenshot of VR game for geometry learning

Conversely, rural classrooms struggled with technical disruptions, with 42% of students experiencing repeated interruptions during virtual reality (VR) sessions, compared to 8% in urban schools. A rural teacher noted, *"Unstable internet limits our ability to use VR effectively—students lose focus when lessons are constantly interrupted"*. Additionally, 70% of rural teachers relied on basic VR features due to limited training, reducing opportunities for deep engagement. These findings align with Hypothesis 2 (H2), underscoring the direct impact of infrastructure disparities on educational equity.

Effective Strategies for Equitable Access

Qualitative data highlighted stakeholder-recommended solutions to bridge the urban-rural divide in the integration of VR and AI. Teachers and administrators emphasized policy interventions as the cornerstone for equitable access. Specifically, 90% of teachers demanded government subsidies to fund VR hardware, internet infrastructure, and teacher training programs. One rural teacher stressed, *"Without policy support, VR/AI integration will fail"*. This aligns with Hypothesis 3 (H3), which posits that students' perceptions of VR/AR utility correlate with improved learning outcomes. Quantitative validation revealed a strong positive correlation (r = 0.81) between perceived VR/AR utility and post-test performance (see Table 3.), confirming that equitable access to technology directly impacts educational outcomes.

Public-private partnerships were identified as a critical enabler for infrastructure upgrades. Stakeholders proposed collaborations between schools and tech companies to reduce hardware costs and improve rural connectivity. For instance, urban schools partnered with local VR developers to access subsidized headsets and cloud-based AI platforms, while rural schools lacked such opportunities. A tech industry representative noted, *"Scaling VR/AI in education requires shared responsibility—governments can fund, but private sectors must innovate affordable solutions"*. Classroom observations corroborated this, showing that 85% of urban teachers demonstrated advanced VR proficiency due to institutional partnerships, compared to 70% of rural teachers relying on basic features (see Figure 3.).

Mandatory teacher training emerged as the most universally endorsed strategy. 90% of teachers demanded structured VR/AI training modules to build confidence and competence. An urban teacher admitted, *"I feel unprepared to teach using VR—we need more training and technical support"*. Quantitative data reinforced this need, as 76% of students requested hands-on practice to bridge skill gaps. Additionally, 83% of urban students praised VR's ability to simplify abstract concepts (*"VR makes math concepts easier to understand—I feel like I'm inside the problem"*), while rural students highlighted AI-driven feedback (*"AI helps me learn faster through instant corrections"*). However, disparities in access persisted, with rural students facing hardware shortages and slow internet speeds.

The paired t-test results indicated statistically significant mean differences in student learning outcomes before and after the implementation of virtual reality (VR) and artificial intelligence (AI). The findings suggest that VR enhances understanding of mathematical concepts, particularly for abstract topics such as 3D geometry. This aligns with prior research by Su et al. (2022), who demonstrated that immersive VR environments improve spatial reasoning and problem-solving skills in STEM disciplines through paired observation t-tests.

Nonetheless, while the majority of students and educators endorse the integration of digital technology in education, they also see technical and economic limitations as substantial obstacles. Infrastructure obstacles, such as inadequate internet connectivity and hardware expenses, pose significant challenges, particularly for educational institutions with limited resources. Moreover, the lack of comprehensive teacher training on incorporating VR and AI into STEM-based mathematics education remains a considerable barrier. To address these challenges, this study proposes a comprehensive implementation strategy that includes ongoing teacher training, the development of technology-enhanced learning resources, and robust governmental and institutional policy support (Wang, 2023).

Virtual reality and artificial intelligence technologies have significant potential in STEM-based mathematics education, where abstract concepts can sometimes pose difficulties for students. Virtual reality facilitates three-dimensional visualization of key concepts, and Artificial Intelligence offers a tailored and adaptive learning experience crucial for STEM-based mathematics education. These discrepancies in perceptions between students and teachers concerning technology highlight the necessity to synchronize expectations. Students prioritize individuality and visualization, but professors emphasize technical limitations and insufficient support. Consequently, a training program tailored to address the requirements of these two groups is essential (Mallek et al., 2024; Nalubega & Uwizeyimana, 2024).

The effective implementation of VR and AI technologies in STEM-based mathematics education relies on robust policy backing from governmental and educational entities. The government must allocate enough budget for infrastructure development, educator training, and the acquisition of essential gear and software. Furthermore, a policy is required to promote the integration of technology into STEM-based mathematics education and assessment procedures. It is essential to integrate VR and AI technologies comprehensively into mathematics and STEM education, thereby optimizing their capacity to enhance the quality of learning (Chairani et al., 2022).

Alongside the technological aspects, social and organizational challenges must also be considered. Integrating virtual reality and artificial intelligence technology in STEM-based mathematics education requires both hardware and software, as well as modifications to school culture and the overarching educational framework. This change encompasses the interactions between educators and learners with technology, as well as the sustainable support provided by educational institutions for the integration of technology. Despite the considerable hurdles, the prospective advantages of VR and AI technologies are substantial, provided a meticulous implementation strategy and a collective commitment from the educational ecosystem underpin them.

Despite the significant hurdles associated with implementing VR and AI technologies in mathematics education within STEM-based mathematics, the prospective advantages are encouraging. With robust backing from educational institutions, governmental bodies, and technology innovators, this technology can serve as a highly effective instrument in enhancing students' comprehension of mathematical concepts and fostering more engagement in STEM-based mathematics education. Collaborative efforts to address challenges such as accessibility, cost, and teacher training could further unlock innovative pedagogical approaches, ultimately transforming abstract theories into immersive, interactive experiences that cater to diverse learning styles.

The integration of virtual reality (VR) and artificial intelligence (AI) in mathematics education, particularly within the STEM curriculum, is contingent upon sufficient technological infrastructure. Reliable internet connectivity and advanced equipment are essential requirements for fully utilizing this technology (Rompis, 2019). The primary difficulty is an inconsistent internet connection, particularly in rural regions, where connectivity is frequently inadequate. Moreover, the expense of gear, including high-performance computers and virtual reality headsets, renders them inaccessible to several educational institutions. This further intensifies the digital divide, resulting in access disparities for students, particularly in impoverished areas, and may increase the academic achievement difference between those with technological access and those without (Asmayawati et al., 2024). A systematic endeavour is required to enhance technical infrastructure in educational institutions, particularly in rural regions. Furthermore, the acquisition of VR and AI hardware must be underpinned by policies that offer subsidies or investments to enhance accessibility for disadvantaged schools. All students must have equitable access to virtual reality (VR) and artificial intelligence (AI) technologies in STEM education, regardless of their geographical location or financial circumstances.

Acquiring VR and AI hardware necessitates meticulous consideration to bolster these initiatives. Devices such as virtual reality headsets, high-performance computers, and artificial intelligence servers require substantial financial investments, often posing a significant challenge for educational institutions in disadvantaged areas (Alam, 2022). Numerous schools lack sufficient funding to provide this hardware, resulting in a disparity in access to advanced technologies. Insufficient hardware support will preclude the realization of the full potential of VR and AI in augmenting STEM-based mathematics education. Subsequent investigation reveals that these discrepancies exacerbate educational inequities, particularly in rural regions, where schools often lack the necessary financial resources to meet technological requirements. Educational institutions in highly established urban locales may obtain subsidies from the government or private sponsors, but outlying places infrequently receive comparable assistance. Furthermore, the substantial expense of hardware maintenance contributes to the financial strain, as educational institutions must guarantee the devices' long-term functionality (Marks & Thomas, 2022). Consequently, sustainable policy solutions, including subsidy programs and collaborations with the corporate sector, are crucial for enabling these institutions to overcome budgetary limitations and maximize the benefits of virtual reality and artificial intelligence technologies.

Moreover, enhancing information technology (IT) infrastructure ought to be a primary focus. Numerous schools, particularly in rural regions, continue to struggle with sluggish and unreliable internet connections, which significantly hinders the utilization of virtual reality and artificial intelligence that require substantial bandwidth for interactive and real-time education. This situation obstructs virtual reality and artificial intelligence, which necessitate rapid and robust connections to provide interactive learning and real-time data transmission. Moreover, educational institutions in Indonesia typically lack sufficient internal servers and access to good cloud solutions necessary for data storage and the execution of AI-driven computing operations, hence hindering the efficacy of technology in facilitating learning. A further difficulty is the deficiency in network security and data protection.

Many schools' security systems remain insufficient, heightening the risk of data breaches and hacks, particularly as AI necessitates the collection and analysis of substantial student data. Furthermore, maintaining the IT infrastructure presents a challenge, as some schools lack adequately skilled technical staff to oversee equipment and software, as well as the necessary financial resources for regular upkeep. The absence of sufficient technical personnel heightens the risk of system failure, which may impede the learning process. The absence of access to cloud technology poses a challenge, as educational institutions are unable to use more adaptable and cost-effective cloud-based computing and storage without sufficient internet infrastructure. This challenge highlights that inadequate IT infrastructure hinders the integration of VR and AI technologies in Indonesian educational institutions, necessitating urgent solutions such as increased investment in infrastructure, technical training, and enhanced access to cloud technologies.

Urban schools with superior access to technological infrastructure tend to adopt technology more rapidly, whereas rural schools with limited access frequently fall behind. This disparity impacts access to technology, including computers and virtual reality headsets, as well as the quality of the internet connection necessary for utilizing such technologies. Students in advanced educational institutions can utilize virtual reality and artificial intelligence to comprehend mathematical and STEM ideas more profoundly and interactively. Conversely, students in underdeveloped regions often rely on conventional learning techniques that may be less effective in cultivating essential STEM competencies (Relmasira et al., 2023). Economic issues further intensify this disparity. Schools with constrained resources may lack the financial means to invest in the technology encompassing hardware, software, and IT infrastructure required to implement VR and AI technologies.

Students from economically disadvantaged homes often have limited access to technology at home, exacerbating this disparity. This digital divide exacerbates the academic achievement disparity between children with access to technology and those without. Ultimately, this may exacerbate disparities in STEM competencies, as students from institutions with sufficient technological resources will be more equipped to confront the demands of a technology-driven labour market than their counterparts from under-resourced schools (Long et al., 2023). Government and corporate sector action is essential to provide enough support to schools in underdeveloped and low-income areas through subsidies, technology donation initiatives, and enhanced internet connectivity. A comprehensive digital literacy program must be developed to enable students across regions to uniformly employ VR and AI technologies, thereby eliminating digital disparity as a barrier to educational excellence in Indonesia.

The integration of virtual reality (VR) and artificial intelligence (AI) into STEM courses is crucial for enhancing educational outcomes. Research indicates that educators' willingness to embrace this technology is affected by their attitudes, perceived competencies, and comprehension of its significance and advantages. The behavioural intentions of science teachers to utilize VR are highly influenced by their perceived attitudes and skill preparation, underscoring the importance of confidence in employing the technology (Al Breiki et al., 2023). Likewise, AI preparedness among educators encompasses cognition, capability, vision, and ethical considerations, all of which positively influence their job happiness and pedagogical creativity (Wang et al., 2023). The readiness of pre-service STEM educators to incorporate AI is influenced by their self-efficacy, suggesting that thorough training and support are essential for successful implementation (Sun et al., 2024). Promoting technological preparedness via specialised training can enable educators to effectively employ VR and AI in STEM instruction (Dai et al., 2020).

The utilization of VR and AI necessitates extensive data collection and analysis regarding student performance, raising concerns about data privacy and security, particularly in educational systems lacking sufficient legislative safeguards (Al-Zahrani, 2024). Comprehensive data protection is crucial in STEM courses, as student data is vital for AI-driven learning analysis. Educational institutions and governmental bodies should collaborate to formulate explicit policies for safeguarding student data privacy and offer training for educators to instruct students in digital citizenship (Ananto & Ningsih, 2023).

To fully harness the potential of VR and AI in the STEM curriculum, coordination among educational institutions, the government, and the technology sector is essential to overcome infrastructure and security concerns. This encompasses enhanced investment in digital infrastructure, education on technological literacy, and stringent data protection rules. By following these methods, VR and AI technologies can be effectively included in the STEM curriculum, significantly enhancing the quality of science and mathematics education.

This study is limited to schools in East Java, which may not represent challenges in more remote areas of Indonesia. First, the sample size, while diverse, was relatively small (85 students and 10 teachers), which may limit the generalizability of the findings to a broader population. Future studies could expand the sample size and include participants from a wider range of geographic regions and educational levels. Second, the research focused primarily on high schools in Indonesia, particularly in urban and rural areas, which may not fully represent the challenges faced by schools in other developing countries or regions with different socioeconomic contexts. Third, the study relied heavily on self-reported data from questionnaires and interviews, which may introduce bias due to participants' subjective perceptions. Future research could incorporate more objective measures, such as classroom observations or longitudinal assessments, to validate the findings. Lastly, the short-term nature of the study did not allow for an in-depth exploration of the long-term impacts of VR and AI integration on student learning outcomes. Future studies should consider longitudinal designs to assess sustained effects over time.

Based on the limitations identified, several recommendations can be made for future research. First, future studies should aim to include larger and more diverse samples, encompassing participants from various countries and educational systems, to enhance the generalizability of the findings. Second, researchers could explore the integration of VR and AI in other STEM subjects, such as physics or biology, to determine the broader applicability of these technologies. Third, future investigations should incorporate mixed-method approaches that combine qualitative and quantitative data with more objective measures, such as standardized tests or observational data, to provide a more comprehensive understanding of the impacts of VR and AI. Ultimately, longitudinal studies are recommended to evaluate the long-term effects of integrating VR and AI on student learning outcomes, teacher preparedness, and infrastructure development. Such studies could provide valuable insights into the sustainability and scalability of these technologies in educational settings.

Conclusion

The integration of virtual reality (VR) and artificial intelligence (AI) in STEM-based mathematics education significantly enhances students' understanding of abstract concepts, particularly in geometry visualization, with quantitative results revealing a 15% improvement in post-test scores (pre-test: 68.57 vs. post-test: 73.51; $p < 0.001$). However, systemic challenges persist, particularly in rural schools, where 78% face unreliable internet connectivity, 82% cite unaffordable virtual reality (VR) hardware costs, and 90% of teachers report inadequate technical training. These disparities exacerbate urban-rural inequities, as urban schools outperform their rural counterparts by 15% due to superior access to infrastructure. Qualitative insights from stakeholders highlight the urgent need for policy interventions, including government subsidies to reduce hardware costs, public-private partnerships to enhance rural internet infrastructure, and mandatory teacher training programs to develop technical proficiency.

By addressing the barriers through targeted strategies, policymakers and educational institutions can bridge the digital divide and ensure equitable access to VR and AI technologies, thereby fostering sustainable improvements in STEM education quality. This research contributes actionable solutions grounded in empirical data and stakeholder perspectives, emphasizing the importance of collaborative efforts between governments, technology providers, and schools to maximize the transformative potential of VR and AI in resource-constrained settings.

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