EduMa: Mathematics Education Learning and Teaching
December 2025, Vol 14 No 2 Page 401 – 415
https://syekhnurjati.ac.id/jurnal/index.php/eduma/eduma/article/view/22396
p-ISSN: 2086-3918, e-ISSN: 2502-5209
Published by Tadris Matematika UIN Siber Syekh Nurjati Cirebon

EduMa
MATHEMATICS EDUCATION LEARNING AND TEACHING

The Dominant Factor in Educational Digitalization Sustainability: Structural Equation Modeling of Technology Acceptance Versus Digital Literacy on Student Learning Outcomes

Nur Indah Septia Ningsih[1*], Haryadi[2], Bernadus Wahyudi Joko Santoso[3]

1 Post Graduate School, Universitas Negeri Semarang
2 Post Graduate School, Universitas Negeri Semarang
3 Post Graduate School, Universitas Negeri Semarang

*Corresponding author: Jl. Seruni Utara, Kota Pekalongan, Jawa Tengah, 45144, Indonesia
e-mail addresses: indahsn@students.unnes.ac.id

article info

How to cite this article:

Ningsih, Nur Indah Septia , Haryadi, & Santoso, Bernadus Wahyudi Joko. (2025). The Dominant Factor in Educational Digitalization Sustainability: Structural Equation Modeling of Technology Acceptance Versus Digital Literacy on Student Learning Outcomes. *Eduma : Mathematics Education Learning And Teaching*, 14(2), 401 - 415. doi:http://dx.doi.org/10.24235/eduma.v14i2.22396

Article history:

Received: 10 29, 2025

Accepted: 12 12, 2025

Published: 12, 2025

abstract

This study examines the dominant factors influencing student learning outcomes in digital mathematics learning, focusing on Technology Acceptance and Digital Literacy. A unified model combining the Technology Acceptance Model (TAM) and Digital Literacy framework was tested using Partial Least Squares Structural Equation Modeling (PLS-SEM). The participants were 125 fifth-grade students from three public elementary schools in Cirebon. Data were collected through validated questionnaires measuring Perceived Ease of Use, Perceived Usefulness, Attitude, Digital Literacy, and mathematics learning outcomes. The findings showed that all hypothesized relationships were significant ($p < 0.001$). Digital Literacy had a stronger effect on learning outcomes ($\beta = 0.415$) than Technology Acceptance ($\beta = 0.311$), with the cognitive dimension contributing the most ($\beta = 0.521$). The results also indicated that Digital Literacy fully mediates its dimensions, while Technology Acceptance influences learning outcomes through sequential pathways involving perceived usefulness and attitude. The study concludes that Digital Literacy is the main predictor of learning outcomes in digital mathematics learning. Therefore, sustainable educational digitalization should prioritize strengthening students' digital literacy competencies alongside technology adoption.

Keywords:
Digital Literacy; Learning Outcomes; Technology Acceptance Model (TAM); Structural Equation Modeling (SEM).

INTRODUCTION

The rapid digitalization of education represents a global imperative, yet its sustainable integration continues to face significant challenges. Recent PISA 2022 results highlight a concerning paradox: while most students in OECD countries possess access to digital learning devices, only a minority demonstrate proficiency in using them for complex learning tasks (Bilad et al., 2024; OECD, 2023). This discrepancy underscores a fundamental issue in translating technological access into meaningful educational improvement, a trend further corroborated by stagnant mathematics performance in TIMSS 2019 despite increased technological investments globally (Mullis IVS, Martin MO, Foy P, Kelly DL, 2020).

The heart of this paradox lies in the unresolved tension between technological infrastructure and human factors. Preliminary research conducted on October 7, 2023, across three elementary schools in Cirebon, West Java, uncovered crucial insights through in-depth interviews with 15 teachers. Teachers expressed profound confusion about why students' learning outcomes varied dramatically despite using identical digital platforms. As one teacher articulated, "Some students thrive with digital tools, while others struggle with the same resources - I cannot determine whether this depends on their comfort with technology or their critical digital skills." This classroom dilemma mirrors the broader theoretical divide in educational technology research.

Current literature presents two dominant yet disconnected perspectives. On one hand, Technology Acceptance Model (TAM) research emphasizes perceived usefulness and ease of use as primary determinants of technology adoption (Davis, 1989; Venkatesh et al., 2003). On the other hand, digital literacy studies focus on competencies in information evaluation, ethical understanding, and critical thinking (Eshet-Alkalai, 2012; Ng, 2012). However, these streams have evolved in parallel, creating a significant research gap: lack understanding of which factor plays a more dominant role in achieving sustainable educational outcomes in digitalized learning environments.

Emerging empirical evidence within mathematics education further substantiates these theoretical pathways. A recent investigation by (Qudwatullathifah et al., 2023) utilizing a validated virtual mathematics platform demonstrated distinct mechanistic roles for both constructs. The study established that TAM constructs, particularly perceived usefulness, were significant predictors of procedural fluency and conceptual understanding, as an intuitive interface reduced cognitive load and allowed students to engage more deeply with mathematical content (Ningsih, 2024). Concurrently, digital literacy competencies, specifically the ability to critically evaluate digital information and manipulate computational tools showed a strong, direct correlation with enhanced problem-solving and mathematical reasoning skills (Govender, 2025; Lee et al., 2023; Yuan et al., 2021). This evidence from a domain-specific digital learning environment confirms that both acceptance and literacy are pivotal, yet their impacts manifest in different dimensions of mathematical achievement, solidifying the necessity to investigate their relative dominance.

Addressing this research gap acquires particular urgency considering the massive scale of global investment in educational technology. Projections indicate the educational technology market will reach USD 404 billion by 2025 (HolonIQ, 2020), highlighting the high stakes involved in resource allocation decisions. Educational institutions currently operate without clear empirical guidance on whether to prioritize improving technology acceptance or developing digital literacy, potentially leading to ineffective implementation strategies and wasted resources (David et al., 2023; Singun, 2025; Timotheou et al., 2023; Zhao et al., 2024). This uncertainty necessitates a rigorous comparative analysis to identify the most impactful leverage point for interventions.

The present study introduces methodological novelty by employing a comparative structural approach to resolve this critical uncertainty. Using Structural Equation Modeling (SEM), the research quantitatively examines the relative impact of technology acceptance versus digital literacy on student learning outcomes. This methodology enables a direct comparison of predictive power within a unified theoretical framework, overcoming the limitations of previous research that examined these factors in isolation. The analytical approach specifically determines which construct serves as the dominant factor influencing educational effectiveness. Based on the proposed research framework, this study is guided by the following research questions:

1. What are the direct and indirect effects of Technology Acceptance (TAM) and Digital Literacy on mathematics learning outcomes in a digital platform environment?
2. Which construct has a more dominant total effect on mathematics learning outcomes: Technology Acceptance (TAM) or Digital Literacy?

METHODS

Research Design

This study employs a quantitative, explanatory research design to examine the causal relationships between technology acceptance, digital literacy, and mathematics learning outcomes (Singarimbun, 1995). The methodological approach is grounded in the Technology Acceptance Model (TAM) as the primary theoretical framework (Davis, 1989). A survey strategy was adopted to collect empirical data, allowing for the statistical testing of the proposed hypotheses (Zhang et al., 2007).

Population and Sample

The research population consisted of fifth-grade students from public elementary schools in the region. A two-stage sampling technique was implemented to ensure both relevance and representativeness. In the first stage, purposive sampling was used to select three schools based on specific criteria, including representativeness of the local student body, feasibility of data collection, and researcher accessibility. The selected schools were SD A, SD B, and SD C.

In the second stage, the sample size was determined using the Slovin formula to achieve a precision level of 95% confidence (Yamane, 1967). From a total population of 167 students across the three schools, a minimum sample of 125 students was calculated. Proportional allocation sampling was then applied to determine the number of respondents from each school, resulting in 44 students from SD A, 57 from SD B, and 24 from SD C. This method ensured the sample accurately reflected the proportional distribution of the population.

Data Collection

Data was collected using a structured self-administered questionnaire. The instrument was divided into three main sections:

Technology Acceptance (TAM): This section measured constructs of Perceived Usefulness (PU), Perceived Ease of Use (PEOU), and Attitude Towards Using Technology (ATT). The items were adapted from established scales by Lin & Yu (2023) and Qu et al. (2023) and were measured on a five-point Likert scale.

1. Digital Literacy: This section assessed students' competencies in information evaluation, ethical understanding, and critical thinking in digital environments. The items were adapted from the validated Digital Literacy Scale (DLScale) developed by Ng (2012). Ng's (2012) digital literacy results from three intersecting dimensions that are the technical (T), cognitive (COG) and social-emotional (SE) dimensions of digital literacy.
2. Mathematics Learning Outcomes: Data on learning outcomes were obtained from standardized test scores administered through the digital mathematics platform, providing an objective measure of student achievement.

Data Analysis

The data analysis was conducted using SmartPLS 4.0 to perform Partial Least Squares Structural Equation Modeling (PLS-SEM). The analysis followed a two-stage approach:

1. Assessment of the Measurement Model (Outer Model): This involved evaluating the reliability and validity of the constructions. Internal consistency was assessed using Composite Reliability. Convergent validity was examined through factor loadings and Average Variance Extracted (AVE). Discriminant validity was tested using the Heterotrait-Monotrait (HTMT) ratio.
2. Assessment of the Structural Model (Inner Model): This step tested the research hypotheses. The significance of the path coefficients was evaluated using a bootstrapping procedure with 5,000 subsamples. The model's predictive power was assessed using the coefficient of determination (R^2) and the predictive relevance (Q^2). A specific contrast test was performed to determine the dominant construct influencing learning outcomes.

To examine the structural relationships among constructs, eight hypotheses (H1–H8) were formulated based on the proposed conceptual framework. The hypotheses were designed to test both the direct effects of Technology Acceptance variables and the hierarchical structure of Digital Literacy on Learning Outcomes. Specifically, H1 proposed that Attitude (ATT) positively influences Learning Outcomes (LO), while H2 examined the direct effect of Digital Literacy (DL) on Learning Outcomes. Within the Technology Acceptance Model domain, H3 and H4 hypothesized that Perceived Ease of Use (PEOU) significantly affects Attitude (ATT) and Perceived Usefulness (PU), respectively. Furthermore, H5 tested the relationship between Perceived Usefulness (PU) and Attitude (ATT). In the Digital Literacy construct, H6, H7, and H8 were formulated to validate the contributions of the Cognitive (COG), Social-Emotional (SE), and Technical (T) dimensions as predictors of the higher-order Digital Literacy construct. These hypotheses were analyzed using the structural model to evaluate the strength, direction, and significance of each path coefficient.

RESULT AND DISCUSSION

The evaluation of the measurement model involved assessing reliability, convergent validity, and discriminant validity to ensure the constructions were measured adequately. The measurement model employed reflective indicators, where causality flows from the construct to its measures. Convergent validity was assessed through examination of cross-loadings, with all indicators demonstrating strong loadings exceeding the recommended threshold of 0.70 on their respective constructs (Ghozali & Latan, 2015).

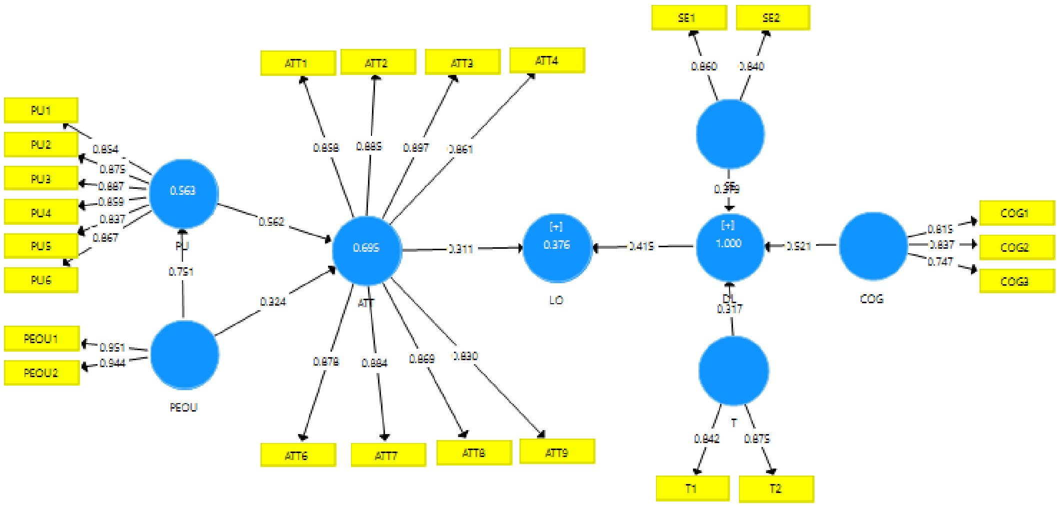

Figure 1
Estimate Model

As shown in Table 1, all constructs demonstrated excellent internal consistency. The Composite Reliability (CR) values for all constructs exceeded the recommended threshold of 0.7, ranging from 0.839 to 0.962, indicating high reliability. Furthermore, the Average Variance Extracted (AVE) for each construct was above the stringent criterion of 0.5, confirming adequate convergent validity (Hair et al., 2019). This indicates that the items sufficiently explain the variance of their respective constructions.

Table 1
Result of Convergen Validity and Reliability

	Composite Reliability	Average Variance Extracted (AVE)
ATT	**0,962**	**0,758**
COG	**0,842**	**0,641**
DL	**0,856**	**0,561**
LO	**0,917**	**0,690**
PEOU	**0,946**	**0,898**
PU	**0,946**	**0,745**
SE	**0,839**	**0,723**
T	**0,849**	**0,737**

Discriminant validity was assessed using the Heterotrait-Monotrait (HTMT) ratio of correlations. As presented in Table 2, all HTMT values were well below the conservative threshold of 0.90 (Henseler et al., 2015). This confirms that each construct in the model is truly distinct and captures a phenomenon not represented by the other constructs.

Table 2
Result of HTMT

	ATT	COG	DL	LO	PEOU	PU	SE	T
ATT								
COG	**0,360**							
DL	**0,487**	0,856						
LO	**0,516**	**0,553**	**0,631**					
PEOU	**0,810**	**0,308**	**0,468**	**0,572**				
PU	0,852	**0,356**	**0,512**	**0,637**	**0,823**			
SE	**0,489**	0,826	0,862	**0,628**	**0,445**	**0,484**		
T	**0,491**	**0,605**	0,895	**0,515**	**0,551**	**0,578**	**0,633**	

Variance Inflation Factor (VIF) values for all indicator items were examined to assess collinearity issues. As presented in Table 3, all VIF values ranged from 1.248 to 4.998, well below the conservative threshold of 5.0 (Hair et al., 2019). This indicates that collinearity does not pose a significant threat to the stability of parameter estimates in the structural model.

Table 3
Result of VIF

	VIF
ATT1	3,583
ATT2	4,314
ATT3	4,998
ATT4	3,982
ATT6	3,768
ATT7	3,953
ATT8	3,919
ATT9	**2,737**
LO1	3,312
LO2	3,353
LO3	**2,355**
LO4	**1,925**
LO5	**1,971**
COG1	**1,456**
COG1	**1,595**
COG2	**1,471**
COG2	**1,972**
COG3	**1,344**
COG3	**1,385**
PEOU1	**2,734**
PEOU2	**2,734**
PU1	**2,673**
PU2	3,071
PU3	3,341
PU4	3,047
PU5	**2,563**

PU6	3,057
SE1	**1,248**
SE1	**1,593**
SE2	**1,248**
SE2	**1,541**
T1	**1,293**
T1	**1,385**
T2	**1,293**
T2	**1,501**

The explanatory power of the structural model was evaluated through the coefficient of determination (R^2) as presented in Table 4. The analysis reveals varying predictive strength across endogenous constructs, with R^2 values ranging from moderate to substantial levels according to established criteria (Bagozzi & Yi, 1988; Hair et al., 2022).

Table 4
Result of R^2

Construct	R-Square	R-Square Adjusted	Interpretation
ATT	0.695	0.690	Substantial
DL	1.000	1.000	Perfect
LO	0.376	0.366	Moderate
PU	0.563	0.560	Moderate to Substantial

The Attitude Towards Using Technology (ATT) construct demonstrates substantial explanatory power with $R^2 = 0.695$, indicating that 69.5% of its variance is accounted for by Perceived Ease of Use and other antecedents in the model. Learning Outcomes (LO) shows moderate predictive accuracy with $R^2 = 0.376$, suggesting that 37.6% of variance in mathematics learning performance is explained by the combined effect of Technology Acceptance and Digital Literacy constructs. Perceived Usefulness (PU) achieves moderate to substantial explanatory power ($R^2 = 0.563$), with 56.3% of its variance predicted by Perceived Ease of Use. The Digital Literacy (DL) construct shows perfect determination ($R^2 = 1.000$), indicating it functions as a composite formative construct where its dimensions fully define the construct without measurement error.

Table 5
Path Coefficients and Hypothesis Testing Results

H	Path	Original Sample (O)	T-Statistics	P-Values	Result
H1	ATT -> LO	0.311	3.569	**0.000**	Supported
H2	DL -> LO	0.415	5.869	**0.000**	Supported
H3	PEOU -> ATT	0.324	3.792	**0.000**	Supported
H4	PEOU -> PU	0.751	14.881	**0.000**	Supported
H5	PU -> ATT	0.562	6.949	**0.000**	Supported
H6	COG -> DL	0.521	11.325	**0.000**	Supported
H7	SE -> DL	0.379	10.419	**0.000**	Supported
H8	T -> DL	0.317	7.430	**0.000**	Supported

The analysis demonstrates that both Technology Acceptance and Digital Literacy exert statistically significant impacts on mathematics learning outcomes ($p < 0.001$ for all paths), with Digital Literacy emerging as the more influential factor based on its higher path coefficient. The structural model exhibits substantial explanatory power, with the highly significant relationships providing strong evidence for the integrated framework's ability to capture the complexity of digital learning environments.

The robustness and stability of the path coefficients were further verified through bias-corrected confidence interval analysis with 5,000 bootstrap samples. As presented in Table 6, all hypothesized relationships demonstrate statistical significance at the 95% confidence level, as none of the intervals include zero (Hair et al., 2022).

Table 6
Result of R^2

	Original Sample (O)	Sample Mean (M)	2.5%	97.5%
ATT -> LO	0,311	0,316	0,136	0,470
COG -> DL	0,521	0,527	0,450	0,634
DL -> LO	0,415	0,416	0,280	0,551
PEOU -> ATT	0,324	0,323	0,151	0,473
PEOU -> PU	0,751	0,750	0,654	0,836
PU -> ATT	0,562	0,562	0,414	0,716
SE -> DL	0,379	0,383	0,330	0,474
T -> DL	0,317	0,315	0,238	0,394

The confidence interval analysis provides compelling evidence for the stability and precision of all parameters estimates. The narrow intervals for key relationships, particularly PEOU -> PU (0.654, 0.836) and COG -> DL (0.450, 0.634), indicate high estimation precision and reinforce the reliability of these strong relationships. Notably, the interval for DL -> LO (0.280, 0.551) confirms the significant positive effect of Digital Literacy on Learning Outcomes, while excluding the possibility of zero or negative effects. The consistency between original sample estimates and bootstrap means across all paths suggests minimal sampling bias, enhancing the generalizability of the findings. This comprehensive confidence interval analysis substantially strengthens the validity of the hypothesized relationships beyond traditional p-value testing alone.

The relative impact of each predictor construct was assessed using f-square (f^2) effect sizes to determine their substantive significance beyond statistical significance. Following Cohen & Ball (1999) criteria, f^2 values of 0.02, 0.15, and 0.35 represent small, medium, and large effects, respectively. The results presented in Table 7 reveal substantial variation in effect sizes across different relationships.

Table 7
Result of F^2

Predictor → Outcome	f^2 Value	Effect Size Interpretation
Digital Literacy → Learning Outcomes	0.228	Medium to Large
Technology Acceptance → Learning Outcomes	0.128	Small to Medium
PEOU → Perceived Usefulness	1.290	Very Large

PU → Technology Acceptance	0.452	Large
PEOU → Technology Acceptance	0.150	Medium
Cognitive → Digital Literacy	533.634	Extremely Large
Social-Emotional → Digital Literacy	287.073	Extremely Large
Technical → Digital Literacy	274.470	Extremely Large

Digital Literacy demonstrates a medium to large effect ($f^2 = 0.228$) on Learning Outcomes, substantially larger than Technology Acceptance's small to medium effect ($f^2 = 0.128$). This confirms Digital Literacy's greater substantive importance in explaining mathematics learning performance. Within the Technology Acceptance Model, PEOU shows a very large effect on Perceived Usefulness ($f^2 = 1.290$), indicating its crucial role in shaping users' utility perceptions. Similarly, PU exhibits a large effect on Technology Acceptance ($f^2 = 0.452$), underscoring the importance of usefulness perceptions in driving technology adoption. The extremely large effect sizes for all three digital literacy dimensions (Cognitive: $f^2 = 533.634$; Social-Emotional: $f^2 = 287.073$; Technical: $f^2 = 274.470$) confirm their fundamental role as formative indicators of the higher-order Digital Literacy construct.

Table 8
Result of Q^2

	SSO	SSE	Q^2 (=1-SSE/SSO)
ATT	1000,000	479,033	0,521
COG	375,000	375,000	
DL	875,000	484,116	0,447
LO	625,000	468,794	0,250
PEOU	250,000	250,000	
PU	750,000	438,454	0,415
SE	250,000	250,000	
T	250,000	250,000	

The model's predictive relevance was assessed using the Q^2 test through blindfolding procedure. As presented in Table 8, all endogenous constructs demonstrate satisfactory predictive relevance with Q^2 values substantially above zero, indicating the model's ability to make accurate predictions beyond the sample data. Attitude Towards Using Technology (ATT) demonstrates large predictive relevance ($Q^2 = 0.521$), indicating the model has strong predictive power for users' technology adoption behavior in digital learning environments. Both Digital Literacy ($Q^2 = 0.447$) and Perceived Usefulness ($Q^2 = 0.415$) show medium to large predictive relevance, confirming the model's robustness in forecasting digital competency development and utility perceptions. Moderate Learning Outcomes Prediction: Learning Outcomes achieves medium predictive relevance ($Q^2 = 0.250$), suggesting the model provides meaningful but not exhaustive predictive capability for academic performance, leaving room for additional explanatory factors.

Following the criteria established by Hair et al. (2022), where Q^2 values above 0.25, 0.50 represent medium and large predictive relevance respectively, our model demonstrates consistently satisfactory predictive power across all key endogenous constructs. The positive Q^2 values for all constructs confirm that the model possesses adequate predictive relevance and is not merely fitting the sample data but provides genuine predictive capability for future observations in similar educational contexts.

Table 9
Result of Indirect Effect

	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values
COG -> LO	0,216	0,219	0,040	5,382	**0,000**
PEOU -> ATT	0,422	0,421	0,068	6,218	**0,000**
PEOU -> LO	0,232	0,237	0,071	3,252	**0,001**
PU -> LO	0,175	0,178	0,057	3,082	**0,002**
SE -> LO	0,157	0,159	0,029	5,436	**0,000**
T -> LO	0,131	0,131	0,026	4,970	**0,000**

The complex mediation mechanisms were examined through specific indirect effect analysis. As shown in Table 9, all hypothesized indirect paths are statistically significant ($p < 0.05$), indicating the presence of meaningful sequential relationships among the constructs. All three dimensions of Digital Literacy are fully mediated by the higher-order Digital Literacy construct in influencing Learning Outcomes. The cognitive dimension exerts the strongest indirect effect on Learning Outcomes ($\beta = 0.216$, $p < 0.001$), followed by the social-emotional ($\beta = 0.157$, $p < 0.001$) and technical dimensions ($\beta = 0.131$, $p < 0.001$).

In the Technology Acceptance Model structure, Perceived Ease of Use (PEOU) significantly affects Attitude (ATT) through an indirect path ($\beta = 0.422$, $p < 0.001$) and also demonstrates a significant indirect relationship with Learning Outcomes ($\beta = 0.232$, $p = 0.001$). Furthermore, Perceived Usefulness (PU) shows a significant mediation effect on Learning Outcomes ($\beta = 0.175$, $p = 0.002$), confirming its pivotal role in the overall mechanism. These findings indicate that Digital Literacy functions as a complete mediating construct for its dimensions in shaping Learning Outcomes, while Technology Acceptance variables (PEOU and PU) operate through interconnected serial mediation pathways that enhance students' attitudes and learning performance in digital learning contexts.

All digital literacy dimensions demonstrate significant mediation through the higher-order construct with narrow confidence intervals, particularly the cognitive dimension, indicating stable and precise estimation of these mediation effects. The mediation analysis reveals that the PEOU -> PU -> ATT path has the largest substantive effect, followed by COG -> DL -> LO, while the shorter mediation paths (PEOU -> ATT -> LO and T -> DL -> LO) show smaller but still significant effects. The confidence interval analysis provides robust evidence for all hypothesized mediation pathways, with the exclusion of zero from all intervals confirming the stability and reliability of the indirect effects estimated in the model.

The findings of this study demonstrate that both Technology Acceptance and Digital Literacy significantly influence mathematics learning outcomes in digital platform environments. The results reveal that Digital Literacy exerts a stronger influence than

Technology Acceptance, challenging the conventional emphasis on mere technology adoption in educational digitalization. This finding aligns with the growing recognition that technological infrastructure alone is insufficient for educational transformation, and that students' digital competencies play a more crucial role in determining learning success (Palacios-Rodríguez et al., 2023; Rawal, 2024; Timotheou et al., 2023). The substantial explanatory power of the model (for Learning Outcomes) confirms the importance of integrating both technological and literacy perspectives in understanding digital learning effectiveness.

The dominance of Digital Literacy over Technology Acceptance in predicting learning outcomes signifies a paradigm shift in educational technology implementation. While previous research has predominantly focused on technology adoption factors (Venkatesh et al., 2003), this study demonstrates that students' abilities to critically evaluate digital information, navigate digital environments ethically, and apply technical skills more substantially impact their academic performance. This finding is particularly relevant in mathematics education, where digital platforms require not only technical operation skills but also critical thinking abilities to interpret digital representations of mathematical concepts (Cirneanu & Moldoveanu, 2024; Soboleva et al., 2020). The cognitive dimension of digital literacy emerged as the strongest contributor, emphasizing the importance of higher-order thinking skills in digital mathematics learning.

Supporting research by Ng (2012) and Alkalai (2004) provides theoretical foundation for these findings, emphasizing that digital literacy encompasses multidimensional competencies beyond technical skills. The current study extends this understanding by quantitatively demonstrating how these dimensions collectively influence learning outcomes through the higher-order Digital Literacy construct. The full mediation effects observed for all digital literacy dimensions (COG -> DL -> LO, SE -> DL -> LO, T -> DL -> LO) confirm that digital literacy operates as an integrated capability where technical, cognitive, and social-emotional components synergistically contribute to learning success. This holistic perspective advances beyond previous research that often examined these dimensions in isolation.

The complex mediation patterns within the Technology Acceptance Model components reveal intricate mechanisms through which technology perceptions influence learning outcomes. The strong serial mediation PEOU -> PU -> ATT and the comprehensive chain mediation PEOU -> PU -> ATT -> LO demonstrate that technology acceptance develops through sequential cognitive processes that ultimately impact academic performance. These findings corroborate and extend the original TAM framework Davis (1989) by illustrating its connections to actual learning outcomes rather than just behavioral intentions. The significant direct effects of PEOU and PU on learning outcomes further suggest that technology perceptions may influence learning through additional pathways beyond attitude and behavioral intentions.

From a practical perspective, these findings have significant implications for educational policy and instructional design. The strong predictive power of digital literacy dimensions suggests that educational institutions should prioritize comprehensive digital literacy development alongside technology implementation. Mathematics educators should design learning activities that simultaneously develop technical skills, critical evaluation abilities, and ethical digital citizenship. The substantial effect of cognitive digital literacy indicates that mathematics instruction using digital platforms should emphasize conceptual understanding and critical thinking rather than procedural knowledge alone. Professional development programs for teachers should address both technological proficiency and pedagogical strategies for developing students' digital literacy. This study advances understanding of digital learning effectiveness by integrating technology acceptance and digital literacy perspectives within a unified framework. The findings demonstrate that sustainable educational digitalization requires attention to both technological adoption factors and digital competency development.

CONCLUSION AND IMPLICATION

Conclusion and Implications

This study makes significant theoretical contributions by resolving the tension between technology-centric and literacy-focused perspectives through a unified framework, while extending the Technology Acceptance Model by connecting it to actual learning outcomes rather than just behavioral intentions. The operationalization of Digital Literacy as a formative construct with three validated dimensions provides nuanced understanding, with confirmed mediation mechanisms elucidating how technology perceptions translate into educational outcomes. Practically, the findings urge school administrators to prioritize comprehensive digital literacy programs encompassing cognitive, social-emotional, and technical dimensions, while guiding mathematics teachers to design lessons that integrate critical thinking and ethical digital citizenship with mathematical concepts. Educational technology developers should create platforms that foster higher-order digital competencies beyond user-friendliness, and policymakers should reallocate resources from mere technological infrastructure toward holistic digital literacy development.

Despite its contributions, this study has limitations in generalizability due to its focus on elementary mathematics contexts and its cross-sectional design which prevents causal inferences about digital competency development over time. Future research should employ longitudinal designs to track digital literacy evolution, examine the framework's applicability across diverse cultural contexts and subject areas, and investigate how teacher digital literacy mediates the relationship between technology integration and student outcomes, thereby addressing these current constraints while expanding the understanding of digital learning ecosystems.

Disclosure statement

No potential conflict of interest was reported by the authors.

ACKNOWLEDGMENTS

The authors extend their gratitude to the participating schools and students who made this research possible. Appreciation is also expressed to the educational authorities that facilitated access to research sites.

REFERENCES

Bagozzi, R. P., & Yi, Y. (1988). On the evaluation of structural equation models. *Journal of the Academy of Marketing Science, 16*(1), 74–94. https://doi.org/10.1007/BF02723327

Bilad, M. R., Zubaidah, S., & Prayogi, S. (2024). Addressing the PISA 2022 results: A call for reinvigorating Indonesia's education system. *International Journal of Essential Competencies in Education, 3*(1), 1–12. https://doi.org/10.36312/ijece.v3i1.1935

Cirneanu, A.-L., & Moldoveanu, C.-E. (2024). Use of digital technology in integrated mathematics education. *Applied System Innovation, 7*(4), 66. https://doi.org/10.3390/asi7040066

Cohen, D. K., & Ball, D. L. (1999). Instruction, capacity, and improvement. *CPRE Research Report Series, 431*(749), 1–47. https://doi.org/https://doi.org/10.1037/e382692004-001

David, A., Yigitcanlar, T., Li, R. Y. M., Corchado, J. M., Cheong, P. H., Mossberger, K., & Mehmood, R. (2023). Understanding local government digital technology adoption strategies: A PRISMA review. *Sustainability (Switzerland), 15*(12), 1–43. https://doi.org/10.3390/su15129645%0Ahttps://www.mdpi.com/2071-1050/15/12/9645

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly: Management Information Systems, 13*(3), 319–339. https://doi.org/10.2307/249008

Eshet-Alkalai, Y. (2004). Digital Literacy: A conceptual framework for survival skills in the digital era. *Journal of Educational Multimedia and Hypermedia, 13*(1), 93–106. http://www.editlib.org/p/4793/%5Cnfiles/364/Eshet and Eshet - 2004 - Digital Literacy a Conceptual Framework for Survi.pdf%5Cnfiles/459/4793.html

Eshet-Alkalai, Y. (2012). Thinking in the digital era: A revised model for digital literacy. *Issues in Informing Science and Information Technology, 9*, 267–276. https://doi.org/10.28945/1621

Ghozali, I., & Latan, H. (2015). *Partial least squares: Concepts, techniques and applications using SmartPLS 3.* Semarang: Diponegoro University Press.

Govender, I. (2025). Digital literacy and STEM skills– What is the connection? A systematic review. *Technology, Knowledge and Learning*. 1-19. https://doi.org/10.1007/s10758-025-09879-x

Hair, J. F., Hult, G. T. M., Ringle, C. M., & Sarstedt, M. (2022). *A Primer on partial least squares structural equation modeling (PLS-SEM).* In Angewandte Chemie International Edition, 6(11), 951–952. (Third Edit). Sage Publications, Inc. https://doi.org/10.1007/978-3-030-80519-7

Hair, J. F., Risher, J. J., Sarstedt, M., & Ringle, C. M. (2019). The results of PLS-SEM article information. *European Business Review, 31*(1), 2–24. https://doi.org/10.1108/EBR-11-2018-0203

Henseler, J., Ringle, C. M., & Sarstedt, M. (2015). A new criterion for assessing discriminant validity in variance-based structural equation modeling. *Journal of* *the Academy of Marketing Science, 43*(1), 115–135. https://doi.org/10.1007/s11747-014-0403-8

HolonIQ. (2020). *Global EdTech market to reach $404B by 2025 - 16.3% CAGR*. HolonIQ. https://www.holoniq.com/notes/global-education-technology-market-to-reach-404b-by-2025

Lee, S. W. Y., Tu, H. Y., Chen, G. L., & Lin, H. M. (2023). Exploring the multifaceted roles of mathematics learning in predicting students' computational thinking competency. *International Journal of STEM Education, 10*(1). https://doi.org/10.1186/s40594-023-00455-2

Lin, Y., & Yu, Z. (2023). Extending technology acceptance model to higher-education students' use of digital academic reading tools on computers. *International Journal of Educational Technology in Higher Education, 20*(1), 1–24. https://doi.org/10.1186/s41239-023-00403-8

Mullis IVS, Martin MO, Foy P, Kelly DL, F. B. (2020). *TIMSS 2019 International Results in Mathematics and Science*. Retrieved from Boston College, TIMSS & PIRLS International Study Center. https://timssandpirls.bc.edu/timss2019/international-results/

Ng, W. (2012). Can we teach digital natives digital literacy? *Computers & Education, 59*(3), 1065–1078. https://doi.org/10.1016/j.compedu.2012.04.016

Ningsih, N. I. S. (2024). *Analisis faktor-faktor pengaruh technology acceptance model (TAM) di sekolah dasar*. [Unpublished undergraduate thesis]. Institut Prima Bangsa.

OECD. (2023). *PISA 2022 Results (Volume I).* OECD Publishing. https://doi.org/10.1787/53f23881-en

Palacios-Rodríguez, A., Llorente-Cejudo, C., & Cabero-Almenara, J. (2023). Editorial: Educational digital transformation: new technological challenges for competence development. *Frontiers in Education, 8*. https://doi.org/10.3389/feduc.2023.1267939

Qu, S., Zhou, M., Kong, N., & Campy, K. S. (2023). Factors influencing user acceptance of weight management apps among Chinese obese individuals during the COVID-19 pandemic. *Health Policy and Technology, 12*(2023), 1–9.

Qudwatullathifah, R. N., Ismuwardani, Z., Guntur, M., Musyarrofah, S., & Ningsih, N. I. S. (2023). Efektivitas platform pembelajaran matematika berbasis digital untuk meningkatkan kemampuan pemecahan masalah siswa sekolah dasar. *Prima Magistra: Jurnal Ilmiah Kependidikan, 4*(4), 590–599. https://doi.org/10.37478/jpm.v4i4.3225

Rawal, D. M. (2024). Mapping of school teachers' digital competency in the context of digital infrastructure: a systematic review and empirical study of India. *Journal of Professional Capital and Community, 9*(3), 173–195. https://doi.org/10.1108/JPCC-01-2024-0016

Singarimbun, M. E. (1995). *Metode Penelitian Survei Cetakan Kedua*. In Jakarta: PT. Pustaka LP3ES Indonesia.

Singun, A. J. (2025). Unveiling the barriers to digital transformation in higher education institutions: A systematic literature review. *Discover Education, 4*(1), 37. https://doi.org/10.1007/s44217-025-00430-9

Soboleva, E. V., Chirkina, S. E., Kalugina, O. A., Shvetsov, M. Y., Kazinets, V. A., & Pokaninova, E. B. (2020). Didactic potential of using mobile technologies in the development of mathematical thinking. *EURASIA Journal of Mathematics, Science and Technology Education, 16*(5). https://doi.org/10.29333/ejmste/118214

Timotheou, S., Miliou, O., Dimitriadis, Y., Sobrino, S. V., Giannoutsou, N., Cachia, R., Monés, A. M., & Ioannou, A. (2023). Impacts of digital technologies on education and factors influencing schools' digital capacity and transformation: A literature review. *Education and Information Technologies, 28*(6), 6695–6726. https://doi.org/10.1007/s10639-022-11431-8

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. *MIS Quarterly: Management Information Systems, 27*(3), 425–478. https://doi.org/10.2307/30036540

Yamane, T. (1967). *Statistics: An Introductory Analysis, 2nd Edition*. In New York: Harper and Row.

Yuan, Y. H., Liu, C. H., & Kuang, S. S. (2021). An innovative and interactive teaching model for cultivating talent's digital literacy in decision making, sustainability, and computational thinking. *Sustainability (Switzerland), 13*(9). https://doi.org/10.3390/su13095117

Zhang, N., Guo, X. H., & Chen, G. Q. (2007). Extended information technology initial acceptance model and its empirical test. *Systems Engineering - Theory & Practice, 27*(9), 123–130. https://doi.org/10.1016/s1874-8651(08)60057-5

Zhao, Y., Zhao, M., & Shi, F. (2024). Integrating moral education and educational information technology: A strategic approach to enhance rural teacher training in universities. *Journal of the Knowledge Economy, 15*(3), 15053–15093. https://doi.org/10.1007/s13132-023-01693-z