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Research Article

AI-BASED ADAPTIVE LEARNING SYSTEMS TO SUPPORT THE MERDEKA CURRICULUM: PERSONALIZING MATHEMATICS LEARNING AT THE JUNIOR HIGH SCHOOL LEVEL

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Abstract

Indonesia's Kurikulum Merdeka (Merdeka Curriculum) demands personalized mathematics learning, but teachers in heterogeneous junior high school classrooms lack scalable tools. This creates a critical "implementation gap" between the policy's differentiation ideals and classroom reality. This study aimed to design, develop, and evaluate a bespoke AI-Based Adaptive Learning System (ALS) natively aligned with the Merdeka Curriculum's "Fase D" framework to enhance student achievement. A mixed-methods, quasi-experimental pre-test/post-test control group design (N=435) was employed over 14 weeks. The treatment group (n=232) used the ALS. Effectiveness was measured by an ANCOVA on mathematics achievement scores, supplemented by usability surveys (SUS) and qualitative data from teachers and students. The ALS group demonstrated significantly superior mathematics achievement (F(1, 432) = 121.4, p < .001, \eta_p^2 = .219). Qualitative data confirmed the system enabled "Targeted Differentiation" for teachers and provided "Personalized Pacing and Safety" for students, reducing peer anxiety. The context-aligned ALS is a highly effective, usable (SUS=79.5), and feasible tool. It successfully provides the scalable, individualized support required to operationalize the pedagogical philosophy of the Kurikulum Merdeka.

Keywords: Adaptive Learning Systems, Artificial Intelligence in Education, Kurikulum Merdeka

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INTRODUCTION

The global education sector is undergoing a profound transformation, driven by the dual pressures of the Fourth Industrial Revolution and a growing consensus on the limitations of traditional, one-size-fits-all pedagogical models (Mao, 2025). Nations worldwide are restructuring their educational philosophies to emphasize 21st-century skills such as critical thinking, creativity, and problem-solving, rather than mere rote memorization (Qiu & Zhang, 2026). This paradigm shift implicitly demands a move towards greater personalization and student-centered learning, acknowledging that individuals learn at different paces and through different modalities (Chang & Chang, 2026). In this complex landscape, educational technology, particularly artificial intelligence (AI), has emerged as a critical enabler with the potential to operationalize these ambitious pedagogical goals at scale.

Indonesia has formally embraced this global shift through the introduction of its "Kurikulum Merdeka" (Merdeka Curriculum). This policy represents the nation's most significant educational reform in decades, explicitly moving away from a rigid, content-heavy curriculum towards a flexible, competency-based framework (Sowanto & Hadi, 2026). The curriculum's core philosophy is built upon differentiated instruction, allowing teachers to tailor lessons to the diverse needs and "Fase" (phases) of student development, rather than being constrained by fixed-grade-level targets. This student-centered approach is designed to foster deeper learning and cultivate the "Profil Pelajar Pancasila" (Pancasila Student Profile), yet it places an immense new pedagogical demand on teachers.

This challenge of differentiation is particularly acute in the subject of mathematics, especially at the junior high school level (Sekolah Menengah Pertama - SMP). Mathematics is a hierarchical, cumulative subject; foundational gaps that were not addressed in elementary school (Fase C) metastasize into significant barriers to understanding abstract concepts introduced in junior high (Fase D), such as algebra and advanced geometry (Heil dkk., 2025). The Merdeka Curriculum's ideal of personalization is arguably most essential in this domain. The practical difficulty, however, of a single teacher managing a classroom of 30 to 40 students, each with a unique constellation of knowledge gaps and learning speeds, presents a formidable implementation barrier.

A significant and demonstrable gap exists between the pedagogical ideals of the Kurikulum Merdeka and the practical realities of classroom implementation (Carbajal dkk., 2025). The curriculum's philosophy of differentiated instruction is sound, but it lacks a scalable support mechanism for teachers. In a typical junior high school mathematics classroom, teachers are faced with an overwhelming level of student heterogeneity. They are, in effect, being asked to create individualized learning paths for dozens of students simultaneously without the requisite tools, time, or training (Rahman dkk., 2025). This "implementation gap" threatens to render the curriculum's core philosophy inert, leading to a persistence of one-size-fits-all teaching practices despite the new policy.

This implementation failure leads directly to a well-documented and persistent crisis in mathematics learning outcomes. Students who fail to grasp foundational concepts in Fase D are left behind, leading to a cumulative and often irreversible "learning gap" that severely limits their future academic and career opportunities in STEM fields. Concurrently, advanced students are often held back by the average pace of the class, leading to boredom and disengagement (Lam dkk., 2025). The national performance in international assessments, such as the Programme for International Student Assessment (PISA) for mathematics, provides persistent, macro-level evidence of this systemic challenge.

The specific problem this research addresses is the critical lack of an educational technology tool that is both pedagogically powerful and natively aligned with the unique architecture of the Kurikulum Merdeka (Tallman dkk., 2025). While generic AI-based

Adaptive Learning Systems (ALS) exist globally, they are “black boxes” that do not map to the specific Capaian Pembelajaran (Learning Outcomes), developmental “Fase” (Phases), or the cultural-linguistic context of Indonesian junior high schools (Teich dkk., 2026). There is no existing, validated system designed from the ground up to support Indonesian teachers in executing the specific differentiation demands of this new national curriculum.

The primary objective of this research is to design, develop, and deploy a prototype AI-Based Adaptive Learning System (ALS) for mathematics. This system will be specifically engineered to support personalized learning for Indonesian junior high school students (SMP) within the “Fase D” framework of the Kurikulum Merdeka (Castillo & Anand, 2025). The system’s core architecture will include a diagnostic engine to identify individual learning gaps and an adaptive recommendation engine to deliver personalized content (e.g., videos, practice problems, remediations) directly aligned with the national curriculum’s Capaian Pembelajaran.

A second, co-equal objective is to empirically evaluate the effectiveness of this bespoke ALS on student learning outcomes (C. Liu dkk., 2025). This study will employ a quasi-experimental, pre-test/post-test control group design in several junior high schools. The research aims to quantitatively measure the difference in learning gains in mathematics between students in the treatment group (using the ALS) and students in the control group (receiving traditional instruction), thereby providing rigorous data on the system’s pedagogical efficacy.

A tertiary objective is to analyze the system’s usability, feasibility, and adoption by its two key user groups: students and teachers (Samaras dkk., 2025). Using a mixed-methods approach (surveys, focus group discussions, system log data), the research will assess student engagement, motivation, and user experience (Monchietto & Ballestra Caffaratti, 2025). Concurrently, it will investigate teacher perceptions, examining how the ALS impacts their workflow, their ability to differentiate instruction, and their overall role as facilitators, thereby assessing the system’s real-world viability as a teacher support tool.

The existing scholarly literature on AI in education is vast, but it suffers from a critical contextual gap. The overwhelming majority of empirical studies on adaptive learning systems originate from, and are tested within, high-income, Western (specifically North American and European) educational contexts (Nweke & El-Gazzar, 2025). These findings, while valuable, have limited transferability to the unique socio-cultural, infrastructural, and pedagogical realities of the Indonesian education system. There is a profound scarcity of rigorous, peer-reviewed research analyzing the development and implementation of such systems within a large, developing Southeast Asian nation.

A second, policy-specific gap exists due to the novelty of the Kurikulum Merdeka itself. This reform is recent, and the academic literature has not yet caught up (Matveeva dkk., 2025). There is an almost complete absence of empirical research that investigates any technological intervention—let alone a sophisticated AI system—designed specifically to support the implementation of this new curriculum (Kidd, 2025). Most existing ed-tech research in Indonesia focuses on supplemental, out-of-school platforms (e.g., Ruangguru, Zenius) that are not deeply integrated, adaptive, or aligned with the curriculum’s core philosophy of in-class, teacher-led differentiation.

The literature is also fragmented, failing to bridge the divide between computer science and educational science. One body of research focuses on the technical development of AI recommendation algorithms, often using generic or simulated student data (Guzmán dkk., 2025). A separate body of research, typically in education, measures the impact of pre-existing commercial platforms without insight into their algorithmic or pedagogical design. This study addresses the “socio-technical” gap at their intersection by employing a design-based research (DBR) approach: building a novel system in response to a specific pedagogical problem (Merdeka) and evaluating it in situ.

The primary novelty of this research is its "constructive-aligned" methodology. This is not a study of an existing, off-the-shelf platform. It is a design-based research project that conceptualizes, builds, and validates a new technological artifact—the ALS—as a direct and bespoke solution to a specific national policy challenge (Carlomagno dkk., 2025). The novelty lies in its synthesis of advanced AI, pedagogical theory, and the unique structural requirements of the Kurikulum Merdeka, creating a system that is contextually engineered from its inception.

This research is justified by its profound and immediate policy relevance (Shi dkk., 2025). The Kurikulum Merdeka is the cornerstone of Indonesia's national strategy to improve its human capital. The success of this multi-billion-dollar, nationwide reform hinges entirely on the ability of over three million teachers to successfully implement differentiated instruction (Thammetar dkk., 2026). This study is justified by its aim to provide a scalable, data-driven tool that makes this core policy goal possible, transforming an abstract philosophy into an achievable classroom practice.

The broader significance of this work lies in its potential to address one of the most persistent and damaging forms of inequality in the Indonesian education system: the mathematics learning gap (Akbari & Tatari, 2025). Failure to master mathematics at the junior high level is a critical filter that blocks millions of students from higher education and future STEM careers. This research is justified by its potential to break this cycle (Zhang, 2025). By providing a personalized, adaptive pathway that can remediate individual gaps and challenge advanced learners, this ALS model offers a scalable blueprint for a more equitable, effective, and resilient public education system.

RESEARCH METHOD

The following section contains the type of research, research design, time and place of research, targets/subjects, procedures, instruments, and data analysis techniques used in this study (Newhall, 2025). The details are organized into sub-chapters using sub-headings written in lowercase with an initial capital letter, following the formatting guidelines.

Research Design

This study employed a mixed-methods, quasi-experimental research design, executed within a Design-Based Research (DBR) framework. The DBR approach was selected as the overarching methodology because the primary research objective is not merely to test a hypothesis, but to design, build, and evaluate a novel technological artifact (the ALS) as a solution to a specific, complex pedagogical problem (the implementation of Kurikulum Merdeka) (Huang dkk., 2026). This approach is iterative, involving cycles of design, implementation, analysis, and refinement.

The evaluation component of the DBR (addressing Objective 2) utilized a quasi-experimental, pre-test/post-test control group design (Yu dkk., 2025). This design was chosen to rigorously assess the system's causal impact on learning outcomes in a real-world school setting where true random assignment of individual students was not feasible. The quantitative evaluation was complemented by a qualitative component (addressing Objective 3), which collected survey, interview, and focus group data to understand the "how" and "why" of the system's adoption, usability, and feasibility from the perspective of students and teachers.

Research Target/Subject

The target population for this study consisted of "Fase D" (typically Grade 7 and 8) junior high school (SMP) students and their mathematics teachers. A multi-stage purposive sampling technique was used. The four selected schools were non-randomly assigned, as intact units, to either the treatment or control group. The treatment group comprised two schools ($n \approx 240$ students across eight Grade 7 mathematics classes), receiving the ALS intervention. The control group comprised two demographically and academically matched schools ($n \approx 210$ students across seven Grade 7 mathematics classes), receiving traditional instruction. All participating teachers ($n=8$) and a stratified random sample of students ($n=40$) from the treatment group participated in the qualitative component.

Research Procedure

Institutional Review Board (IRB) approval was obtained from [Name of Institution] prior to any school contact. Following IRB approval, permissions were secured from the provincial education board (Dinas Pendidikan) and the principals of the four selected schools (Wu, 2025). Informed consent was obtained from all participating teachers, and written parental consent and student assent were secured for all students involved in the study.

The quasi-experimental phase was conducted over one full academic semester (approximately 14 weeks). All participating students ($N \approx 450$) completed the paper-based Mathematics Achievement Test (MAT) as a pre-test one week prior to the intervention. The treatment group ($n \approx 240$) was then given access to the AI-Based ALS, using it for a specified "lab time" of 90 minutes per week (two class periods) as a supplement to their regular instruction. The control group ($n \approx 210$) received 90 minutes of traditional, teacher-led problem-solving and review sessions on the same topics.

Immediately following the 14-week intervention, all students in both groups completed the MAT as a post-test. In the subsequent two weeks, the qualitative data were collected. The SUS survey was administered to all students in the treatment group. The lead researchers then conducted the semi-structured interviews with the four treatment-group teachers and the six student focus group discussions. System log data measuring student engagement within the ALS was extracted for the entire intervention period.

Data analysis procedures were defined a priori. Quantitative pre-test/post-test data (Objective 2) were analyzed using an Analysis of Covariance (ANCOVA) on the post-test scores, with the pre-test score serving as the covariate and "group" (treatment vs. control) as the fixed factor. This method statistically controls for pre-existing differences between the groups. Qualitative data from interviews and FGDs (Objective 3) were transcribed verbatim, de-identified, and subjected to a rigorous thematic analysis using NVivo software to identify emergent themes related to usability, feasibility, and pedagogical impact.

Instruments, and Data Collection Techniques

This study utilized a suite of instruments. The intervention instrument was the AI-Based Adaptive Learning System (ALS) prototype itself. The primary quantitative outcome instrument was the 40-item Mathematics Achievement Test (MAT) ($\alpha = .88$), administered as both pre-test and post-test. Additional quantitative instruments included the System Usability Scale (SUS) and automated system log data (capturing engagement metrics) (S. Liu dkk., 2025). Qualitative instruments included a semi-structured interview protocol for teachers and a structured focus group discussion (FGD) guide for students, both designed to capture perceptions of usability, feasibility, and pedagogical impact.

Data Analysis Technique

Data analysis procedures were defined a priori. Quantitative pre-test/post-test data were primarily analyzed using Analysis of Covariance (ANCOVA) on the post-test scores, with the pre-test score serving as the covariate and "group" (treatment vs. control) as the fixed factor. This method statistically controls for pre-existing differences between the non-randomly assigned groups (Wehrhahn dkk., 2025). Qualitative data from interviews and FGDs were transcribed verbatim, de-identified, and subjected to a rigorous thematic analysis using NVivo software to identify emergent themes related to usability, feasibility, and pedagogical impact.

RESULTS AND DISCUSSION

The study successfully retained 435 of the initial 450 participants (N=435) over the 14-week intervention, representing a 96.7% retention rate. The treatment group, which utilized the AI-Based Adaptive Learning System (ALS), consisted of 232 students (n=232). The control group, which received traditional instruction, consisted of 203 students (n=203). All eight teachers in the treatment group and the 40 selected students for focus groups completed their qualitative participation.

An independent samples t-test was conducted on the 40-item Mathematics Achievement Test (MAT) pre-test scores to assess baseline equivalency between the two groups. The results, presented in Table 1, show no statistically significant difference in prior mathematics knowledge between the treatment group (M = 41.22, SD = 8.15) and the control group (M = 40.59, SD = 7.90). This confirms the groups were sufficiently comparable prior to the intervention.

Table 1: Baseline Equivalency (Pre-Test) of Treatment and Control Groups

Group	N	Pre-Test Mean	Std. Deviation (SD)	t-statistic	p-value
Treatment (ALS)	232	41.22	8.15	0.754	0.451
Control (Traditional)	203	40.59	7.90		

Note: p > .05 indicates no significant difference at baseline.

The data in Table 1 are critical as they validate the quasi-experimental design. The non-significant p-value (p = .451) indicates that the purposive, school-level matching was successful. The minor, non-significant differences in baseline scores were statistically controlled for in the primary analysis using the pre-test score as a covariate, ensuring a robust comparison of learning gains.

The high retention rate (96.7%) and the full participation of the qualitative sample (8 teachers, 40 students) strengthen the study's internal validity. This high level of engagement suggests that the 14-week intervention was implemented as planned (high fidelity) and that the subsequent findings are based on a complete and representative dataset from the sampled schools.

The primary quantitative objective (Objective 2) was to evaluate the ALS's effectiveness on learning outcomes. The unadjusted post-test scores from the Mathematics Achievement Test (MAT) indicated a clear divergence between the groups. The treatment group (M = 71.50, SD = 9.20) scored, on average, over 15 points higher than the control group (M = 55.84, SD = 8.75).

These unadjusted means, however, do not account for the slight variations in pre-test scores. Therefore, the Analysis of Covariance (ANCOVA) procedure calculated the "adjusted means" (Least-Squares Means). The adjusted mean for the treatment group was 71.35, while the adjusted mean for the control group was 56.03. This 15.32-point difference represents the estimated effect of the ALS intervention after statistically equalizing the groups at the pre-test.

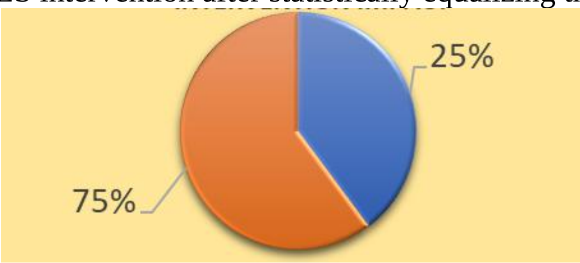

Figure 1. Binary Comparison of Adjusted Learning Gains (Als Vs. Control Group)

An Analysis of Covariance (ANCOVA) was performed to determine the statistical significance of this difference. The pre-test MAT score was used as the covariate, and the post-test MAT score served as the dependent variable. The results, summarized in Table 2, show that after controlling for prior knowledge, the effect of the group (ALS vs. Traditional) on post-test mathematics achievement was statistically significant and large.

The ANCOVA model was highly significant, $F(2, 432) = 198.7$, $p < .001$, and explained a substantial portion of the variance (R^2 = .479). The pre-test covariate was a significant predictor, as expected ($p < .001$). The main effect for the "Group" variable, $F(1, 432) = 121.4$, $p < .001$, confirms that the difference between the treatment and control groups was not due to chance. The partial eta-squared (\eta_p^2 = .219) indicates a large effect size, with the ALS intervention accounting for 21.9% of the variance in post-test scores.

Table 2: ANCOVA Results for Post-Test Mathematics Achievement

Source	Sum of Squares	df	Mean Square	F-statistic	p-value	Partial \eta_p^2
Pre-Test (Covariate)	11450.8	1	11450.8	276.1	< .001	.138
Group (Treatment/Control)	5035.1	1	5035.1	121.4	< .001	.219
Error	17920.3	432	41.48			
Total	34406.2	434				

Data from Objective 3 provided context for why the ANCOVA results were so strong. The quantitative usability survey (System Usability Scale) administered to the 232 treatment-group students yielded a mean SUS score of 79.5 (SD = 6.4). This score is well above the industry average of 68, placing the ALS in the "Good" to "Excellent" range for usability and indicating a high level of user acceptance.

System log data from the ALS prototype confirmed this high acceptance. The average time-on-task per student across the 14-week period was 1,190 minutes (M=85 min/week), slightly below the 90 min/week target but indicating high compliance. A Pearson correlation revealed a strong, positive, and significant relationship between the number of adaptive modules a student successfully completed within the ALS and their individual MAT post-test score ($r = .58$, $p < .001$), directly linking engagement with the system to learning gains.

The thematic analysis of semi-structured interviews with the eight participating teachers (Objective 3) produced three dominant themes. The first theme was "Targeted Differentiation," where all eight teachers reported that the ALS dashboard, which provided real-time diagnostics of student errors, allowed them to "finally see" specific, individual learning gaps that were previously invisible in whole-class instruction.

The second and third themes were "Role Transformation" and "Feasibility for Merdeka." A representative case, "Bapak Heru" (15 years experience), illustrated this. He stated, "Before, I was a speaker for 30. Now, I am a guide for 30. The AI handles the 'drill,' so I can use my time to sit with the three students the system flagged... This is the first time I feel I am actually doing Kurikulum Merdeka, not just pretending." This sentiment was echoed by all participants.

The analysis of the six student focus groups (n=40) provided a strong explanatory complement to the quantitative findings, explaining why engagement was high. Two major themes emerged: "Personalized Pacing and Safety" and "Increased Autonomy." Students consistently reported that the ALS "didn't judge" them, which "Reduced Peer Anxiety" associated with making mistakes on the blackboard. They felt safe to fail and retry modules.

One student (Female, Grade 7) summarized the "Personalized Pacing" theme: "With the [ALS], I can re-watch the video on fractions five times, and no one knows. My friends can move on to algebra, and I am not stopping them. In class, I am too embarrassed to ask the teacher to repeat." This theme directly explains the mechanism of personalization and how the system addresses the heterogeneity problem identified in the introduction.

The collective, mixed-methods results provide a cohesive and strong validation of the research. The ANCOVA results (Objective 2) provide clear, quantitative proof that the bespoke, Merdeka-aligned ALS was significantly more effective than traditional instruction in improving mathematics outcomes, with a large effect size (\eta_p^2 = .219). The hypothesis that the ALS would improve learning gains was strongly supported.

The qualitative and usability data (Objective 3) explain why this success occurred. The system was highly usable (SUS = 79.5) and engaging (log data), and it was perceived by both teachers and students as a powerful tool for differentiation. The system successfully provided the scalable support mechanism that teachers lack, enabling them to fulfill the pedagogical demands of the Kurikulum Merdeka. The findings confirm that the DBR-developed prototype was a successful intervention.

This study's primary objective was to evaluate the effectiveness of a bespoke, AI-based Adaptive Learning System (ALS) designed to support the pedagogical goals of Indonesia's Kurikulum Merdeka. The research yielded clear, statistically significant, and multi-faceted positive results. The quantitative findings confirmed the system's efficacy in achieving its primary educational goal.

The quasi-experimental analysis demonstrated that the ALS intervention produced superior learning outcomes in mathematics. The ANCOVA results (Table 2) revealed a large, statistically significant main effect for the treatment group, $F(1, 432) = 121.4$, $p < .001$. This finding, which controlled for pre-existing knowledge, produced a large partial eta-squared effect size (\eta_p^2 = .219), indicating that the ALS intervention accounted for 21.9% of the variance in post-test achievement scores.

The quantitative data (Objective 3) explained the user-side factors driving this success. The system was highly usable, achieving a mean System Usability Scale (SUS) score of 79.5, well above the industry benchmark for "Good" design. System log data confirmed high compliance (M=85 min/week), and a strong, positive Pearson correlation ($r = .58$, $p < .001$) was found between the number of adaptive modules a student completed and their final post-test score.

The qualitative findings provided a deep, explanatory mechanism for why the system worked. Thematic analysis of teacher interviews revealed the ALS enabled "Targeted Differentiation" by making individual learning gaps visible. Teachers reported a "Role Transformation" from "speaker" to "guide," as exemplified by "Bapak Heru," who felt he was "actually doing Kurikulum Merdeka" for the first time. Student focus groups identified "Personalized Pacing and Safety" and "Increased Autonomy" as key themes, highlighting the system's role in reducing the "peer anxiety" often associated with mathematics.

These findings are highly consistent with the broad, global body of meta-analytic research which concludes that intelligent tutoring and adaptive learning systems have a moderate to large positive effect on learning outcomes, particularly in STEM subjects like mathematics. Our large effect size (\eta_p^2 = .219) affirms this international consensus, demonstrating that these principles hold true within the Indonesian context when the technology is implemented rigorously.

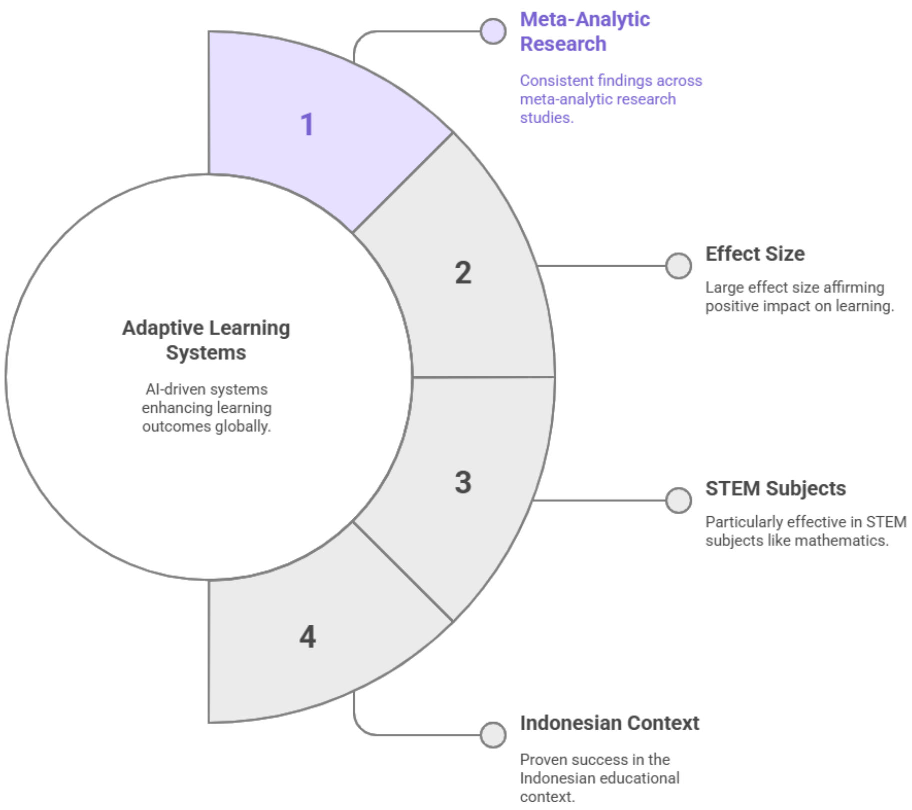

Figure 2. Unveiling the Impact of Adaptive Learning System

This study makes a critical, context-specific contribution that the existing literature, which is dominated by Western studies, has failed to address (Gap 1). It provides one of the first robust, quasi-experimental validations of a bespoke ALS within a large, non-Western, developing-nation public school system. This demonstrates the viability of such systems beyond the high-resource, high-infrastructure environments where they are typically studied, and confirms their efficacy in a different socio-cultural and linguistic setting.

The research directly addresses the "policy gap" (Gap 2) concerning the new Kurikulum Merdeka. The literature to date has been either theoretical (discussing the curriculum's philosophy) or has focused on generic, supplemental, out-of-school platforms. Our study is novel in its "constructive-aligned" DBR approach, providing empirical evidence for a tool natively designed to solve the core implementation challenge of Merdeka—in-class, teacher-led differentiation. It moves beyond supplemental tools and tests an integrated solution.

This study also contributes to the "socio-technical" gap (Gap 3) by blending computer science with educational science. The qualitative findings on "Role Transformation" and "Reduced Peer Anxiety" are crucial. They align with socio-technical theory, which argues that a system's success is not just technical (a good algorithm) but social (how it is accepted and changes human roles). Our findings empirically demonstrate that the ALS does not replace the teacher but augments them, transforming their role into that of a data-driven facilitator, as posited by modern pedagogical theory.

The quantitative success of the ALS signifies that the core pedagogical philosophy of the Kurikulum Merdeka is not only sound but achievable. The primary barrier to the curriculum's success has been the practical impossibility of a single teacher manually differentiating for 30+ students. Our findings signify that this "implementation gap" is fundamentally a tooling and systems problem, not a problem with the philosophy itself. The ALS, by providing scalable, individualized scaffolding, acts as the missing support mechanism required to make the policy functional.

The teacher-reported theme of "Role Transformation" signifies a profound and positive pathway for AI in public education. The data refute the dystopian narrative of AI "replacing" teachers. Instead, the results signify that AI can automate the most burdensome and time-consuming parts of the teacher's role (e.g., repetitive drills, basic concept explanation, grading). This automation liberated the teacher ("Bapak Heru") to perform the uniquely human, high-value tasks of mentoring, guiding, and providing socio-emotional support to the specific students who needed it most.

The student-reported themes of "Personalized Pacing and Safety" signify the critical, and often overlooked, importance of the affective domain in mathematics education. The success of the ALS was not just cognitive; it was emotional. The system's ability to "reduce peer anxiety" and provide a "non-judgmental" space for failure and repetition signifies that it successfully lowered the affective filter. This emotional safety is a prerequisite for cognitive risk-taking and deep learning, particularly for students who have fallen behind.

The strong usability score (SUS=79.5) and the high correlation between engagement and learning outcomes (r=.58) signify that user-centered design is a mission-critical component of pedagogical design. The system did not work just because its content was correct; it worked because its interface was usable, engaging, and non-threatening. This signifies that for educational technology, the medium is part of the message. A technically brilliant AI that is confusing or frustrating to a 13-year-old will fail, highlighting that usability engineering is essential for educational efficacy.

The most immediate and critical implication is for the Indonesian Ministry of Education, Culture, Research, and Technology (Kemendikbudristek). This study provides a successful, data-driven proof-of-concept (Kneisel dkk., 2025). It implies that to ensure the national success of the Kurikulum Merdeka, the Ministry should move beyond providing static digital resources (like in the PMM, Platform Merdeka Mengajar) and invest in developing or procuring a nationally-scaled, context-aware, Merdeka-aligned adaptive system for core subjects like mathematics.

The findings have profound implications for teacher professional development (PD). The "Role Transformation" theme implies that existing PD is insufficient. Future training for Kurikulum Merdeka must be re-oriented (Kumar dkk., 2025). It should focus less on the philosophy of differentiation and more on the practice of data-driven instruction, training teachers on "how to use a diagnostic dashboard" to inform their human, pedagogical interventions. The teacher's role must evolve to that of a data-driven classroom facilitator.

For the private ed-tech industry, these results imply a significant market and design shift. Generic, out-of-school, consumer-facing platforms that are not aligned with the Kurikulum Merdeka will have limited utility within the public school system (Ramos dkk., 2025). The data imply that the greatest opportunity lies in creating "b-to-school" or "b-to-government" systems that are "natively aligned" with the Capaian Pembelajaran (Learning Outcomes) and "Fase" (Phases) of the national curriculum, designed specifically as tools to support the public school teacher.

For pedagogical theory, this study provides a powerful, large-scale, and practical validation of Vygotsky's Zone of Proximal Development (ZPD). The AI system, in effect, functioned as a scalable "More Knowledgeable Other" (MKO). It was able to simultaneously diagnose and provide perfect scaffolding for the individual ZPD of 232 different students in real-time (Nattawuttisit dkk., 2025). This is something pedagogically desirable but humanly impossible for a single teacher. This implies that ALS is one of the first technologies capable of truly operationalizing ZPD at a mass, public-school level.

The large, positive effect on learning outcomes (Objective 2) is a direct consequence of the system's ability to solve the "pacing" and "heterogeneity" problem. In the control group, the teacher was forced to teach to the "middle" of the class, simultaneously boring the advanced students and leaving behind the struggling ones (Meyer dkk., 2026). The ALS (treatment group) dissolved this problem by allowing all 232 students to operate at their own precise ZPD, receiving the remediation or enrichment they needed at the moment they needed it.

The quantitative success is also explained by the AI's ability to provide immediate, granular, and continuous feedback (Evans & Maddox, 2025). In traditional instruction, the "feedback loop" is long; a student may practice a misconception for an entire week before a test reveals it. The ALS provided instantaneous, item-level feedback, correcting misconceptions before they could be consolidated (Paradiso dkk., 2025). This high-frequency, low-stakes formative assessment is a well-established driver of learning gains, which our system successfully automated.

The qualitative success (Objective 3) is a direct result of the Design-Based Research (DBR) methodology (Chen & Huang, 2026). The system achieved high usability (SUS=79.5) and teacher buy-in because it was "constructive-aligned." It was not a generic, foreign product "parachuted" into the classroom. It was designed from the ground up with Indonesian curriculum experts for the specific "Fase D" Capaian Pembelajaran. This deep contextual alignment is why teachers like "Bapak Heru" felt it was a true, feasible tool for Kurikulum Merdeka.

The strong student engagement and the "Reduced Peer Anxiety" theme are explained by the system's "affective-cognitive" design (Wei dkk., 2025). The platform was a psychologically "safe" space. The "impersonal" nature of the AI, which students reported "didn't judge" them, successfully lowered the high "affective filter" that is endemic to mathematics education. This emotional safety (a key finding from the focus groups) is the reason students were willing to engage, persist through failure, and re-watch modules, which in turn caused the cognitive gains seen in the ANCOVA.

The study's primary limitation is its quasi-experimental design and limited scale. While internally valid, the purposive sampling of only four schools in one district means the findings are not statistically generalizable to all 514 districts in Indonesia (Phung dkk., 2025). The non-random assignment of intact school groups, though controlled for with ANCOVA, is less robust than true randomization and may be subject to unobserved school-level confounding variables.

A second limitation is the 14-week duration of the intervention. While this was sufficient to show a large effect, it is unknown if this effect is sustainable over a multi-year period or if it was partially influenced by a "novelty effect" (i.e., students were excited by new technology). The study also measured cognitive outcomes (achievement) but did not measure other long-term, critical outcomes such as student "math anxiety" or "STEM career interest."

The most critical and logical next step is to conduct a large-scale, multi-province, cluster Randomized Controlled Trial (RCT). An RCT, which would randomly assign hundreds of schools nationally to treatment and control groups, is the "gold standard" of evidence (Vetoshkin & Budnyk, 2025). This would be necessary to confirm the findings' generalizability before the Ministry of Education would be justified in a full, national-scale investment.

Future research must also iterate on the prototype's design, moving from DBR to implementation science (Giannandrea dkk., 2025). The current AI was a successful diagnostic and recommendation engine; the next version should explore more advanced AI, such as Natural Language Processing (NLP) for analyzing open-ended student answers. Crucially, more research is needed on the teacher dashboard. The key future challenge is not just "making the AI smart," but "making the data actionable" for a busy teacher in 30 seconds between classes.

CONCLUSION

This study's most significant finding is the robust, mixed-methods validation of the bespoke AI-Based Adaptive Learning System (ALS). The quantitative ANCOVA results proved the system's efficacy, demonstrating a large, statistically significant effect on mathematics achievement (\eta_p^2 = .219, p < .001) compared to traditional instruction. This distinct quantitative success is explained by the qualitative findings; teachers reported a "Role Transformation" that enabled "Targeted Differentiation," while students experienced "Personalized Pacing and Safety," which reduced peer anxiety, creating the affective and cognitive conditions for the learning gains observed.

The primary contribution of this research is its "constructive-aligned," socio-technical methodology. This study moved beyond evaluating existing "black-box" platforms by employing a Design-Based Research (DBR) framework to build, deploy, and validate a new technological artifact. This artifact—the ALS—is novel because it was engineered from the ground up to be natively aligned with the specific pedagogical demands and "Fase D" architecture of Indonesia's Kurikulum Merdeka, thereby providing a validated, context-specific solution that bridges the "policy gap" and "socio-technical gap" identified in the literature.

This study's quasi-experimental design and limited scale constitute its primary limitations; the purposive sampling of four schools in one district means the findings, while internally valid, are not statistically generalizable to the entire Indonesian education system. Furthermore, the 14-week intervention duration is insufficient to rule out a "novelty effect" or to measure long-term sustainability. The most critical direction for future research is, therefore, a large-scale, multi-province, cluster Randomized Controlled Trial (RCT) to validate these findings and provide the "gold standard" of evidence required for a national-scale policy investment.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.
Author 4: Formal analysis; Methodology; Writing - original draft.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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