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An Integrative Model of Learning Quality: The Contribution of Augmented Reality, Virtual Reality, and Principals' Digital Leadership in elementary Schools

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Abstract

The rapid development of digital technology has encouraged the integration of immersive technologies and digital leadership to improve learning quality in elementary education. However, the implementation of Augmented Reality (AR), Virtual Reality (VR), and principals' digital leadership remains limited, particularly in rural schools. This study aimed to examine the effects of AR utilization, VR utilization, and principals' digital leadership on learning quality in public elementary schools in Jumo District, Temanggung Regency, Indonesia. A quantitative approach with an explanatory and ex post facto design was employed. The study involved 64 respondents, consisting of 48 teachers and 16 principals from 16 public elementary schools, selected through total sampling. Data were collected using Likert-scale questionnaires and analyzed using descriptive statistics and multiple linear regression with IBM SPSS version 26. The findings indicated that AR utilization significantly affected learning quality (R^2 = 0.517), followed by VR utilization (R^2 = 0.546) and principals' digital leadership (R^2 = 0.384). Simultaneously, the three variables explained 72.6% of the variance in learning quality (R^2 = 0.726), with AR emerging as the most dominant predictor. The novelty of this study lies in the development of an integrative model combining immersive technologies and digital leadership to explain learning quality in rural elementary schools. The findings provide practical implications for strengthening digital transformation and technology-based learning ecosystems in elementary education.

Introduction

Digital transformation has fundamentally reshaped the educational paradigm toward more adaptive, collaborative, and student centered learning. In the era of Society 5.0, information and communication technologies (ICT) are no longer regarded as supplementary tools but as strategic components for developing educational ecosystems capable of fostering twenty first century competencies, including critical thinking, creativity, collaboration, communication, and digital literacy (AlGerafi et al., 2023; Tene et al., 2024; Zhao et al., 2023). Despite these developments, improving learning quality remains a major challenge, particularly in developing countries such as Indonesia. The results of the Programme for International Student Assessment (PISA) indicate that Indonesian students continue to perform below the OECD average in reading, mathematics, and science literacy. These findings suggest that current instructional practices have not yet fully succeeded in developing higher-order thinking skills and problem-solving abilities. Therefore, improving learning quality requires not only curriculum reform but also innovative instructional approaches supported by technologies capable of creating meaningful, contextualized, and interactive learning experiences. Understanding the factors associated with learning quality has consequently become an

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important research priority in educational management, particularly within the context of ongoing digital transformation.

Learning quality is a fundamental indicator of educational effectiveness because it reflects the extent to which instructional processes achieve intended educational objectives. High quality learning is characterized by systematic instructional planning, interactive teaching practices, appropriate utilization of learning media, and continuous assessment that facilitates students' cognitive, affective, and psychomotor development (Ismaniati, 2022; Tuerah & Tuerah, 2023; Mulyasa, 2021; Sagala, 2020). Likewise, Hamalik (2019) and Uno (2020) argue that learning quality is reflected in students' behavioral changes resulting from effective educational interactions within supportive learning environments. Previous studies have consistently demonstrated that learning quality is increasingly influenced by teachers' ability to integrate digital technologies into classroom instruction, thereby enhancing student engagement, learning motivation, and conceptual understanding. A systematic review by Ibáñez and Delgado-Kloos (2018) revealed that digital technology integration significantly improves conceptual understanding and learning outcomes, whereas Makransky and Lilleholt (2018) demonstrated that immersive technology-based learning environments promote both cognitive and emotional engagement, leading to more effective learning experiences.

Among the most promising innovations in educational technology are immersive learning technologies, particularly Augmented Reality (AR) and Virtual Reality (VR). These technologies facilitate the presentation of instructional content through three-dimensional visualization, interactive simulations, and authentic learning experiences that surpass conventional instructional media. Numerous studies have reported that AR enhances students' learning motivation, classroom participation, conceptual understanding, and problem-solving skills (Ibáñez & Delgado-Kloos, 2018; Ismail et al., 2019; Rachim et al., 2024; Fadilasari & Nugraheni, 2025; Rosita, 2025). Similarly, VR has been shown to improve student engagement, knowledge retention, immersive learning experiences, and academic achievement (Makransky & Lilleholt, 2018; Wu et al., 2020; Makransky & Mayer, 2022; Supriadi & Hignasari, 2019; Tsaaqib et al., 2022; Tene et al., 2024). More recent systematic reviews further conclude that integrating AR and VR simultaneously strengthens students' cognitive, affective, and psychomotor development, making immersive technologies a promising approach for improving learning quality across educational contexts (AlGerafi et al., 2023; Tene et al., 2024; Zekeik et al., 2025).

Nevertheless, the successful implementation of immersive technologies depends not only on the availability of technological infrastructure and teachers' digital competencies but also on school principals' ability to lead digital transformation effectively. As instructional and digital leaders, school principals play a strategic role in establishing organizational vision, institutional policies, innovative cultures, and professional support systems that facilitate technology integration into teaching and learning. Sheninger (2019) defines digital leadership as the strategic use of technology to foster innovation, strengthen professional learning, and enhance communication and collaboration throughout educational organizations. Likewise, Kasim and Surya (2025) argue that digital leadership encompasses organizational change management and human resource development to support technology driven educational transformation. Empirical studies have demonstrated that principals' digital leadership significantly contributes to teachers' digital competence, technology integration, and the overall quality of instructional practices (Hamzah et al., 2021; Aufar & Setia, 2023; Yuliati et al., 2025).

Despite the growing evidence supporting immersive technologies, their implementation in Indonesian elementary schools remains limited. Preliminary observations conducted in 16

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public elementary schools in Jumo District, Temanggung Regency, revealed that most teachers still rely primarily on traditional lecture-based instruction, textbooks, and simple presentation media. Only approximately 35% of teachers actively utilize AR in classroom instruction, while VR adoption remains minimal. Furthermore, around 60% of teachers exhibit low levels of digital competence, and only about 15% are capable of integrating digital technologies effectively into instructional activities. Similar limitations were identified regarding principals' digital leadership. Most schools have yet to establish systematic digital transformation strategies, professional development programs for teachers remain limited, and financial support for technology-based instructional innovation is still insufficient. These findings indicate that digital transformation in elementary schools has not yet been optimally implemented because it lacks the necessary synergy among technological readiness, teachers' digital competence, and principals' digital leadership.

Previous studies have extensively examined the roles of AR in enhancing students' motivation, engagement, and conceptual understanding (Fadilasari & Nugraheni, 2025; Ibáñez & Delgado-Kloos, 2018; Ismail et al., 2019; Rachim et al., 2024; Rosita, 2025), the contribution of VR to learning outcomes, immersive learning experiences, and knowledge retention (Makransky & Lilleholt, 2018; Makransky & Mayer, 2022; Supriadi & Hignasari, 2019; Tene et al., 2024; Tsaaqib et al., 2022; Wu et al., 2020), and the role of principals' digital leadership in promoting technology integration and teachers' professional competence (Hamzah et al., 2021; Aufar & Setia, 2023; Sheninger, 2019; Yuliati et al., 2025). However, these variables have generally been examined separately, primarily in secondary or higher education contexts, with academic achievement or learning outcomes serving as the principal dependent variables. Comparatively little attention has been devoted to examining learning quality as a multidimensional construct encompassing instructional planning, implementation, assessment, learning outcomes, and the learning environment. Furthermore, empirical evidence remains limited regarding the extent to which AR utilization, VR utilization, and principals' digital leadership are jointly associated with learning quality in rural elementary school contexts. Consequently, an important empirical gap remains concerning the development of an integrated explanatory model capable of examining the predictive relationships among these variables within elementary education.

To address these gaps, this study proposes an integrative model that examines the predictive relationships among Augmented Reality utilization, Virtual Reality utilization, principals' digital leadership, and learning quality. The novelty of this study lies in simultaneously investigating these three predictors within the perspective of educational management to explain how immersive learning technologies and digital leadership are collectively associated with learning quality in elementary schools. Conducted in sixteen public elementary schools in Jumo District, Temanggung Regency, this study extends empirical evidence concerning the implementation of immersive learning technologies in rural primary education, where digital infrastructure and teachers' digital readiness remain relatively limited. Specifically, this study aims to analyze the predictive contributions of Augmented Reality utilization, Virtual Reality utilization, and principals' digital leadership to learning quality. Rather than establishing causal relationships, the study seeks to identify the relative contributions of these predictors and develop an integrative model for understanding learning quality in the context of digital transformation. The findings are expected to contribute to the advancement of educational management theory while providing practical implications for policymakers, school leaders, and teachers in designing sustainable technology-supported learning environments for elementary education.

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Methods

This study employed a quantitative approach using a cross-sectional explanatory research design with an ex post facto approach. The quantitative approach was selected to examine the predictive relationships among Augmented Reality (AR) utilization, Virtual Reality (VR) utilization, principals' digital leadership, and learning quality in public elementary schools in Jumo District, Temanggung Regency, Indonesia. Since all variables were observed under naturally occurring conditions without experimental manipulation, the study adopted an ex post facto design. Furthermore, because all data were collected at a single point in time, the study represents a cross-sectional survey. Accordingly, the findings are interpreted as associations and predictive relationships rather than causal effects.

The study was conducted from January to June 2025 in sixteen public elementary schools located in Jumo District, Temanggung Regency, Indonesia. The research setting was selected because these schools had begun implementing digital learning practices, demonstrated varying levels of teachers' digital competence and technological infrastructure, and represented rural educational contexts where empirical studies on immersive learning technologies and principals' digital leadership remain limited.

The study population consisted of all Grade IV, Grade V, and Grade VI classroom teachers from the sixteen public elementary schools. A total of 48 teachers participated in the study, representing three classroom teachers from each school. Since the target population was relatively small and fully accessible, a saturated sampling (total sampling) technique was employed, whereby all eligible teachers were included as research participants. Consequently, the unit of analysis in this study was the individual teacher (n = 48), while the sixteen schools served as the research setting rather than the analytical unit.

All research variables, including Augmented Reality utilization (X_1), Virtual Reality utilization (X_2), principals' digital leadership (X_3), and learning quality (Y), were measured through teachers' perceptions using self-administered questionnaires. Teachers reported their own implementation of AR and VR during classroom instruction, evaluated learning quality in their classrooms, and assessed their principals' digital leadership based on their professional experiences and daily interactions within the school. Therefore, all variables were measured at the same analytical level (teacher level), eliminating concerns regarding cross-level data integration or clustered observations. The demographic characteristics of the respondents are presented in Table 1.

Table 1. Characteristics of the Research Respondents

Respondents	Frequency	Percentage (%)
Grade IV Teachers	16	33.33
Grade V Teachers	16	33.33
Grade VI Teachers	16	33.33
Total	48	100.00

The study included three independent variables and one dependent variable. The independent variables comprised Augmented Reality utilization (X_1), Virtual Reality utilization (X_2), and principals' digital leadership (X_3), whereas the dependent variable was learning quality (Y). Each variable was operationalized into several dimensions and indicators, as presented in Table 2.

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Table 2. Operational Definition of Research Variables

Variable	Code	Dimensions	Number of Indicators
Augmented Reality Utilization	X_1	Integration of real and virtual environments, real-time interaction, three-dimensional object visualization, contextual learning, and student engagement	15
Virtual Reality Utilization	X_2	Visual presentation, user interaction, immersive experience, learning engagement and motivation, and ease of use	15
Principals' Digital Leadership	X_3	Digital vision and strategy, digital competence and literacy, teachers' digital capacity development, digital instructional leadership, and digital innovation and collaboration culture	20
Learning Quality	Y	Instructional planning, instructional implementation, learning assessment, learning outcomes and impacts, and learning environment	15

Based on these operational definitions, a structured questionnaire was developed to measure each construct. The indicators were derived from established theories and previous empirical studies concerning immersive learning technologies, digital educational leadership, and instructional quality. To improve measurement reliability and adequately represent each construct, every indicator was operationalized into three questionnaire statements reflecting different behavioral manifestations of the same dimension. Consequently, the fifteen indicators of AR utilization, VR utilization, and learning quality generated forty-five questionnaire items for each variable ($15 \times 3 = 45$), whereas the twenty indicators of principals' digital leadership generated sixty questionnaire items ($20 \times 3 = 60$).

The questionnaire consisted of four sections completed entirely by classroom teachers. The first section measured AR utilization, the second assessed VR utilization, the third evaluated principals' digital leadership, and the fourth measured learning quality. Representative questionnaire items included: "I integrate AR applications to explain abstract concepts" (AR utilization), "VR activities increase students' engagement during learning" (VR utilization), "The principal encourages teachers to integrate digital technologies into classroom instruction" (digital leadership), and "Learning activities actively involve students in meaningful participation" (learning quality).

Table 3. Distribution of Research Instrument Items

Variable	Code	Number of Dimensions	Number of Items
Augmented Reality Utilization	X_1	5	45
Virtual Reality Utilization	X_2	5	45
Principals' Digital Leadership	X_3	5	60
Learning Quality	Y	5	45
Total		20	195

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Prior to the main survey, the questionnaire underwent content validation by three experts in educational management and educational technology to evaluate the relevance, clarity, and representativeness of each item. Recommendations provided by the experts were incorporated before the instrument was administered. Subsequently, a pilot study was conducted involving teachers from public elementary schools outside the research sample who possessed characteristics similar to those of the target respondents. Construct validity was evaluated using Pearson Product–Moment item-total correlation. Items with corrected item-total correlation coefficients greater than 0.30 and significance values below 0.05 were considered valid. The obtained item-correlation coefficients ranged from 0.46–0.82 for AR utilization, 0.44-0.84 for VR utilization, 0.48–0.86 for principals' digital leadership, and 0.45-0.81 for learning quality.

Internal consistency reliability was assessed using Cronbach's alpha coefficient. The reliability coefficients were 0.931 for AR utilization, 0.938 for VR utilization, 0.957 for principals' digital leadership, and 0.926 for learning quality, indicating excellent reliability for all research instruments.

Data were collected from March to May 2025 following approval from the District Education Office and participating schools. Eligible respondents were active Grade IV, Grade V, and Grade VI classroom teachers who had been teaching at their respective schools during the 2024/2025 academic year. Before data collection, all respondents received an explanation regarding the study objectives and procedures and voluntarily agreed to participate by providing informed consent. The questionnaires were administered directly by the researchers during scheduled school visits. All forty-eight distributed questionnaires were returned and completed, resulting in a response rate of 100%. The questionnaires were examined immediately after collection to ensure completeness. Since no missing responses were identified, no data imputation procedures were required. To provide contextual support for interpreting the quantitative findings, classroom observations and document analyses were also conducted. Classroom observations focused on teachers' implementation of AR- and VR-supported learning activities, while document analysis examined lesson plans, digital learning programs, and school policies related to technology integration. These qualitative data were used solely to strengthen the interpretation of the quantitative findings and were not included in the regression analysis.

Data analysis was performed using IBM SPSS Statistics version 26 based on responses from the forty-eight teacher participants. Descriptive statistics were first computed to summarize the characteristics of each research variable. Prior to hypothesis testing, multiple regression assumptions were evaluated using regression residual diagnostics. Normality was assessed using the Shapiro–Wilk test, linearity through ANOVA tests of linearity, multicollinearity using Tolerance and Variance Inflation Factor (VIF) values, heteroscedasticity using the Glejser test, and influential observations using Cook's Distance. Subsequently, multiple linear regression analysis was employed to examine the predictive relationships between AR utilization, VR utilization, principals' digital leadership, and learning quality. Partial regression coefficients were evaluated using t-tests, whereas the overall regression model was assessed using the F-test. The Adjusted R^2 coefficient was calculated to estimate the proportion of variance in learning quality explained jointly by the independent variables. Statistical significance was established at $\alpha = 0.05$. Because all variables were measured from the same respondents at the teacher level, no cross-level data integration or aggregation procedures were required. To reduce the possibility of common method bias, procedural remedies were implemented, including respondent anonymity, voluntary participation, clear questionnaire instructions, and separating questionnaire sections according to the measured constructs.

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Nevertheless, because all variables were collected through self-reported questionnaires at a single point in time, the findings should be interpreted with appropriate caution.

Results and Discussion

Descriptive Statistics of the Research Variables

All statistical analyses were conducted using data obtained from 48 classroom teachers (n = 48) representing Grades IV, V, and VI across sixteen public elementary schools in Jumo District, Temanggung Regency. The teachers served as respondents for all research variables, including Augmented Reality (AR) utilization, Virtual Reality (VR) utilization, principals' digital leadership, and learning quality.

Descriptive statistics were calculated to summarize the characteristics of each research variable. The results showed that all variables exhibited relatively high average scores with moderate variability, indicating that the implementation of digital learning and school digital leadership had generally been perceived positively by the respondents. Because the digital leadership instrument consisted of 60 questionnaire items whereas the remaining variables contained 45 items, comparisons were conducted using mean scores per item rather than raw total scores. The average score per item for learning quality was 4.10, followed by AR utilization (4.04), principals' digital leadership (3.98), and VR utilization (3.87) on a five-point Likert scale. These results indicate that learning quality received the highest overall evaluation, whereas VR utilization showed comparatively greater opportunities for improvement. A summary of the descriptive statistics is presented in Table 4.

Table 4. Descriptive Statistics of the Research Variables

Variable	Mean	Mean Per Item	Standard Deviation
Learning Quality (Y)	184.58	4.10	7.75
AR Utilization (X_1)	181.77	4.04	8.07
VR Utilization (X_2)	174.35	3.48	8.48
Digital Leadership (X_3)	238.73	11.18	11.18

Instrument Validity and Reliability

Prior to hypothesis testing, the questionnaire underwent validity and reliability evaluation as described in the Methods section. Item validity was assessed using Pearson Product-Moment corrected item-total correlations, whereas internal consistency reliability was evaluated using Cronbach's alpha coefficients. The corrected item-total correlation coefficients ranged from 0.346 to 0.798 for Augmented Reality (AR) utilization, 0.339 to 0.814 for Virtual Reality (VR) utilization, 0.342 to 0.815 for principals' digital leadership, and 0.396 to 0.785 for learning quality. All corrected item-total correlation coefficients exceeded the minimum acceptable criterion of 0.334, indicating that every questionnaire item adequately represented its intended construct and was therefore considered valid. The reliability analysis further demonstrated excellent internal consistency across all research variables. Cronbach's alpha coefficients were 0.954 for AR utilization (45 items), 0.961 for VR utilization (45 items), 0.971 for principals' digital leadership (60 items), and 0.965 for learning quality (45 items). Since all Cronbach's alpha values substantially exceeded the recommended threshold of 0.70, the instruments were considered highly reliable and appropriate for subsequent statistical analyses

Assumption Testing

Before performing multiple linear regression analysis, the underlying statistical assumptions were evaluated using regression residual diagnostics. Normality was assessed using the

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Shapiro–Wilk test, linearity using the deviation-from-linearity test, heteroscedasticity using the Glejser test, and multicollinearity using tolerance and Variance Inflation Factor (VIF) values. The results indicated that all assumptions required for multiple linear regression analysis were satisfied. Specifically, all variables were normally distributed (Shapiro–Wilk $p > 0.05$), the relationships between each independent variable and learning quality were linear (deviation-from-linearity $p > 0.05$), no evidence of heteroscedasticity was detected (Glejser $p > 0.05$), and multicollinearity was absent, as tolerance values ranged from 0.557 to 0.711 and VIF values ranged from 1.406 to 1.796. A summary of the assumption testing results is presented in Table

Table 5. Summary of the Assumption Tests

Assumption Test	Statistical Result	Interpretation
Normality (Shapiro–Wilk)	Learning Quality: W = 0.982, p = 0.665; AR: W = 0.967, p = 0.193; VR: W = 0.976, p = 0.442; Digital Leadership: W = 0.965, p = 0.154	All variables were normally distributed
Linearity (Deviation from Linearity)	AR → Learning Quality: F = 1.665, p = 0.115; VR → Learning Quality: F = 2.758, p = 0.210; Digital Leadership → Learning Quality: F = 0.587, p = 0.899	Linear relationships were confirmed
Multicollinearity	Tolerance = 0.557–0.711; VIF = 1.406–1.796	No multicollinearity
Heteroscedasticity (Glejser Test)	AR: p = 0.205; VR: p = 0.524; Digital Leadership: p = 0.373	No heteroscedasticity

Hypothesis Testing

Pearson correlation analysis demonstrated statistically significant positive relationships between each independent variable and learning quality. AR utilization showed a strong positive association with learning quality ($r = 0.719$, $p < 0.001$). Simple regression analysis further indicated that AR utilization explained 51.7% of the variance in learning quality ($R^2 = 0.517$). The resulting regression equation was: $\hat{Y}=59.166+0.690X_1$. These findings indicate that higher levels of AR utilization were associated with higher perceived learning quality.

VR utilization also demonstrated a strong positive relationship with learning quality ($r = 0.739$, $p < 0.001$). The regression model explained 54.6% of the variance in learning quality ($R^2 = 0.546$), producing the following regression equation: $\hat{Y}=66.777+0.676X_2$. Among the three simple regression models, VR utilization exhibited the largest coefficient of determination, indicating the strongest individual predictive contribution to learning quality.

Principals' digital leadership was likewise positively associated with learning quality ($r = 0.620$, $p < 0.001$). The regression model accounted for 38.4% of the variance in learning quality ($R^2 = 0.384$), with the regression equation: $\hat{Y}=82.076+0.429X_3$**.** These results indicate that stronger digital leadership was associated with better perceived learning quality, although its predictive contribution was smaller than those of AR and VR utilization.

Multiple Regression Analysis

The analysis produced a multiple correlation coefficient of $R = 0.852$, indicating a very strong collective relationship between the independent variables and learning quality. The overall regression model was statistically significant ($F(3,44) = 38.958$, $p < 0.001$), demonstrating

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that the three predictors jointly explained a substantial proportion of variance in learning quality. The model yielded an R^2 of 0.726 and an Adjusted R^2 of 0.708, indicating that approximately 72.6% of the variance in learning quality could be explained jointly by AR utilization, VR utilization, and principals' digital leadership, while the remaining 27.4% was attributable to variables beyond the scope of the present study. The resulting regression equation was $\hat{Y} = 12.997 + 0.410 X_1 + 0.360 X_2 + 0.144 X_3$. The regression coefficients are summarized in Table 6.

Table 6. Multiple Regression Results

Variable	B	Beta	t	p
Constant	12.997	–	0.803	0.426
AR Utilization	0.410	0.428	4.572	<0.001
VR Utilization	0.360	0.393	3.723	0.001
Digital Leadership	0.144	0.207	2.088	0.043

The standardized regression coefficients indicate that AR utilization emerged as the strongest predictor within the multiple regression model ($\beta = 0.428$), followed by VR utilization ($\beta = 0.393$) and principals' digital leadership ($\beta = 0.207$). It is important to distinguish this finding from the separate regression analyses, where VR utilization explained a slightly larger proportion of variance ($R^2 = 0.546$) than AR utilization ($R^2 = 0.517$). Thus, AR should be interpreted as the strongest predictor only after controlling simultaneously for the effects of VR utilization and principals' digital leadership. Overall, the findings demonstrate that higher levels of AR utilization, VR utilization, and principals' digital leadership were positively associated with better perceived learning quality among elementary school teachers. These associations support the proposed research hypotheses while remaining consistent with the cross-sectional ex post facto design adopted in this study, which identifies predictive relationships rather than causal effects.

The findings of this study indicate that Augmented Reality (AR) utilization is positively and significantly associated with learning quality ($r = 0.719$, $p < 0.001$), explaining 51.7% of the variance in learning quality ($R^2 = 0.517$). These findings suggest that greater integration of AR into classroom instruction is associated with higher perceived learning quality. The use of three-dimensional visualization, real-time interaction, and the integration of real and virtual environments enables students to experience learning that is more concrete, contextual, and meaningful. These findings support the constructivist theories of Piaget and Vygotsky, which emphasize that knowledge is constructed through learners' active interaction with their learning environment. Furthermore, the findings reinforce Mayer's Cognitive Theory of Multimedia Learning (CTML), which argues that combining text, images, audio, animation, and interactive visualization enhances conceptual understanding while reducing students' cognitive load. The present findings are consistent with those of Ibáñez and Delgado-Kloos (2018) and Sirakaya and Kılıç (2019), who reported that AR improves students' motivation, engagement, and academic achievement. Moreover, the systematic review conducted by Akçayır and Akçayır (2017) concluded that AR consistently enhances learning motivation, interest, conceptual understanding, and student engagement, while the meta-analysis by Garzón and Acevedo (2019) demonstrated its positive effects on academic achievement, knowledge retention, and higher-order thinking skills. Likewise, Anum and Apriyanto (2025) found that mobile augmented reality strengthens inquiry-based learning and students' problem-solving abilities. Unlike previous studies that primarily focused on learning outcomes or student motivation, this study employed learning quality as the dependent variable, encompassing instructional planning, instructional implementation, assessment,

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learning outcomes, and the learning environment. In addition, the research was conducted in rural elementary schools, thereby extending empirical evidence that AR remains relevant despite limited digital infrastructure and teachers' technological competencies. Because the present study adopted a cross-sectional ex post facto design, the findings should be interpreted as indicating a predictive relationship rather than direct causality. These findings suggest that the successful implementation of AR is closely associated with teachers' ability to design interactive and contextual learning experiences. Therefore, improving learning quality may require strengthening teachers' digital competencies, expanding digital infrastructure, and establishing policies that promote the sustainable integration of AR into classroom instruction.

The findings also reveal that Virtual Reality (VR) utilization is positively and significantly associated with learning quality ($r = 0.739$, $p < 0.001$), explaining 54.6% of the variance in learning quality ($R^2 = 0.546$). Among the three separate regression analyses, VR demonstrated the largest coefficient of determination, indicating the strongest individual predictive contribution to learning quality. These results suggest that immersive and simulation-based learning experiences are associated with higher levels of student engagement, making learning more authentic, engaging, and meaningful. These findings support Kolb's Experiential Learning Theory, which emphasizes that effective learning is achieved through direct experience. They also reinforce the Cognitive Affective Model of Immersive Learning (CAMIL), which explains that immersive learning environments enhance learners' attention, motivation, emotional engagement, and knowledge retention. The findings are consistent with those reported by Wu et al. (2020), Makransky and Mayer (2022), and AlGerafi et al. (2023), who concluded that VR improves academic achievement, learning motivation, student engagement, and overall learning experiences. Similarly, Radianti et al. (2020) demonstrated that VR positively influences instructional effectiveness by providing immersive learning experiences. Pottle (2019) and Alam et al. (2024) argued that VR enables simulations of situations that are difficult to recreate in conventional classrooms, while Gavish et al. (2015) found that the combined use of VR and AR enhances procedural skills, problem-solving abilities, and conceptual understanding. More recent studies have also consistently reported that VR improves student engagement and learning outcomes across different educational levels (Annisa et al., 2025; Styadi & Istiyowti, 2025; Al-Khalidy et al., 2024; Radita, 2025). A major contribution of this study lies in examining VR implementation within rural elementary schools, a context that has received limited scholarly attention. Furthermore, learning quality was adopted as a more comprehensive outcome variable than academic achievement alone. The present findings indicate that greater utilization of VR is associated with better perceived learning quality rather than demonstrating a direct causal influence. Consequently, schools should be supported through the provision of technological infrastructure, continuous teacher training, and policies that encourage the systematic integration of VR into instructional practices.

The results demonstrate that principals' digital leadership is positively and significantly associated with learning quality, explaining 38.4% of the variance ($R^2 = 0.384$). Although this predictive contribution is smaller than those of AR and VR utilization, digital leadership remains an important organizational factor associated with learning quality. These findings support Sheninger's (2019) Digital Leadership framework, which positions school principals as change agents responsible for developing a digital vision, fostering an innovative school culture, and enhancing teachers' digital competencies. The findings are also consistent with Distributed Leadership Theory, which emphasizes teacher empowerment and organizational collaboration as essential drivers of school improvement. The results are in agreement with the findings of Hamzah et al. (2023) and Aufar and Setia (2023), who reported that digital

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leadership strengthens technology integration, improves teachers' digital competencies, and enhances instructional effectiveness. Recent studies further suggest that successful technology implementation depends on principals' ability to formulate a digital vision, manage organizational change, and build teachers' professional capacity (Helmie et al., 2022). In addition, digital leadership plays a critical role in fostering an innovative culture that supports the adoption of AR and VR technologies (Chen et al., 2024), while supportive school policies, technological infrastructure, and continuous professional development are essential factors for successful technology integration (Surya et al., 2025; Kibat et al., 2023). Unlike previous studies that mainly associated digital leadership with teacher performance or organizational effectiveness, this study specifically examined its relationship with learning quality. The findings indicate that stronger perceptions of principals' digital leadership are associated with higher perceived learning quality, although the study design does not permit causal inference. Consequently, strengthening principals' digital leadership through continuous professional development and mentoring should become a strategic priority for supporting improvements in instructional quality.

The multiple regression analysis indicates that AR utilization, VR utilization, and principals' digital leadership jointly explain 72.6% of the variance in learning quality (Adjusted $R^2 = 0.708$), indicating a strong predictive relationship between the three variables and learning quality. These findings suggest that higher learning quality is associated with the combined presence of immersive learning technologies and supportive digital leadership. From a theoretical perspective, the findings support the Technological Pedagogical Content Knowledge (TPACK) framework developed by Mishra and Koehler. Within this framework, AR and VR represent the technological dimension, while principals' digital leadership functions as the contextual factor that enables effective technology integration. The findings also align with Systems Theory, which conceptualizes schools as integrated systems whose effectiveness depends on the interaction among leadership, teachers, technology, and the learning environment. The results are further supported by recent studies demonstrating that successful digital learning depends on the synergy among technology, pedagogy, and organizational support (Samala et al., 2025). The integration of AR and VR, supported by strong digital leadership, creates more interactive, collaborative, and student-centered learning environments (Anwar et al., 2025). Several systematic reviews have likewise concluded that immersive technologies achieve optimal educational outcomes when accompanied by teachers' digital competence, appropriate pedagogical strategies, and a school ecosystem that supports digital transformation (Anderson, 2023). Importantly, the standardized regression coefficients revealed that AR utilization emerged as the strongest predictor only within the multiple regression model ($\beta = 0.428$), followed by VR utilization ($\beta = 0.393$) and principals' digital leadership ($\beta = 0.207$). This finding should be interpreted together with the separate regression analyses, in which VR utilization explained a slightly larger proportion of variance ($R^2 = 0.546$) than AR utilization ($R^2 = 0.517$). Therefore, AR should be regarded as the strongest predictor only after the simultaneous influence of VR utilization and principals' digital leadership has been statistically controlled. The primary contribution of this study lies in developing an integrative model that links AR, VR, and principals' digital leadership in explaining learning quality in rural elementary schools. Rather than demonstrating causal effects, the findings identify a pattern of predictive relationships suggesting that successful digital transformation in elementary education is associated with the integration of immersive learning technologies, teacher digital competence, and supportive school leadership. From a practical perspective, the findings highlight the need for integrated policies involving the government, educational authorities, and schools to support the implementation of AR and VR technologies, enhance teachers' digital competencies, and strengthen principals' digital

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leadership capacities. The synergy among these three components is expected to foster an innovative, adaptive, and sustainable digital learning ecosystem capable of supporting continuous improvements in learning quality.

Conclusion

This study demonstrates that Augmented Reality (AR) utilization, Virtual Reality (VR) utilization, and principals' digital leadership are positively and significantly associated with learning quality in public elementary schools in Jumo District, Temanggung Regency, both individually and collectively. In the separate regression analyses, AR utilization explained 51.7% of the variance in learning quality, VR utilization explained 54.6%, and principals' digital leadership explained 38.4%. When examined simultaneously, the three variables jointly accounted for 72.6% of the variance in learning quality, indicating that higher levels of learning quality are associated with the combined implementation of immersive learning technologies and supportive digital leadership.

The findings further indicate that Virtual Reality demonstrated the largest individual predictive contribution in the separate regression analyses, whereas Augmented Reality emerged as the strongest predictor only in the multiple regression model, as reflected by the largest standardized regression coefficient ($\beta = 0.428$), followed by VR ($\beta = 0.393$) and principals' digital leadership ($\beta = 0.207$). These findings suggest that the integration of AR and VR contributes to more interactive, contextual, and immersive learning experiences, while principals' digital leadership provides organizational support that facilitates teachers' digital practices, promotes innovation, and strengthens the implementation of technology-enhanced learning.

This study extends the Technological Pedagogical Content Knowledge (TPACK) framework, the Cognitive Theory of Multimedia Learning (CTML), Experiential Learning Theory, and Digital Leadership Theory by demonstrating that learning quality is closely associated with the complementary roles of immersive learning technologies and digital leadership. The principal contribution of this study lies in the development of an integrative model linking AR utilization, VR utilization, and principals' digital leadership to explain learning quality in rural elementary school contexts, where technological infrastructure and digital readiness remain uneven.

From a practical perspective, the findings highlight the importance of strengthening the digital learning ecosystem through continuous professional development for teachers, wider integration of AR- and VR-supported instructional practices, and sustained capacity building for principals' digital leadership. Although the cross-sectional ex post facto design does not permit causal inference, the identified predictive relationships provide useful empirical evidence to support educational policies and school improvement initiatives aimed at fostering innovative, adaptive, and sustainable digital learning environments in elementary education.

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