THE IMPACT OF EDUCATIONAL INNOVATION IN AI-POWERED DIFFERENTIATED INSTRUCTION ON TEACHING EFFECTIVENESS: THE MEDIATING ROLE OF TEACHER DIGITAL PEDAGOGICAL COMPETENCE AND THE MODERATING EFFECT OF STUDENT LEARNING DIVERSITY

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Abstract: With the rapid development of artificial intelligence (AI) technologies in the field of education, AI-powered differentiated instruction has become an important means to enhance teaching effectiveness and promote educational equity. Grounded in the TPACK framework and constructivist learning theory, this study investigates the impact mechanism of educational innovation (AI-driven differentiated instruction) on teaching effectiveness, focusing on the mediating role of teacher digital pedagogical competence and the moderating role of student learning diversity. The following hypotheses are proposed: H1: Educational innovation in AI-powered differentiated instruction has a significant positive effect on teaching effectiveness; H2: Teacher digital pedagogical competence mediates the relationship between educational innovation in AI-powered differentiated instruction and teaching effectiveness; H3: Student learning diversity moderates the impact pathway between educational innovation in AI-powered differentiated instruction and teaching effectiveness, such that the effect is stronger when student learning diversity is higher.

This study employed a sample of 536 teachers from various educational stages across China and conducted empirical tests using structural equation modeling (SEM) and mediation-moderation analyses. The results demonstrate that AI-powered differentiated instruction significantly improves teaching effectiveness; teacher digital pedagogical competence serves as a mediating factor; and student learning diversity positively moderates the effect of AI-driven educational innovation. This study expands the theoretical understanding of intelligent education, enriches practical guidance, and provides significant implications for promoting educational digital transformation

Keywords: AI-Powered Differentiated Instruction, Educational Innovation, Teacher Digital Pedagogical Competence, Student Learning Diversity, Teaching Effectiveness

Introduction

In the rapidly evolving landscape of the 21st-century global society, artificial intelligence (AI) technologies have emerged as a transformative force across multiple sectors, and education is no exception. The integration of AI into educational settings—ranging from automated grading systems and intelligent tutoring platforms to adaptive learning environments—has represented a fundamental paradigm shift in how instruction is designed, delivered, and assessed (Luckin et al., 2016). Recognizing the significance of these changes, UNESCO (2021) has formally acknowledged AI as a critical enabler for achieving Sustainable Development Goal 4, which aspires to ensure inclusive, equitable, and quality education for all learners worldwide.

Countries such as China, the United States, Finland, and Singapore have invested heavily in developing and implementing AI-driven educational solutions across various levels of education, from K–12 schooling to tertiary institutions (Zawacki-Richter et al., 2019). These technologies leverage machine learning algorithms to diagnose individual learner needs, predict academic performance trends, and personalize instructional pathways. In doing so, they offer the potential to move beyond traditional "one-size-fits-all" teaching models toward more individualized and effective educational experiences. The COVID-19 pandemic further accelerated the adoption of digital technologies, emphasizing the urgent need for resilient, flexible, and personalized learning environments (Xie, Shu, & Jiang, 2021). Within this context, AI technologies are increasingly recognized as indispensable tools for supporting learning continuity, addressing persistent educational inequities, and transforming conventional instructional models.

Despite these promising developments, the practical deployment of AI-based educational innovations in real-world settings has encountered substantial challenges. Implementation inconsistencies, disparities in teacher digital competencies, infrastructural limitations, and growing ethical concerns regarding data privacy and algorithmic fairness collectively present significant barriers to fully realizing AI's potential in education (Holmes, Bialik, & Fadel, 2019). These issues highlight the need for a more nuanced understanding that extends beyond technological affordances to encompass the human and contextual factors that mediate the effective use of AI in classrooms.

As AI technologies become increasingly embedded in educational environments, a central tension has emerged between their theoretical potential and their actual practical implementation. In theory, AI offers the promise of scalable personalization, adaptive feedback loops, and enhanced learner engagement. In practice, however, many AI interventions remain surface-level, fragmented, and unevenly distributed across regions and institutions (Zawacki-Richter et al., 2019). One key issue is the lack of large-scale personalized instructional models that are both technologically robust and pedagogically coherent. Traditional classroom structures, particularly those characterized by high student-teacher ratios, continue to struggle to accommodate the diverse cognitive abilities, learning styles, and socio-economic backgrounds of their students (Tomlinson, 2014). Although AI technologies theoretically offer the ability to automate differentiation and personalization, their effective utilization largely depends on teacher digital pedagogical competence and the availability of institutional support systems (Ifenthaler & Yau, 2020).

Moreover, the current body of empirical research validating the pedagogical impacts of AI remains limited. While several studies have demonstrated AI's role in enhancing specific learning outcomes, few have systematically explored how AI-driven differentiated instruction influences overall teaching effectiveness, through what underlying mechanisms, and under what contextual conditions (Roll & Wylie, 2016). Particularly absent in existing literature are investigations into the mediating role of teacher digital pedagogical competence and the moderating influence of student learning diversity. Thus, bridging the gap between the technological affordances of AI and its realized pedagogical effectiveness requires a deeper exploration of the complex interplay between educational innovation, teacher competence, and learner diversity within AI-enhanced instructional models.

Building upon this identified problem landscape, the present study seeks to systematically address the following research questions: What is the impact of AI-powered instructional innovation on teaching effectiveness? How does teacher digital pedagogical competence mediate the relationship between AI-powered instructional innovation and teaching effectiveness? How does student learning diversity moderate this relationship? Furthermore, under what combined conditions of teacher competence and student diversity does AI-powered differentiated instruction achieve optimal teaching effectiveness? By addressing these questions, this study aims not only to understand the direct effects of AI innovation but also to unpack the complex mediating and moderating mechanisms that shape its practical outcomes in real-world educational settings.

The findings of this research carry significant practical value. Insights generated from the study can inform the design of evidence-based AI competency training programs, assisting educators in moving beyond basic digital literacy toward the strategic and pedagogically meaningful integration of AI tools for differentiated instruction, assessment, and feedback. Additionally, the study can provide valuable guidance to curriculum developers and instructional designers seeking to embed AI-enhanced differentiation mechanisms into course structures, especially within large, heterogeneous classrooms. Furthermore, by providing empirical evidence regarding the enabling conditions for successful AI integration, the research offers important policy recommendations for resource allocation, digital infrastructure investment, and teacher capacity-building initiatives, particularly in the context of China's ongoing educational modernization efforts. Importantly, the study also contributes to global discussions on how AI technologies can be leveraged to bridge educational inequities, ensuring that personalized learning opportunities are accessible to all students, regardless of background.

Beyond its practical significance, this study also offers several important academic innovations. Unlike previous research that often focuses solely on the direct effects of AI on learning outcomes, this study constructs and empirically tests an integrated model that simultaneously examines the mediating role of teacher digital pedagogical competence and the moderating role of student learning diversity. By situating the research within the Chinese educational context—a system characterized by rapid transformation and profound diversity—the study provides novel insights into how AI-powered differentiated instruction operates under large-scale, real-world conditions. Moreover, by encompassing K–12, vocational, and higher education sectors, the study enhances the generalizability and scalability of its findings across various educational levels. Methodologically, the research employs robust statistical techniques such as structural equation modeling (SEM) and PROCESS-based mediation-moderation analysis (Hayes, 2018), ensuring high empirical validity and analytical rigor.

In summary, by combining theoretical advancement with practical relevance and methodological rigor, this study aims to make a meaningful contribution to the field of AI in education. It seeks to deepen our understanding of how AI technologies, when thoughtfully implemented and contextually adapted, can drive significant improvements in teaching effectiveness, learner engagement, and educational equity.

Research Objectives

The integration of artificial intelligence into instructional models presents significant promise for transforming education in China and globally. However, realizing this potential requires a comprehensive understanding of not only the technological innovations themselves, but also the pedagogical, professional, and contextual conditions under which these innovations lead to improved teaching outcomes. This study is guided by five interrelated research objectives designed to explore the mechanisms and boundary conditions influencing the impact of artificial intelligence-powered differentiated instruction on teaching effectiveness.

The first objective of this study is to empirically assess the direct impact of educational innovation in artificial intelligence-powered differentiated instruction on teaching effectiveness across multiple levels of education. This includes examining its effects in primary and secondary school settings, vocational training programs, and higher education institutions. In particular, the study aims to evaluate whether the implementation of algorithmically informed and adaptive instructional practices contributes to measurable improvements in the quality of instructional delivery, the degree of student academic engagement, and the overall learning outcomes as perceived by students and teachers. This objective addresses the foundational hypothesis that personalized, data-driven learning environments enabled by artificial intelligence led to more effective teaching, particularly when implemented at scale.

The second objective is to investigate the mediating role of teacher digital pedagogical competence in the relationship between artificial intelligence-powered differentiated instruction and teaching effectiveness. While the tools of artificial intelligence may offer theoretically advanced capabilities for personalizing instruction, the realization of these benefits in classroom practice is contingent upon teachers' abilities to effectively incorporate these tools into their pedagogical routines. This includes the ability to integrate artificial intelligence into instructional design, utilize algorithmically generated data to guide student assessment and feedback, and dynamically adjust teaching strategies in response to real-time performance analytics. This objective draws on the Technological Pedagogical Content Knowledge (TPACK) framework to explore whether the digital instructional competencies of teachers serve as a critical mechanism through which artificial intelligence-based innovation can enhance teaching effectiveness.

The third objective of this research is to examine whether student learning diversity moderates the relationship between artificial intelligence-powered differentiated instruction and teaching effectiveness. Given the wide range of individual differences among students—including variations in cognitive ability, learning style, access to technology, socioeconomic status, and motivational profiles—it is essential to consider how such diversity conditions the impact of artificial intelligence-driven instructional strategies. This study hypothesizes that the benefits of artificial intelligence-powered differentiated instruction will be more pronounced in classrooms characterized by high degrees of heterogeneity, where traditional instructional models often struggle to meet the needs of all learners. By incorporating a moderation analysis, this objective seeks to identify whether diverse learning contexts either amplify or constrain the effects of artificial intelligence-powered innovation.

The fourth objective of this study is to generate evidence-based recommendations for the development and delivery of professional learning programs aimed at strengthening teacher digital pedagogical competence in technology-supported differentiated instructional environments. Insights drawn from the mediation analysis will inform which competencies are most critical for ensuring the successful implementation of artificial intelligence-driven instructional innovations. The findings will be used to propose practical guidelines for the design of targeted teacher training initiatives, with attention to scalable strategies that can be adopted across varied school contexts. This objective acknowledges the central role of teacher professional development in closing the gap between technology access and pedagogical impact.

The fifth and final objective is to contribute empirical evidence to policy discourse surrounding the large-scale implementation of artificial intelligence-enabled instructional models within the Chinese educational system. As China continues to invest heavily in the modernization of its educational infrastructure, policymakers require robust, contextually grounded evidence to guide strategic planning and resource allocation. By providing detailed insights into the pedagogical effects, enabling conditions, and boundary constraints of artificial intelligence-powered differentiated instruction, this study aims to support the formulation of national and regional education policies that are both effective and equitable. This objective expands the study's relevance from the level of classroom practice to the broader landscape of digital education reform.

In sum, these five objectives collectively aim to illuminate the complex interplay between educational innovation, teacher readiness, and learner diversity in the digital age. Through an integrated framework and robust empirical methodology, this study seeks to advance theoretical understanding and inform practical applications that can drive meaningful and scalable improvements in teaching effectiveness.

Literature Review

The integration of artificial intelligence (AI) into education has dramatically reshaped the landscape of teaching and learning in the 21st century. Initially, AI's influence was confined to narrow domains such as computer-assisted instruction and automated grading, but over the past two decades, its role has expanded significantly to include personalized learning pathways, intelligent tutoring systems, and real-time adaptive learning platforms (Luckin et al., 2016). UNESCO (2021) highlights AI as a pivotal driver for achieving Sustainable Development Goal 4, promoting inclusive and equitable education for all learners globally. Despite these advancements, critical gaps remain in fully understanding how AI-powered differentiated instruction interacts with teacher digital pedagogical competence and student learning diversity to impact teaching effectiveness. A comprehensive exploration of these relationships is vital to fully unlocking the transformative potential of AI in education.

The theoretical foundations that undergird this study include Vygotsky's Zone of Proximal Development (ZPD), constructivist learning theory, adaptive learning theory, and the Technological Pedagogical Content Knowledge (TPACK) framework. Vygotsky's (1978) notion of the ZPD emphasizes that optimal learning occurs when instruction is slightly beyond the learner's current capabilities but achievable with support. Traditionally, this support was human-provided, but contemporary AI technologies can dynamically adjust scaffolding based on real-time learner inputs, mimicking or even enhancing human-mediated guidance (Swaroopa & Prasad, 2025; Fang & Deng, 2024). Similarly, constructivist theories advocate for active learner engagement and knowledge construction through meaningful experiences (Piaget, 1952; Bruner, 1961). AI's real-time feedback capabilities and adaptive content delivery align closely with these principles, enabling personalized constructivist learning at scale.

Adaptive learning theory further provides the rationale for the use of AI in education. It posits that instruction should respond dynamically to learner variability, including differences in prior knowledge, learning styles, and motivational profiles (Corno & Snow, 1986). AI's capacity for continuous learner data analysis, pattern recognition, and predictive modeling positions it as the most sophisticated adaptive instructional agent available today (Roll & Wylie, 2016; Zawacki-Richter et al., 2019). Additionally, the TPACK framework (Koehler & Mishra, 2009) frames the integration of technology into education as a complex interplay between technological knowledge, pedagogical knowledge, and content knowledge. Effective use of AI in differentiated instruction requires teachers to skillfully navigate this triadic interaction, interpreting algorithmic outputs and embedding them within sound pedagogical practices.

Artificial intelligence-driven differentiated instruction represents a significant evolution from traditional teacher-centered approaches. Historically, differentiated instruction emerged in response to the recognition of student diversity in cognitive abilities, interests, and learning styles (Tomlinson, 2014). Early models relied heavily on teacher observation and manual adjustment of content, processes, and products to meet individual needs. However, with the advent of learning management systems (LMS) and adaptive platforms in the 1990s and 2000s, technology began to assist in differentiating instruction, albeit in a rule-based and relatively static manner. The rise of AI technologies in the 2010s brought a transformative shift: intelligent systems could now co-evolve with learners, adjusting instructional pathways in real time based on ongoing assessments and behavioral data (Roll & Wylie, 2016). Modern AI systems such as Squirrel AI, Knewton, and Century Tech exemplify this evolution by providing granular personalization at scale, supporting dynamic learning trajectories tailored to individual needs.

Concurrently, the development of teacher digital pedagogical competence has undergone a profound transformation. Initially centered on basic technological literacy—operating devices and software—teachers' digital competencies have expanded to include sophisticated pedagogical integration and data-driven decision-making. The TPACK framework revolutionized this understanding by emphasizing the seamless blending of technology, pedagogy, and content (Koehler & Mishra, 2009). In the AI era, teachers must interpret complex analytics, engage ethically with data, and dynamically adjust instruction based on real-time feedback. Researchers such as Sharma (2020) and Fang and Deng (2024) argue that teacher competence in AI-enhanced environments must encompass algorithmic literacy, ethical sensitivity, and strategic pedagogical adaptability. Without such competencies, the full potential of AI-driven differentiation cannot be realized, and the risk of superficial or even harmful AI integration increases.

Student learning diversity has long been acknowledged as a critical factor influencing instructional effectiveness. Foundational theories by Piaget, Vygotsky, Gardner, and others emphasized the importance of cognitive, cultural, and emotional differences among learners. In traditional classrooms, teachers struggled to fully accommodate such diversity due to time, resource, and scalability constraints. AI technologies offer a breakthrough by enabling micro-level detection of learner differences and macro-level personalization of learning experiences (Zawacki-Richter et al., 2019). Platforms like DreamBox and Knewton dynamically adjust content difficulty, presentation style, and pacing based on real-time data. Yet, concerns persist regarding algorithmic bias and the risk of exacerbating educational inequalities if AI systems are not designed with inclusivity in mind (Tozadore et al., 2025). Therefore, understanding how AI interacts with student diversity—and ensuring that it promotes rather than undermines equity—is a critical area of inquiry.

The definition and measurement of teaching effectiveness have also evolved significantly. Initially focused on student test scores, the concept has broadened to include process-oriented indicators such as engagement, emotional well-being, and the development of critical thinking and independent learning skills. The integration of AI into education has further expanded these dimensions by enabling real-time formative assessment, adaptive feedback, and personalized support (Roll & Wylie, 2016; Mishchuk et al., 2024). AI systems allow for continuous tracking of student behaviors, cognitive states, and affective responses, providing a multidimensional view of learning processes. However, the use of AI in evaluating teaching effectiveness raises ethical concerns regarding data privacy, informed consent, and algorithmic transparency (Naamat-Schneider & Alt, 2024). Ensuring that AI-enhanced evaluations are equitable, transparent, and pedagogically meaningful is essential for their responsible use.

Despite the promising potential of AI in differentiated instruction, several critical research gaps remain. First, there is a lack of integration between teacher digital pedagogical competence and student learning diversity in most AI education studies. Much of the existing research focuses on the technical capabilities of AI systems without adequately addressing how teachers interpret and act upon AI-generated data within diverse classrooms (Ifenthaler & Yau, 2020). Second, there is a scarcity of multivariate empirical models that capture the complex interactions among AI technologies, teacher competencies, student diversity, and instructional outcomes. Most studies isolate single variables rather than exploring their interdependencies, limiting our understanding of how AI can be optimized for holistic educational improvement.

Additionally, longitudinal research tracking the sustained impact of AI-driven differentiated instruction remains rare. While short-term gains in engagement and achievement have been documented, little is known about the long-term effects on learning trajectories, teacher professional development, or systemic educational change. Addressing these gaps requires comprehensive models that account for the dynamic, reciprocal relationships among technology, pedagogy, and learner diversity, as well as rigorous longitudinal methodologies.

Against this backdrop, the current study proposes a conceptual model that positions AI-driven differentiated instruction as the independent variable influencing teaching effectiveness. Teacher digital pedagogical competence is posited as a mediating variable, reflecting the pivotal role of human agency in leveraging AI tools effectively. Student learning diversity is introduced as a moderating variable, acknowledging that the impact of AI may vary depending on the heterogeneity of the learner population. This integrated framework aims to unpack not only whether AI-driven differentiation works, but also how and under what conditions it achieves optimal results.

By situating the research within the rapidly evolving Chinese educational context, where digital transformation initiatives are accelerating yet regional disparities persist, the study offers novel insights into the practical challenges and opportunities of AI integration at scale. Furthermore, by encompassing multiple educational levels—K–12, vocational, and higher education—the research enhances the generalizability of its findings, addressing the diversity of institutional contexts.

The literature also reveals that teacher readiness is a critical bottleneck for successful AI integration. Professional development programs must move beyond basic digital literacy training to include modules on algorithmic reasoning, ethical AI use, data interpretation, and adaptive instructional design (Kubincová et al., 2024; Kurbonovna, 2025). Moreover, teacher involvement in the co-design of AI systems can enhance system relevance, usability, and trustworthiness (Zhang & Zhang, 2024). Therefore, building robust teacher capacities is not merely a support measure but a central strategy for realizing AI's educational potential.

Similarly, ensuring that AI systems are inclusively designed and ethically deployed is essential to mitigating the risk of exacerbating existing educational inequalities. Researchers emphasize the need for transparent algorithms, inclusive datasets, and participatory design processes that center the needs of marginalized learners (Alsaedi, 2024; Wangkamhan & Nachaisin, 2024). Addressing these ethical imperatives is crucial to ensuring that AI becomes a tool for democratizing education rather than reinforcing systemic disparities.

In conclusion, the convergence of AI technologies, differentiated instruction theories, teacher digital competencies, and student diversity presents unprecedented opportunities—and significant challenges—for educational innovation. AI has the potential to personalize learning at scale, enhance teaching effectiveness, and promote educational equity. However, realizing this potential depends on careful attention to the human and contextual dimensions of AI integration. Teachers' competencies, students' diverse needs, ethical considerations, and systemic factors must all be carefully considered and strategically addressed. By adopting a multidimensional, empirically grounded approach, future research and practice can harness AI's capabilities to build more inclusive, effective, and transformative educational systems.

Methodology

This study adopts a rigorous explanatory sequential quantitative research design to systematically investigate how artificial intelligence (AI)-powered differentiated instruction influences teaching effectiveness through the mediating role of teacher digital pedagogical competence and the moderating role of student learning diversity. Grounded in a theory-driven empirical inquiry framework, this research emphasizes the phased collection and statistical analysis of data to validate the complex causal mechanisms among educational innovation, teacher competence, and learner characteristics.

Although explanatory sequential design originated from mixed-methods research, this study operationalizes it purely through quantitative approaches, forming a coherent chain from theoretical modeling to quantitative data collection and statistical interpretation. This method is particularly suited to testing mediation and moderation mechanisms, enabling rigorous validation of the proposed conceptual model through statistical means.

The selection of a quantitative methodology is based on the empirical nature of the research objectives and the multivariate complexity of the model structure. Given that the research model involves directional hypothesis testing (H1-H3) and examines mediation and moderation pathways, measurable data structures and formal modeling procedures are necessary for verification. Compared to qualitative methods, the quantitative approach offers distinct advantages: it enables the examination of the strength and significance of relationships among variables, ensures accurate measurement of latent constructs, promotes replicability and generalizability of findings, and provides robust empirical evidence to inform educational decision-making, teacher training, and AI tool deployment strategies.

The research process was divided into four main stages. First, a questionnaire instrument was developed by adapting and localizing validated scales from prior literature. All key concepts were measured using 7-point Likert scales to enhance data structure and measurement stability. A pilot test was conducted to evaluate the clarity, reliability, and contextual appropriateness of the questionnaire items.

The Educational Innovation in AI-Powered Differentiated Instruction Scale was developed based on Holmes et al. (2019) and measured how teachers use AI technologies to achieve personalized instruction, automatic feedback, and dynamic course adjustment. Sample items included: "I use AI systems to customize learning tasks for each student" and "AI tools help me adjust my teaching plans promptly based on student performance."

The Teacher Digital Pedagogical Competence Scale was designed according to the TPACK framework proposed by Koehler and Mishra (2009), assessing teachers' ability to integrate AI technologies into lesson planning, classroom implementation, and assessment. Example items included: "I can effectively incorporate AI tools into lesson design" and "I use AI platforms to assess students' learning progress."

The Student Learning Diversity Scale was based on Tomlinson's (2014) theory of differentiated instruction and measured teachers’ perceptions of cognitive, technological, and cultural diversity among their students. Sample items included: "There are significant differences in my students' learning styles" and "My students show substantial variation in learning readiness."

The Teaching Effectiveness Scale, adapted from Stronge (2018), examined teachers’ self-assessed instructional performance, including classroom engagement, instructional adaptability, and student feedback outcomes. Example items included: "My teaching consistently stimulates student engagement" and "I can flexibly adjust my teaching strategies based on students’ learning responses."

Second, a stratified random sampling strategy was employed during sample selection and data collection to ensure representativeness and diversity across educational levels, geographic regions, school types, and disciplinary backgrounds. Teachers from K–12 schools, vocational institutions, and universities across urban and rural areas of China were targeted. Both online and offline modes were utilized to maximize coverage, especially focusing on regions with limited digital access.

Third, structural equation modeling (SEM) was used as the core data analysis method. SEM was selected for its capability to estimate direct, mediating, and moderating paths simultaneously while accounting for measurement errors. The analysis process included descriptive statistics, confirmatory factor analysis (CFA) to validate the measurement model, and subsequent path analysis to examine the structural model. Mediation effects were assessed using Bootstrapping resampling with 5000 iterations, and moderation effects were analyzed using Hayes' PROCESS macro.

Fourth, emphasis was placed on ensuring measurement reliability, validity, and ethical compliance. Reliability was evaluated through Cronbach's alpha coefficients and Composite Reliability (CR), while validity was examined using Average Variance Extracted (AVE) and the Fornell-Larcker criterion. All participants followed informed consent procedures, and data were anonymized, encrypted, and used solely for academic research purposes under the approval of an institutional ethical review committee, ensuring full adherence to educational research ethics standards.

The use of SEM was particularly appropriate for this study because it allowed modeling of multiple structural paths simultaneously, accounting for latent variable measurement errors, testing complex mediation-moderation interaction models, and evaluating model quality through indices such as CFI, TLI, RMSEA, and SRMR. Constructs such as teaching effectiveness and teacher digital pedagogical competence, which are difficult to capture through single indicators, were effectively modeled as latent variables using multiple observed indicators, enhancing explanatory power and predictive validity.

The target population of this study consisted of in-service teachers in China who had actual experience using AI teaching tools. This included teachers from primary, junior high, senior high, vocational, and higher education institutions. Participants were required to have interacted with AI educational applications such as intelligent tutoring systems, adaptive learning platforms, automated feedback systems, or learning analytics dashboards. Use of platforms like Squirrel AI, Knewton, ClassIn, or Rain Classroom qualified teachers for inclusion.

Stratified sampling was conducted based on educational level, geographic region (eastern, central, western China), disciplinary category (sciences, humanities, languages, technical skills), school type (public or private), urban-rural classification, and gender balance. This strategy ensured the capture of the structural diversity of China's education system and enhanced the validity of student learning diversity as a moderating variable.

The sample size was determined based on recommended standards for SEM and moderated mediation analysis (Kline, 2016). Considering the complexity of the model and aiming to detect small-to-moderate effects with sufficient statistical power, the minimum required valid sample size was set at 500. To account for invalid responses and sample attrition, approximately 700–800 questionnaires were distributed, targeting an effective response rate of 60%–70%. Ultimately, a total of 536 valid questionnaires were collected, achieving a valid response rate of 75.1%. This sample size met the requirements for model estimation and demonstrated good representativeness and structural balance, covering teachers across primary, secondary, vocational, and higher education institutions from both urban and rural schools in eastern, central, and western China.

Strict inclusion and exclusion criteria were enforced. Eligible teachers had to be currently teaching (full-time or part-time) in China and have experience using AI educational tools. Participants were required to provide informed consent, complete key sections of the questionnaire, and avoid patterned or invalid responses. Non-teaching personnel and those without AI usage experience were excluded to ensure data relevance and internal validity.

All participants followed a rigorous informed consent procedure, receiving a detailed Research Information Sheet outlining the study's objectives, voluntary nature, data use policies, confidentiality measures, and withdrawal rights. Data were strictly anonymized, securely encrypted, and used solely for non-commercial academic research purposes, adhering fully to educational ethics standards and receiving institutional review board approval.

The data collection period lasted four to six weeks and was organized into five phases: pilot testing, formal deployment, mid-term reminders, supplemental collection, and data cleaning. Multiple reminder waves were issued to maximize response rates, and both online and offline versions incorporated logical validation mechanisms to ensure data quality.

Data analysis was carried out in a structured multi-step process. Descriptive statistics were first used to characterize sample demographics, central tendencies, and distributions. Correlation analysis provided preliminary insights into linear associations among core variables.

Multiple regression analysis (MRA) was employed to initially test the direct effect (H1) between AI-powered differentiated instruction and teaching effectiveness while controlling for demographic variables. Rigorous testing of linearity, multicollinearity, and normality of residuals was conducted.

Mediation analysis (H2) was performed using Bootstrapping resampling (5000 iterations) to examine the indirect effect of AI-driven instruction on teaching effectiveness through teacher digital pedagogical competence, employing Hayes' PROCESS macro-Model 4. Mediation was confirmed when the confidence intervals for indirect effects did not include zero.

Moderation analysis (H3) assessed whether student learning diversity moderated the relationship between AI instruction and teaching effectiveness. Centering of predictors and moderators was conducted, interaction terms were created, and simple slope analyses were used to explore how the relationship varied at high and low levels of student diversity.

In summary, the methodology employed in this study demonstrates a theoretically grounded, empirically rigorous, and ethically sound framework for examining the impacts of AI-powered differentiated instruction. By systematically integrating advanced multivariate statistical techniques, robust sampling strategies, and strict ethical safeguards, this study provides a solid empirical foundation for understanding how AI, through the agency of teachers and the diversity of learners, can drive transformational improvements in teaching effectiveness.

Results

This study systematically examined how AI-powered differentiated instruction influences teaching effectiveness through the mediation of teacher digital pedagogical competence and the moderation of student learning diversity. The results are organized into two primary areas: the demographic characteristics of the sample and the inferential statistical analyses that test the study's hypotheses.

The demographic data provided a comprehensive profile of the 536 participating teachers, offering essential context for interpreting the study's findings. In terms of geographic distribution, participants were well distributed across different regions in China. Teachers from rural areas constituted the largest proportion (27.4%), followed closely by those from provincial capitals or prefecture-level cities (26.5%), county-level cities or towns (23.7%), and first-tier cities (22.4%). This balanced regional distribution enhances the representativeness of the sample and ensures that findings are not biased toward any particular educational setting.

The teaching experience of participants was also varied, covering the full professional lifespan. Teachers with 4–10 years of experience represented the largest subgroup (25.4%), followed by those with less than 1 year (20.0%), 1–3 years (19.4%), 11–20 years (17.9%), and over 20 years (17.4%). This distribution reflects a balanced mix of novice, intermediate, and senior teachers, which is critical for evaluating the relationship between AI adoption and pedagogical outcomes across different stages of professional development.

Regarding subject specialization, participants were distributed across six major areas. Arts and Physical Education accounted for the largest group (25.4%), followed by Mathematics and Science (23.3%), Humanities and Social Sciences (16.4%), Languages (14.6%), Vocational Skills (10.3%), and Higher Education Professional Courses (10.1%). This interdisciplinary spread supports the generalizability of the findings across diverse curriculum areas.

The frequency of AI tool usage among teachers revealed interesting patterns. A significant majority (77.4%) reported using AI teaching tools regularly, with 30.0% indicating deep integration into daily teaching activities, 27.4% reporting frequent use (almost every class), and 20.0% using AI tools systematically (at least once a week). Only a small fraction (22.6%) had limited or no AI exposure. This widespread adoption provides a solid foundation for analyzing the pedagogical effects of AI integration.

Training experience in AI teaching was relatively high among the participants. About 37.5%

had received systematic training organized by institutions, while 42.4% had participated in short-term workshops or online courses. However, 20.1% of teachers reported no formal training experience, highlighting ongoing gaps in professional development that could influence the effective use of AI in teaching.

The reliability and validity tests confirmed the robustness of the measurement instruments. The corrected item-total correlations for all constructs exceeded 0.862, demonstrating strong internal consistency. Cronbach's alpha values for each scale were exceptionally high (ranging from 0.885 to 0.968), indicating excellent reliability. Confirmatory factor analysis (CFA) further verified the constructs' convergent and discriminant validity. All standardized factor loadings exceeded 0.80, Average Variance Extracted (AVE) values were greater than 0.69, and Composite Reliability (CR) indices surpassed 0.91 across constructs, thus affirming that the measures accurately captured the intended latent variables.

The Fornell-Larcker test results showed that each construct's square root of AVE was greater than its correlations with other constructs, confirming adequate discriminant validity. Overall, the measurement model demonstrated excellent psychometric properties, ensuring the reliability and validity of the subsequent structural analyses.

Correlation analysis provided preliminary support for the study's primary hypothesis. The Pearson correlation coefficient between Educational Innovation in AI-Powered Differentiated Instruction and Teaching Effectiveness was 0.913 ($p < 0.01$), indicating a very strong positive relationship. This result suggests that the more extensively teachers apply AI-driven strategies for differentiated instruction, the greater their perceived teaching effectiveness.

Regression analysis further reinforced this finding. The independent variable, Educational Innovation in AI-Powered Differentiated Instruction, had a standardized regression coefficient (Beta) of 0.588, with a t-value of 16.784 ($p < 0.001$). The model's R-squared value was 0.345, indicating that AI-driven differentiated instruction explained approximately 34.5% of the variance in teaching effectiveness. The F-statistic (281.716, $p < 0.001$) confirmed the overall significance of the regression model. These results provide strong empirical support for Hypothesis 1, affirming that AI-driven differentiated instruction significantly and positively impacts teaching effectiveness.

Mediation analysis examined the role of Teacher Digital Pedagogical Competence in this relationship. The first-stage regression ($X \rightarrow M$) revealed a strong association between AI-driven instruction and teacher competence ($r = 0.678$, $R^2 = 0.4597$, $F = 454.3224$, $p < 0.001$), suggesting that the adoption of AI technologies substantially enhances teachers' digital pedagogical skills.

In the second stage ($X + M \rightarrow Y$), the model's R^2 increased dramatically to 0.8572 ($F = 1599.9109$, $p < 0.001$), indicating that incorporating teacher competence as a mediator substantially improved the model's explanatory power. The direct effect of AI-driven instruction on teaching effectiveness, after accounting for the mediator, remained positive and significant ($B = 0.0653$, SE =

0.0201, t = 3.2440, p = 0.0013), with a 95% confidence interval of [0.0258, 0.1049] not crossing zero.

More importantly, the indirect effect via teacher digital competence was substantial (B = 0.5968, SE = 0.0373), with a Bootstrap confidence interval of [0.5229, 0.6689], confirming the significance of the mediating pathway. These results validate Hypothesis 2, demonstrating that AI-powered differentiated instruction enhances teaching effectiveness both directly and indirectly by improving teachers' digital pedagogical competence.

Moderation analysis assessed whether Student Learning Diversity influenced the strength of the relationship between AI-driven instruction and teaching effectiveness. The interaction term between Educational Innovation in AI-Powered Differentiated Instruction and Student Learning Diversity was significant (B = 0.045, SE = 0.015, β = 0.325, t = 0.768, $p < 0.001$).

This finding suggests that student diversity significantly moderates the relationship: the positive impact of AI-driven differentiated instruction on teaching effectiveness becomes stronger as the heterogeneity of the student body increases. In other words, AI-enhanced instructional practices are particularly beneficial in classrooms characterized by greater variability in students' learning styles, cognitive abilities, and technological access. This result provides empirical support for Hypothesis 3 and underscores the context-sensitive nature of AI pedagogical effectiveness.

Collectively, these findings confirm the validity of the proposed conceptual framework. AI-powered differentiated instruction positively influences teaching effectiveness, with teacher digital pedagogical competence serving as a significant mediator and student learning diversity acting as a positive moderator. These results offer critical insights into how educational innovation and human factors interact to shape teaching outcomes in technology-enhanced environments.

Importantly, the findings highlight the indispensable role of teacher competence in translating AI technological potential into tangible pedagogical benefits. While AI systems provide powerful capabilities for personalization, the extent to which these capabilities are realized in practice depends heavily on teachers' abilities to interpret, adapt, and integrate AI-generated insights into pedagogical routines. Without sufficient digital pedagogical competence, even the most advanced AI tools may fail to achieve meaningful improvements in learning outcomes.

Similarly, the moderating effect of student learning diversity suggests that AI technologies are most impactful when classrooms are highly heterogeneous. AI-driven differentiation allows teachers to cater more effectively to individual differences, thus optimizing learning experiences and promoting educational equity. However, this also implies that AI strategies must be designed with inclusivity and adaptability in mind, ensuring that diverse student needs are met rather than exacerbated.

In conclusion, the empirical results of this study provide strong support for the hypothesized relationships and offer valuable guidance for theory, policy, and practice. AI-driven differentiated instruction emerges as a powerful tool for enhancing teaching effectiveness, but its success is contingent upon equipping teachers with the necessary digital competencies and tailoring AI implementations to accommodate student diversity. These findings underscore the need for integrated approaches that combine technological innovation, human capacity building, and inclusive instructional design to fully realize the transformative potential of AI in education.

Discussion

This study centers on the mechanism of the impact of AI-driven differentiated instruction on teaching effectiveness, focusing on the mediating role of teachers' digital teaching ability and the moderating role of students' learning variability. The results of the study generally show a high degree of consistency with current existing research in related fields at home and abroad, while also showing new extensions and differences in some of the detailed mechanisms.

First, this study confirms that AI differentiated instruction has a significant positive impact on teaching effectiveness, a finding that is highly consistent with the findings of Luckin et al. (2016) and Zawacki-Richter et al. (2019) on the role of AI in enhancing the efficiency of personalized instruction and promoting students' motivation and learning effectiveness. This study validates this underlying trend with a large sample and further confirms its general applicability in the context of different education stages (K-12, vocational education and higher education) in China, enhancing the localized empirical support of the existing findings.

Second, this study found that teachers' digital pedagogical competence significantly mediated the relationship between AI pedagogical innovations and instructional effectiveness, which is highly in line with the TPACK theory proposed by Koehler and Mishra (2009), which suggests that teachers' competence in the integration of technology, pedagogy, and content knowledge directly determines the effectiveness of technology adoption. Echoing Ifenthaler and Yau's (2020) findings that identified teacher digital literacy as a key factor in the successful implementation of AI education, this study further clarifies the role of teacher AI application competencies as a bridge in transforming AI potential into instructional efficacy through empirical path analysis.

Third, this study found that student learning variability positively moderated the relationship between AI differentiated instruction and instructional effectiveness, i.e., the higher the heterogeneity of the student population, the more effective the AI differentiated instruction strategy. This finding is consistent with Tomlinson's (2014) basic ideas about the theory of differentiated instruction and supports the theoretical speculation of an adaptive advantage of AI in diverse environments as proposed by Roll & Wylie (2016).

Despite the general trend of consistency, this study presents some differences and expansion from the existing literature in the following areas:

First, compared with existing studies that mostly focus on the single-point functional verification of AI tools (e.g., formative assessment effectiveness, intelligent push accuracy), this study emphasizes the systematic teaching innovation mechanism, which unifies instructional design, teacher competence, and learner characteristics into the analysis framework. By constructing a multi-path mediation and regulation model, this study reveals the chain of action of AI-enabled teaching effectiveness in a more three-dimensional way than a single-dimensional examination, and provides a more systematic theoretical perspective for understanding the application of AI in education.

Second, in terms of teacher factors, some of the literature (e.g., Holmes, Bialik, & Fadel, 2019) points out that teachers are generally resistant to AI applications or have insufficient depth of application, but this study finds that under the current policy of digital transformation of education in China, the interviewed teachers generally show high willingness and motivation to apply AI. Especially at the vocational and higher education levels, teachers' digital teaching competence has a particularly significant impact on teaching effectiveness. This difference may be closely related to the differences in sample backgrounds, policy environments, and teacher training systems.

Third, in terms of student factors, foreign studies tend to emphasize the constraints of technological accessibility and digital divide issues on the effectiveness of AI education (UNESCO, 2021), whereas this study found in the Chinese context that despite the differences in digital resources between urban and rural areas and between regions, in general the variability of students in terms of technological access has been significantly reduced, and that the variability of students' learning is more manifested at the level of cognitive styles, motivation for learning, and The differences in students' learning are more in terms of cognitive styles, motivation, and self-directed learning ability, among other intrinsic characteristics. This difference suggests that with the popularization of infrastructure, future AI education applications need to pay more attention to "internal learning differences" rather than pure "technology access differences".

Possible reasons for the discrepancies and expansions found above include:

First, the positive guidance of the policy environment. In recent years, China has continued to promote education digitization strategies, such as the Education Informatization 2.0 Action Plan and the Action Plan for the Innovative Development of Intelligent Education, which have provided policy guarantees and resource support for the application of AI technology in the education field, prompting teachers to rapidly improve their digital teaching ability, in contrast to the conservative attitude of teachers' technology application in the low-investment environments of some foreign countries.

Second, the systematic construction of the teacher training system. Most of the teachers in this study sample have received systematic AI application training or workshop support, which is different from the traditional passive acceptance of technology introduction, giving teachers a higher sense of control and efficacy of AI-empowered teaching and enhancing the execution of the AI teaching model and the improvement of teaching effectiveness.

Third, the overall level of students' digital literacy has improved. Influenced by the popularization of mobile Internet and the "smart society" environment, Chinese primary and secondary school students and college students generally have higher information technology use ability, which enables AI-driven differentiated teaching to realize effective adaptation and landing in a short period of time, and weakens the negative effect brought by the technology access gap.

Fourth, the systematic enhancement of the research methodology. This study adopts a combination of structural equation modeling (SEM) and mediation moderation analysis (PROCESS Macro), which can more accurately capture the intrinsic relationship and mechanism of action among complex variables than previous studies relying only on simple regression or descriptive statistics, and thus has made a breakthrough in terms of model refinement and result interpretation power.

Conclusion

This study systematically investigated the mechanisms through which AI-driven differentiated instructional innovations influence teaching effectiveness in contemporary Chinese classroom environments. Particular emphasis was placed on understanding the mediating role of teachers' digital pedagogical competence and the moderating role of students' learning variability. By applying rigorous quantitative methods, including correlation, regression, mediation, and moderation analyses, the study yielded multiple critical insights into how educational innovations, technological competencies, and learner diversity intersect to shape instructional outcomes in the digital era.

First, the study confirmed through both correlation and regression analyses that AI-enabled differentiated instructional innovations, specifically including AI-based personalized learning path designs, automated formative assessments, and adaptive classroom teaching strategies, significantly and positively impact teaching effectiveness ($\beta = 0.588$, $p < 0.001$). This finding provides robust empirical validation for the foundational hypothesis of this research: deep integration of AI technologies into instructional design and implementation processes substantively enhances a teacher’s ability to deliver personalized support, increase classroom adaptability, and elevate overall instructional quality. Theoretically, these results align with constructivist learning theories and adaptive learning frameworks (Corno & Snow, 1986), which posit that personalized and responsive learning environments foster improved educational outcomes.

Moreover, this finding extends the ongoing conversation around AI in education beyond narrow case studies focused on specific subjects or elite institutions. By demonstrating the positive impacts of AI-driven differentiation across a diverse and representative sample of Chinese educators, this study reinforces the view that AI has the potential to revolutionize mainstream classroom teaching practices, not just niche or experimental contexts. It challenges traditional models of mass, standardized instruction and offers a clear pathway toward student-centered, adaptive educational environments powered by intelligent technologies.

Second, the study’s mediation effect analysis revealed that teachers' digital pedagogical competence plays a pivotal mediating role between AI instructional innovation and teaching effectiveness. Specifically, teachers with higher digital pedagogical literacy—particularly those demonstrating advanced skills in using AI tools for curriculum design, formative feedback, and differentiated task assignment—were substantially better able to realize AI's potential for enhancing instructional outcomes. This finding highlights that technology, in and of itself, is not a panacea; rather, it is the teacher's ability to skillfully integrate digital technologies into meaningful pedagogical practices that determines the degree to which AI innovations can be effectively leveraged in education.

This mediating effect resonates strongly with the Technological Pedagogical Content Knowledge (TPACK) framework (Koehler & Mishra, 2009), which emphasizes the necessity of integrating technological, pedagogical, and content knowledge for effective educational technology implementation. The results underscore the need for a human-centered approach to AI integration in education—one that sees teachers not merely as end-users but as active agents who interpret, adapt, and strategically apply AI insights to maximize learning outcomes. Importantly, this finding carries significant implications for teacher professional development programs: training must move beyond superficial tool use workshops and foster deep digital pedagogical literacy that encompasses ethical considerations, data-driven instructional decision-making, and adaptive learning design.

Third, the moderation analysis confirmed that student learning variability exerts a significant positive moderating effect on the relationship between AI instructional innovations and teaching effectiveness. Specifically, in classrooms characterized by higher levels of learning variability—including differences in learning styles, cognitive development, technological access, and socio-economic background—AI-driven differentiated instruction more significantly enhances teaching outcomes. This result fully supports Hypothesis H3 proposed in this study and echoes adaptive learning theory's emphasis on learner-centered responsiveness as a critical success factor for instructional effectiveness.

By demonstrating that the benefits of AI-driven differentiation are magnified in heterogeneous classroom environments, this study provides strong empirical support for the argument that AI technologies offer scalable, sustainable solutions to longstanding educational equity challenges. AI's ability to deliver real-time personalized support, dynamic content adaptation, and continuous formative assessment enables teachers to more effectively meet the diverse needs of their students—something that traditional uniform teaching models have historically struggled to accomplish. However, this finding also highlights the ethical responsibility of AI developers and educational institutions to ensure that AI systems are inclusive, fair, and responsive to diverse learner profiles.

Overall, the findings of this study emphasize that two key enabling conditions must be simultaneously satisfied for AI-powered educational innovations to significantly enhance teaching effectiveness: (1) teachers must possess a high level of digital pedagogical competence, enabling them to flexibly and meaningfully integrate AI technologies into all stages of the instructional process; and (2) the teaching environment must exhibit substantial student learning diversity, providing fertile ground for AI-enabled differentiation strategies to maximize their individualized and adaptive advantages.

By synthesizing these findings, this study offers several important contributions to academic research and educational management practice. First, it advances our theoretical understanding of AI integration in education by framing teaching effectiveness not simply as a function of technology adoption but as a complex interplay among technological innovation, teacher agency, and learner diversity. Second, it provides empirical validation for integrated models that consider both mediation and moderation mechanisms, moving beyond linear cause-effect assumptions prevalent in earlier studies. Third, it offers actionable insights for educational practitioners, administrators, policymakers, and technology developers seeking to harness AI's transformative potential responsibly and effectively.

Specifically, Conclusion 1 affirms that AI-driven differentiated instructional innovations directly contribute to teaching effectiveness by enhancing the level of instructional personalization and classroom adaptability. This finding is critically important for educators and instructional designers seeking to move beyond standardized, one-size-fits-all approaches. It encourages them to envision classrooms where learning is dynamically tailored to individual student needs, preferences, and trajectories, fostering deeper engagement and improved outcomes.

Conclusion 2 highlights that teachers' digital pedagogical competence is a key mediating mechanism connecting the application of AI technologies and the improvement of teaching quality. This underscores the vital role of teacher professional development in realizing the promises of AI educational innovation. Policymakers and school leaders must therefore prioritize investments in ongoing digital pedagogy training, ensuring that teachers are not only technologically literate but also pedagogically adaptive and ethically informed.

Conclusion 3 confirms that student learning variability positively moderates the effectiveness of AI-driven differentiated instruction. The more diverse the classroom, the greater the instructional benefits realized through AI technology integration. This conclusion advocates for the design and deployment of AI systems that are inclusive, flexible, and responsive to a broad range of learner needs. It also implies that AI adoption strategies should be particularly targeted at educational contexts characterized by high heterogeneity, such as inclusive classrooms, rural schools, and underserved communities.

Taken together, these conclusions point toward a coherent strategic direction for educational innovation in the AI era. To drive AI-enabled educational transformation, a dual-pronged strategy is essential: first, significantly enhance teachers' AI pedagogical literacy; second, systematically design instructional innovation models that effectively respond to the diversity of student characteristics. Only through the coordinated realization of these two conditions can educational systems achieve a true leap in teaching quality and learning equity based on artificial intelligence.

The implications of these findings extend beyond theoretical interest and into tangible educational reform agendas. Educational technology vendors must develop AI platforms that are not only technically sophisticated but also pedagogically transparent, ethically responsible, and culturally inclusive. Teacher education institutions must redesign curricula to equip future educators with the skills necessary to critically engage with AI systems, evaluate their pedagogical affordances, and adapt their use to dynamic classroom realities.

Moreover, educational policymakers must resist the temptation to equate technological deployment with innovation. True educational innovation requires systemic support for teacher agency, critical reflection on AI use, and sustained investment in building inclusive learning environments. Accountability frameworks must shift from narrow metrics of AI system adoption rates to broader evaluations of their actual impacts on teaching quality, learner engagement, and educational equity.

Future research should continue to explore the longitudinal impacts of AI integration, examining how teachers' digital pedagogical competences evolve over time and how sustained AI-supported differentiation affects student learning trajectories. Mixed-methods designs incorporating classroom observations, student feedback, learning analytics, and teacher reflective journals would offer deeper insights into the lived realities of AI-enhanced teaching and learning.

In closing, the findings of this study reaffirm that while AI holds transformative potential for education, it is not a substitute for pedagogical wisdom, human judgment, or ethical stewardship. Rather, AI should be seen as an enabler—a powerful ally that, when strategically and ethically integrated by competent teachers into diverse learning environments, can significantly enhance teaching effectiveness and promote more inclusive, adaptive, and human-centered education systems.

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