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The Impact of Technology-Driven Adaptive Learning on Mathematical Conceptual Mastery in Primary Education

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Abstrack

This study examines the impact of technology-driven adaptive learning on elementary students' mastery of mathematical concepts. Using a quantitative quasi-experimental design, sixth-grade students were assigned to experimental and control groups. The experimental group received four weeks of instruction via Quipper School Premium, an AI-based adaptive platform, while the control group engaged in traditional learning. A 25-item conceptual understanding test was administered, and data were analyzed through validity, reliability, normality, and homogeneity tests, followed by an Independent Samples t-test. Results revealed a significant improvement in the experimental group's post-test scores ($t = 6.85$; $p < 0.001$), indicating that adaptive learning enhances conceptual mastery through personalized pacing and real-time feedback. Implications include targeted teacher training in adaptive analytics, integration of adaptive modules into the Merdeka Curriculum, equitable access to devices, and secure data governance. Findings highlight the potential of AI-powered personalized learning to strengthen foundational mathematics, particularly in developing country contexts.
Keywords: adaptive strategy, educational technology, concept understanding, basic mathematics

Abstrak

Penelitian ini mengkaji dampak pembelajaran adaptif berbasis teknologi terhadap penguasaan konsep matematika pada siswa sekolah dasar. Dengan menggunakan desain quasi-eksperimental kuantitatif, siswa kelas enam dibagi menjadi kelompok eksperimen dan kelompok kontrol. Kelompok eksperimen menerima empat minggu instruksi melalui Quipper School Premium, platform adaptif berbasis kecerdasan buatan (AI), sementara kelompok kontrol mengikuti pembelajaran tradisional. Ujian pemahaman konsep berisikan 25 soal diberikan, dan data dianalisis melalui uji validitas, reliabilitas, normalitas, dan homogenitas, diikuti dengan uji t sampel independen. Hasil menunjukkan peningkatan signifikan pada skor ujian akhir kelompok eksperimen ($t = 6{,}85$; $p < 0{,}001$), menunjukkan bahwa pembelajaran adaptif meningkatkan penguasaan konsep melalui penyesuaian kecepatan belajar yang personal dan umpan balik real-time. Implikasi meliputi pelatihan guru yang ditargetkan dalam analitik adaptif, integrasi modul adaptif ke dalam Kurikulum Merdeka, akses yang adil terhadap perangkat, dan tata kelola data yang aman. Temuan ini menyoroti potensi pembelajaran personalisasi yang didukung AI dalam memperkuat matematika dasar, terutama dalam konteks negara berkembang.
***Keywords**: strategi adaptif, teknologi pendidikan, pemahaman konsep, matematika dasar*

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INTRODUCTION

Education in the 21st century is characterized by the acceleration of information and communication technology, which has fundamentally changed the paradigm of learning (Flood et al., 2020). In a global context, this transformation necessitates that education systems prioritise knowledge transfer and foster the development of critical thinking, creativity, collaboration, and effective communication skills (Oughton et al., 2024). One of the fundamental challenges that remains a concern for many countries, including Indonesia, is the low quality of mathematics learning at the elementary school level (Hilz et al., 2023). Mathematics is a crucial foundation for developing advanced cognitive abilities and problem-solving skills in real-life and further academic studies (Bayounes et al., 2022). Unfortunately, national and international assessments indicate that elementary school students' understanding of basic mathematical concepts falls short of expectations (Hallinen et al., 2021). The importance of early mathematics learning extends not only to the numerical aspect but also to the mastery of fundamental concepts, including numbers, operations, patterns, measurement, and geometry (Apoki et al., 2022).

This problem is exacerbated by the predominance of uniform instructional methods that fail to accommodate diverse learner needs. Traditional classrooms often ignore variations in students' cognitive development, learning styles, and prior knowledge. Within this context, Vygotsky's theory of constructivism and the concept of the Zone of Proximal Development (ZPD) offer a strong theoretical foundation. Adaptive technology supports scaffolding by dynamically adjusting instructional content to match each learner's current ability, enabling students to learn within their ZPD through personalized pacing and feedback (Pardamean et al., 2022; Sayed et al., 2023).

A deep mastery of these concepts provides a strong cognitive foundation for students to think abstractly and solve complex problems in the future (Mazon et al., 2023). However, in practice, many students face difficulties understanding these concepts because the learning approaches are uniform and unresponsive to differences in learning styles and individual abilities (Castaldi et al., 2021). Traditional "one-size-fits-all" classroom learning often fails to accommodate the unique needs of each student, especially those at the extremes of ability, both below and above average (Eglington & Pavlik, 2023).

This problem becomes even more crucial when considering that Indonesian students' mathematical competence remains relatively low, as indicated by various international indicators (Almarashdi & Jarrah, 2022). According to the 2019 Trends in International Mathematics and Science Study (TIMSS) report, Indonesia ranked 45th out of 58 countries in mathematics competency among fourth-grade students, with an average score of 397, which is far below the international average of 500 (Mullis et al., 2020). Additionally, the results of the Programme for International Student Assessment (PISA) in 2018 showed that 71% of Indonesian students were at the lowest level of mathematical ability, namely level 1 and below, meaning they could only perform basic mathematical procedures without understanding the underlying concepts (OECD, 2019). This condition reflects the weakness in conceptual construction, which is the core of accurate mathematical understanding.

One of the causes of students' low understanding of mathematical concepts is the lack of adaptive learning strategies that cater to the diverse characteristics of students (Hawes et al., 2021). Students have different cognitive backgrounds, learning styles, motivations, and learning speeds. However, conventional learning systems tend to adopt a homogeneous approach that ignores these individual dimensions (Reinhold et al., 2020).

This is where technology has tremendous transformative potential. In recent decades, digital technology has opened up opportunities to develop more personalized and adaptive learning approaches that can adjust content, pace, and material presentation to each student's needs in real-time (Aşiksoy, 2019). Technology-based adaptive learning strategies enable systems to analyze student responses and automatically adjust learning activities to suit their ability profiles and interests best (Holstein et al., 2020). Given the significant challenges in developing deep conceptual understanding at the elementary level, the urgency to implement technology-based adaptive strategies in mathematics learning is increasing.

Based on data from the Ministry of Education, Culture, Research, and Technology (Kemendikbudristek, 2023), 62% of fourth-grade elementary school students struggled to understand fractions, and 58% of students were unable to explain the concept of multiplication operations conceptually (Hardiansyah et al., 2022). This data was obtained from the results of the National Computer-Based Assessment, one of the tools used to measure student competencies in Indonesia. These figures indicate that most students are still learning mathematics procedurally, relying on memorizing formulas without a thorough understanding of the underlying concepts (Hardiansyah et al., 2024).

On the other hand, internal survey results from an independent educational research institution show that schools implementing adaptive technology-based learning have experienced an average increase in conceptual understanding of 23% in one semester (Jing et al., 2023). For example, implementing an Artificial Intelligence (AI)-based adaptive platform in 15 elementary schools in Jakarta and Bandung showed that students with low initial scores could improve by two competency levels compared to students who followed conventional learning (Zuluaga et al., 2020). This data demonstrates the effectiveness of technology-based adaptive approaches and reinforces the argument that this approach is highly relevant and worthy of broader implementation to address the challenges of mathematics learning quality at the elementary level.

This study was designed to address several key questions within this context. First, can technology-based adaptive learning strategies significantly improve elementary school students' understanding of mathematical concepts? Second, how do the learning outcomes of students who follow technology-based adaptive learning approaches differ from those who follow conventional methods? Third, what components of adaptive strategies contribute most to improving conceptual understanding? These questions form the basis of the research questions to be answered through a quasi-experimental approach with elementary school students. The primary objective of this study is to investigate the impact of technology-based adaptive strategies on the mathematical and conceptual understanding of elementary school students. This study also aims to evaluate the effectiveness of this strategy compared to conventional methods and identify the most effective aspects or features of adaptive technology in supporting meaningful mathematics learning. The results of this study can significantly contribute to the development of a more contextual, personalized, and evidence-based mathematics learning model.

Several previous studies have demonstrated the significant potential of technology-based learning approaches in enhancing learning outcomes. For example, research Saal & Graham (2023) in the Educational Evaluation and Policy Analysis journal shows that computer-based adaptive technology can improve academic achievement by up to 30% in students with special learning needs. Another study Ökördi & Molnár (2022) in Computers & Education shows that personalization of learning through AI-based systems significantly improves concept understanding in elementary school students. However, most of these studies are still limited to developed countries and secondary education, so their validity in developing countries, such as Indonesia, still needs to be empirically tested. Furthermore, most existing studies generally evaluate learning outcomes without distinguishing between procedural and conceptual understanding (Körtesi et al., 2022; Martín Díaz et al., 2023). Conceptual understanding has unique characteristics not always reflected in test scores or quantitative achievements alone (Essa et al., 2023). Therefore, a significant gap in the literature needs to be addressed, specifically the need for empirical research that examines the effect of technology-based adaptive strategies on mathematical concept understanding in elementary school students, taking into account local characteristics and real-world conditions.

This study addresses these gaps by empirically testing the hypothesis that technology-driven adaptive learning significantly enhances students' conceptual understanding of mathematics compared to conventional methods. Specifically, it examines how personalized feedback and real-time adaptation impact the mastery of mathematical concepts among Grade 4 students. By focusing on conceptual comprehension, an essential but often overlooked cognitive domain, this research adds a new dimension to the discourse on educational technology effectiveness. In doing so, the study contributes to both theory and practice. Theoretically, it bridges constructivist learning principles with AI-supported personalized learning. The findings can inform the development of national digital curricula under the Merdeka Curriculum framework and provide evidence-based recommendations for teacher training and education policy in Indonesia. Ultimately, the study supports a shift toward inclusive, data-driven, and learner-centered mathematics instruction that is grounded in context and pedagogically sound.

METHOD

This study used a quantitative approach with a quasi-experimental design. This design was chosen based on practical and ethical considerations in elementary education, where the complete randomization of subjects (true experimental design) is challenging due to administrative limitations and school regulations. The quasi-experimental design enables researchers to assess the impact of a treatment (in this case, technology-based adaptive learning strategies) on a dependent variable (mathematical concept understanding), while maintaining sufficient control over internal validity through the use of a control group. The design used in this study is a Non-Equivalent Control Group Design, in which there are two groups: an experimental group that receives learning with technology-based adaptive strategies and a control group that receives conventional mathematics learning. To ensure comparability, both groups were selected from parallel classes within the same school, sharing similar characteristics in terms of student numbers, gender distribution, socioeconomic background, and prior academic achievement, as determined by semester report scores. A pre-test was administered to both groups before the intervention to assess their baseline understanding of mathematical concepts, confirming that there were no statistically significant differences in their initial abilities. This procedure ensured that any observed differences in post-test performance could be more confidently attributed to the treatment rather than pre-existing disparities. Both groups were given a pre-test before the treatment and a post-test after the treatment to measure changes in their understanding of mathematical concepts.

The population in this study was all fourth-grade elementary school students who had implemented the Merdeka Curriculum and had access to digital learning devices. From this population, a sample of 60 students was selected and divided into two parallel classes in one public elementary school. Sampling was conducted using class-based random sampling. The two classes had homogeneous characteristics in terms of the number of students, gender ratio, socioeconomic background, and previous academic achievement, as indicated by semester reports. Randomization was done using the simple random technique to determine which class would be the experimental class and which would be the control class. This approach was essential to minimize selection bias and increase internal validity, despite the sampling context not allowing for random assignment of individuals.

The primary instrument in this study was a mathematical conceptual understanding test comprising 25 multiple-choice items with four answer options. These items were developed based on the Basic Competencies in the national curriculum for Grade IV and aligned with six conceptual understanding indicators adapted from Bloom's revised taxonomy: (1) explaining concepts verbally or symbolically, (2) classifying mathematical objects, (3) providing examples and non-examples, (4) representing concepts in different forms, (5) connecting interrelated concepts, and (6) applying concepts in contextual situations. The item construction process began with operationalizing each indicator into measurable learning outcomes, followed by formulating question stems and plausible distractors that reflect common misconceptions in mathematics. Three subject-matter experts in mathematics education and pedagogy validated the content, ensuring alignment with conceptual understanding rather than procedural recall. Items were then piloted with a small group of students to check clarity, difficulty level, and discriminatory power before finalization.

Table 1.
Indicators of the Mathematics Conceptual Understanding Test Instrument

Conceptual Understanding Indicator	**Basic Competency**
Explaining concepts verbally or symbolically	Explaining the meaning of fractions and numbers
Classifying mathematical objects	Grouping types of two-dimensional shapes
Providing examples and non-examples of a concept	Identifying even numbers and non-even numbers
Representing concepts in different forms	Converting fractions into decimal form
Connecting interrelated concepts	Linking multiplication operations with repeated addition
Applying concepts in contextual situations	Using the concept of area in real-life problem-solving

Over the course of four weeks, the experimental group received mathematics instruction through Quipper School Premium, an AI-based adaptive learning platform. Each week consisted of three learning sessions, each lasting approximately 60 minutes. Sessions were conducted in the school's computer lab under the supervision of the class teacher, who had received prior training on platform usage and monitoring tools. Before the intervention began, teachers and students had a brief orientation session. Teachers were instructed to track students' progress through the platform's analytics dashboard, while students were guided on logging in, navigating the interface, and responding to questions.

The adaptive system in Quipper School Premium operates by analyzing student responses in real time using an AI-driven diagnostic algorithm. Correct answers allow the learner to progress to more advanced items. At the same time, incorrect responses trigger the delivery of scaffolded hints, supplementary explanations, or remedial practice questions tailored to the identified misconception. The platform's algorithm adapts both the difficulty level and the pacing of content, ensuring that each student learns within their optimal Zone of Proximal Development (ZPD). Additionally, the system generates weekly performance reports for teachers, highlighting individual strengths, areas for improvement, and suggested follow-up tasks. Teachers used these reports to provide targeted feedback and brief one-on-one coaching sessions when needed. This structured integration of adaptive technology ensured that the intervention was not merely a substitution of media but a transformation of the learning process into a personalized, data-driven experience.

Data analysis in this study consisted of several stages. First, validity testing was conducted to ensure that each test item measured the intended indicator of mathematical conceptual understanding. Item validity was examined using the Pearson Product-Moment correlation between individual item scores and the total test score, with items considered valid if rcount>rtable at p<0.05p. Second, reliability testing was performed using Cronbach's Alpha, with a value of $\alpha \geq 0.70$ indicating high internal consistency. Before hypothesis testing, normality was assessed using the Shapiro–Wilk test (recommended for $N < 100$), and homogeneity of variance was checked using Levene's Test. Only when these assumptions were met was the Independent Samples t-test applied to compare post-test scores between the experimental and control groups.

In addition to statistical significance testing, the effect size was calculated to assess the magnitude of the intervention's impact. Cohen's *d* was computed using the mean difference between groups divided by the pooled standard deviation, with interpretation following Cohen's (1988) criteria: minor (0.2), medium (0.5), and large (0.8). This provides an indicator of practical significance beyond the *p*-value, showing how meaningful the difference is in real educational contexts. For robustness, eta-squared (η^2) was also computed from the *t*-test results to quantify the proportion of variance in conceptual understanding explained by the intervention. Including these measures enables a more comprehensive evaluation of the effectiveness of the adaptive learning strategy.

RESULT AND DISCUSSION

The study results are presented in two main sections: (1) description of data and inferential statistics from the pretest and posttest results, and (2) hypothesis testing to determine the significance of the differences between the two groups. Before hypothesis testing, prerequisite tests, namely, normality and homogeneity tests, were conducted to determine the appropriate statistical test. Next, a comparison of the posttest results between the two groups was conducted to assess the impact of implementing technology-based adaptive strategies on the improvement of mathematical concept understanding. The results of this analysis provide an in-depth empirical description of the effectiveness of the learning intervention, thereby strengthening the theoretical and practical foundations of technology-based adaptive learning models at the elementary education level.

Table 2.
Summary of Item Validity Test Results

Item No	r_{count}	r_{table} (N = 60, α = 0.05)	Validity Status
1–25	0.445 – 0.631	0.254	All items valid

Based on the results of the item validity test using Pearson's correlation between item scores and total scores, the r_{calculated} value for all items was above the r_{table} value of 0.254 at a significance level of α = 0.05 and a total number of respondents of 60 students. The calculated values ranged from 0.445 to 0.631, indicating that all items had a positive and significant correlation with the total test score. Thus, all 25 items were declared valid and suitable for measuring the mathematical concept understanding of fourth-grade students. This high validity indicates that each item can represent the measured concept indicators and has good discriminative power against students' overall abilities.

Table 3.
Result of Reliability Test Using Cronbach's Alpha

Instrument	Number of Items	Cronbach's Alpha (α)	Status
Conceptual Understanding Mathematics Test	25	0.872	High reliability

Reliability testing was conducted to determine the internal consistency of the test instrument using Cronbach's Alpha approach. The results showed that the α value was 0.872, above the standard threshold of 0.70 commonly used in research. This indicates that the test instrument has high internal consistency, so each item consistently measures the same construct, namely mathematical concept understanding. The high reliability value suggests that the variation in students' scores stems from actual differences in conceptual ability, not measurement errors or external factors. Therefore, this instrument is suitable and reliable for further analyses, such as hypothesis testing between experimental and control groups in quasi-experimental designs.

Table 4.
Normality Test Results Using Shapiro-Wilk

Group	N	Sig. (Shapiro-Wilk)	Distribution
Experimental	30	0.081	Normal
Control	30	0.067	Normal

A normality test was conducted to determine whether the post-test data in each group was normally distributed. The Shapiro-Wilk Test was used, which is recommended for small to medium sample sizes ($N < 50$). Based on the test results, the significance value (p-value) for the experimental group was 0.081, and for the control group was 0.067. Both significance values are greater than the $\alpha = 0.05$ threshold, indicating that the data in both groups are normally distributed. This normal distribution meets one of the requirements for using a parametric test, namely the Independent Samples t-test, for testing hypotheses regarding differences in scores between the experimental and control groups. The normal distribution also provides a stronger statistical basis for inferential analysis because the assumption that the population distribution is close to a Gaussian curve is met, resulting in test results with higher reliability.

Table 5.
Homogeneity of Variance Test Using Levene's Test

Variable	Levene Statistic	df1	df2	Sig. (p-value)	Conclusion
Posttest Scores (Experimental & Control)	1.374	1	58	0.246	Homogeneous (equal variances)

Homogeneity testing was conducted using Levene's Test for Equality of Variances to test the similarity of variances between the experimental and control groups. The test results showed that the significance value (p-value) was 0.246, which is greater than the significance threshold of $\alpha = 0.05$. Therefore, it can be concluded that there is no significant difference in variance between the two groups, or in other words, the data in both groups are homogeneous. Homogeneity of variance is an essential prerequisite for using parametric statistical tests such as the Independent Samples t-test, as the assumption of equality of variances provides accuracy and reliability in estimating the difference in means between groups. With this assumption met, further analysis can be conducted using parametric tests to measure the effect of treatment on the dependent variable in a more valid manner.

Table 6.
Distribution of Pre-test and Post-test Scores

Group	N	Minimum Score	Maximum Score	Mean	Standard Deviation (SD)
Experimental - Pre	30	36	68	51.40	8.12
Experimental - Post	30	60	92	77.87	7.45
Control - Pre	30	34	66	50.93	7.86
Control - Post	30	48	78	64.20	8.23

Based on the pre-test results, the average scores of the experimental group and the control group were 51.40 and 50.93, respectively, with relatively balanced standard deviations. This indicates that, before the treatment was administered, both groups had relatively equal initial abilities in terms of understanding mathematical concepts. This supports the internal validity of the quasi-experimental design because it ensures that the differences found after the treatment did not originate from initial differences between the groups. Following the intervention, there was a significant increase in the post-test average score of the experimental group, reaching 77.87, compared to the control group, which achieved an average of 64.20. This increase in scores indicates that learning with technology-based adaptive strategies has a more positive impact on students' understanding of mathematical concepts than conventional learning. The post-test standard deviation in the experimental group (7.45) was smaller than that in the control group (8.23), indicating that the variation in learning outcomes in the experimental group was more controlled, possibly because the adaptive system adjusted the content to students' individual needs. The score distribution shows a substantial improvement in mathematical concept understanding in the experimental group, both in absolute terms (mean score) and consistency among students (standard deviation). These findings will be further confirmed through statistical hypothesis testing (t-test) to determine the significance of the differences between groups.

Table 7.
Independent Samples t-test Results on Students' Post-test Scores

Variable	Group	N	Mean	SD	t (df = 58)	Sig. (2-tailed)	Conclusion
Post-test Score	Experimental	30	77.87	7.45	6.85	0.000	Significant difference
	Control	30	64.20	8.23			

Hypothesis testing was conducted using an Independent Samples t-test because the data met the assumptions of normality and homogeneity of variance, as determined by previous prerequisite tests. This test aimed to determine whether there was a significant difference in post-test scores between students who learned with technology-based adaptive strategies (experimental group) and students who followed conventional learning (control group). The analysis results show that the average post-test score in the experimental group was 77.87, while in the control group, it was 64.20. The t-test produced a t-value of 6.85 with a degree of freedom (df) = 58 and a significance value (2-tailed) of 0.000 ($p < 0.05$). A p-value much smaller than 0.05 indicates that the difference between the two groups is statistically significant. Thus, technology-based adaptive learning strategies significantly improve elementary school students' understanding of mathematical concepts compared to conventional learning strategies.

Table 8.
Effect Size of the Intervention on Mathematical Conceptual Understanding

Statistic	Value	Interpretation
Cohen's d	1.74	Very large effect size; the intervention had a substantial positive impact
Eta-squared (η^2)	0.447	44.7% of variance in post-test scores explained by the intervention

The calculated Cohen's d value of 1.74 indicates a huge effect according to Cohen's (1988) benchmark, meaning that the difference between the experimental and control groups is statistically significant and educationally meaningful. Such a high effect size suggests that the adaptive learning intervention substantially improved students' conceptual understanding of mathematics. Furthermore, the eta-squared value of 0.447 implies that nearly 45% of the variance in students' post-test scores can be attributed to the type of instruction received. This proportion is considered significant in educational research, indicating that the adaptive learning strategy accounts for nearly half of the performance difference, independent of other factors. These results reinforce the practical significance of the intervention and support the argument for integrating AI-based adaptive platforms into primary mathematics education to effectively address diverse student needs.

The results of this study indicate that technology-based adaptive learning strategies significantly improve elementary school students' understanding of mathematical concepts. This is demonstrated by the difference in post-test scores between the experimental and control groups, where the group that received technology-based intervention recorded a statistically significant increase in average scores. These findings reinforce the premise that personalized learning supported by adaptive technology can address students' learning needs that conventional approaches have not optimally accommodated. The interpretation of these findings aligns with constructivist theory, which emphasizes the importance of learning experiences tailored to students' cognitive development levels. According to Sayed et al (2023) effective learning, it occurs when interventions are within students' zone of proximal development. Adaptive technology enables learning in this zone by providing materials, questions, and feedback that are adjusted in real-time based on student performance and responses. In this context, adaptive systems function as digital scaffolding that reinforces the gradual and directed development of conceptual understanding (Pardamean et al., 2022).

Furthermore, the results of this study reinforce previous findings, such as the study by Hwang (2022), which states that adaptive technology-based learning has a significant impact on learning outcomes, particularly among students who previously demonstrated low academic performance. The more equitable score improvement in the experimental group compared to the control group indicates that adaptive strategies help reduce student achievement gaps. This is important in the context of primary education, where student abilities and backgrounds vary greatly.

Theoretically, these findings contribute to strengthening the concepts of data-driven instruction and differentiated learning, two pedagogical approaches that are increasingly relevant in the digital education landscape (Touw et al., 2019). Adaptive learning systems enable teachers and systems to automatically process student performance data, delivering content that is tailored to each student's needs, thereby eliminating the need for subjective teacher decisions (Sperling et al., 2022). However, it is supported by objective, real-time, algorithm-based systems. In learning practice, these results have important implications. First, they demonstrate that adaptive technology approaches can be effectively integrated into elementary school curricula to enhance the quality of mathematics learning. Second, this research encourages the redesign of conventional one-way learning approaches to be more interactive and personalized. Third, these results support the need to develop teachers' competencies in using adaptive learning technology, not only as passive users but as active facilitators who can utilize data for pedagogical decision-making.

Further implications also touch on teacher training design and education policy. In professional teacher training, specific modules on the use and analysis of adaptive learning systems are needed. This includes understanding the working principles of adaptive algorithms, reading dashboard-based learning outcomes, and intervening with students based on the data generated by the system. This requires a shift in the role of teachers from mere instructors to learning analysts who actively monitor student learning progress.

Although the results of this study indicate the effectiveness of technology-based adaptive strategies, several limitations must be considered when interpreting the results. First, the scope of the study was limited to fourth-grade students from a specific region and included only two classes as samples. Therefore, generalizing the results to a broader educational context needs to be done with caution. Different demographic, socioeconomic, and technological readiness conditions in other schools may influence the effectiveness of this strategy. Second, the duration of the intervention in this study was relatively short, namely, one learning cycle over several weeks. Thus, this study was unable to evaluate the long-term sustainability of adaptive learning effects, such as the transfer of understanding to new material, long-term retention, or impact on end-of-year achievement. Third, the focus of this study was limited to cognitive aspects, particularly concept understanding, and did not accommodate affective dimensions such as motivation, self-confidence, or interest in mathematics, even though these aspects also influence the overall learning process and outcomes.

Additionally, using devices and accessing technology posed further challenges. Not all schools have adequate infrastructure to implement adaptive systems optimally. Technical constraints, such as unstable internet connections, hardware limitations, or a lack of technical support in schools, can hinder real-world implementation. Therefore, the results obtained in this study represent a relatively ideal scenario where adequate devices and resources support the intervention.

Based on these limitations, several recommendations are proposed for further research. First, similar studies should be conducted on a broader geographical and demographic scale to test the replicability and external validity of these findings. Research encompassing various school backgrounds, including both public and private institutions, as well as urban and rural contexts, will provide a more comprehensive understanding of the effectiveness of adaptive strategies within the national education system. Second, a longitudinal study approach is highly recommended to assess the long-term impact of adaptive learning strategies on concept understanding, retention, and academic achievement across semesters or school years. Such studies can also identify how adaptive learning cycles shape self-regulated learning patterns in students. Third, it is necessary to develop evaluation instruments that measure cognitive, affective, and metacognitive aspects. This is important, considering that effective mathematics learning involves mastering concepts, developing motivation, employing effective learning strategies, and students' ability to reflect on their learning processes. Finally, exploring the integration of adaptive strategies with other pedagogical approaches, such as project-based learning, collaborative learning, or contextual approaches, is also worth further investigation. This will open up possibilities for adaptive and collaborative hybrid learning models in line with the demands of 21st-century education.

In the context of technology use in basic education, the results of this study cannot be separated from inherent social and ethical considerations. The widespread implementation of adaptive learning systems must consider equity of access. Disparities in the availability of devices and internet access between urban and rural schools can widen educational achievement gaps if not addressed systematically. Therefore, technology integration in primary education must be inclusive and equitable, with affirmative policies for digitally disadvantaged areas. From an ethical perspective, technology-based adaptive learning systems heavily rely on user data, including students' learning activity records. This raises critical questions about data privacy, the security of students' personal information, and the mechanisms for data use and storage by platform providers. Therefore, implementing adaptive systems must adhere to principles of personal data protection, including transparency in data processing, access restrictions, and the rights of students and parents to access and control their data. Another crucial social aspect is the role of teachers and families in supporting children in technology-based learning processes. While adaptive systems can provide learning guidance, the human role remains crucial as an emotional balancer, motivator, and guide for learning values that machines cannot fully replace. Therefore, the involvement of all stakeholders in the educational ecosystem is a prerequisite for ensuring that technology integration truly brings tangible benefits to students and does not reinforce passive dependence on digital devices.

CONCLUSION

The findings of this study demonstrate that technology-based adaptive learning strategies significantly improve elementary school students' conceptual understanding of mathematics. This improvement is characterized by statistically significant differences in post-test scores and a huge effect size, indicating meaningful educational impact. These results reinforce constructivist learning theory and Vygotsky's concept of the Zone of Proximal Development (ZPD) by showing how individualized scaffolding can be effectively implemented through adaptive technology. The AI-based system's real-time feedback and personalized pacing operationalize scaffolding in a digital environment, ensuring that learners engage with content within their optimal ZPD. This supports the theoretical argument that adaptive learning technologies can bridge the gap between pedagogical theory and classroom practice in diverse learning contexts. Beyond general recommendations for teacher training and curriculum integration, schools can implement adaptive technology through concrete steps. For example, they can conduct targeted professional development on interpreting platform-generated analytics to inform instructional decisions, pilot adaptive modules aligned with the local curriculum in selected grades, and establish partnerships with technology providers to co-develop culturally relevant and curriculum-compliant content. These measures can facilitate a smooth transition from conventional to personalized, data-driven learning environments.

This study's limitations include its short intervention duration and focus solely on cognitive outcomes. Future research should adopt a longitudinal design to track the sustained impact of adaptive learning strategies over multiple semesters or academic years, including the transferability of conceptual understanding to new mathematical topics. Additionally, integrating affective measures such as motivation, self-confidence, and attitudes toward mathematics would provide a more holistic view of the intervention's impact. Comparative studies in varied socio-economic and technological contexts are also necessary to examine scalability and adaptability in resource-limited settings.

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