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Serial Mediation Effects of Perceived Usefulness and Attitude in Sustainable Mobile Learning: Extending the Technology Acceptance Model in Higher Education

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Abstract

The sustainability of mobile learning has emerged as a critical concern in higher education, particularly in developing countries where technological adoption does not always translate into long-term usage. While prior studies have predominantly examined initial behavioral intention, limited research has explored the determinants of sustained mobile learning engagement. Grounded in the Technology Acceptance Model (TAM), this study develops and tests an integrative framework to examine how perceived ease of use and perceived usefulness influence sustainable mobile learning use through personal attitude and sequential mediation mechanisms. Data were collected from undergraduate students enrolled in Bangladeshi universities, and the proposed hypotheses were tested using structural equation modeling. The findings reveal that perceived ease of use significantly enhances perceived usefulness and personal attitude, which in turn positively influence sustainable use. Perceived usefulness and personal attitude both function as significant mediators in the relationship between ease of use and sustainability. Moreover, a serial mediation pathway linking ease of use to sustainable use via perceived usefulness and personal attitude was supported, demonstrating the cumulative cognitive and affective processes underlying sustained engagement. These results extend TAM by shifting the analytical focus from short-term adoption to long-term sustainability outcomes within a developing-country context. The study contributes theoretically by validating an integrated mediation framework and, practically, by offering policy-relevant insights for universities and other educational stakeholders seeking to promote durable mobile learning ecosystems. Implications for sustainable digital transformation in higher education are discussed.

Keywords: *Mobile learning; Sustainable use; Mediation analysis; Technology Acceptance Model; Higher education.*

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Introduction

The rapid advancement of mobile technologies has fundamentally transformed the landscape of higher education worldwide. Mobile learning, defined as the use of portable digital devices to support learning anytime and anywhere, has emerged as a critical component of contemporary educational ecosystems (Ahmad et al., 2025). Particularly in developing countries, mobile learning offers an affordable and flexible alternative to traditional infrastructure-intensive educational delivery systems (Al-Emran et al., 2016; Nikou & Economides, 2018). In Bangladesh, where smartphone penetration has increased substantially over the past decade, and mobile internet access has expanded across urban and semi-urban areas, mobile learning has become an increasingly viable modality for undergraduate education (Islam et al., 2025; Roy, 2023b). However, despite its growing adoption, sustaining long-term engagement with mobile learning systems remains a significant challenge.

Most prior research on mobile learning has concentrated on initial acceptance or behavioral intention rather than sustained usage behavior (Al-Rahmi et al., 2021; Venkatesh et al., 2012). While intention is an important precursor to behavior, it does not guarantee continued or consistent use over time. In developing-country contexts such as Bangladesh, sustainability is particularly critical due to limited institutional resources, infrastructure variability, and uneven levels of digital literacy (Roy & Sarkar, 2025). Technologies that are adopted but not sustained may fail to generate meaningful educational impact. Consequently, understanding the determinants of sustainable use, defined as continued and consistent engagement with mobile learning technologies over time, represents a pressing theoretical and practical concern (Alias & Razak, 2025).

The Technology Acceptance Model (TAM) (Davis, 1989) remains one of the most widely validated frameworks for explaining user acceptance of information systems. TAM posits that perceived ease of use and perceived usefulness are primary cognitive determinants of technology-related attitudes and behavioral intentions. Subsequent extensions, including the Unified Theory of Acceptance and Use of Technology (UTAUT), have further emphasized the importance of performance expectancy, effort expectancy, and attitudinal mechanisms in shaping usage behavior (Venkatesh et al., 2003, 2012; Roy, 2023c). Although these models have been extensively applied in educational technology research, much of the empirical literature has focused on adoption decisions rather than long-term sustainability outcomes (Al-Emran et al., 2016). There remains limited empirical investigation into how cognitive beliefs and affective evaluations interact to promote sustained use of mobile learning, particularly in emerging economies.

In the Bangladeshi higher education context, mobile learning adoption has accelerated significantly in recent years, particularly with the integration of blended and hybrid learning approaches (Ahmed et al., 2025; Beneragama et al., 2021; Roy & Musfika, 2025). However, adoption alone does not ensure effective or enduring engagement. Students often discontinue using digital learning platforms if they perceive them as complex, unreliable, or lacking clear academic value. Therefore, examining how perceived ease of use and perceived usefulness influence personal attitude and, ultimately, sustainable use is essential for understanding long-term educational transformation in resource-constrained environments. Furthermore, mediation and serial mediation mechanisms may offer deeper insights into how usability perceptions translate into sustained behavioral outcomes through cognitive and affective pathways (Al-Rahmi et al., 2021; Voicu & Muntean, 2023).

Addressing these gaps, the present study develops and empirically tests an integrative framework grounded primarily in TAM and extended through sustainability-oriented behavioral mechanisms. Specifically, this research examines (1) the direct effects of perceived ease of use and perceived usefulness on personal attitude and sustainable use, (2) the mediating roles of perceived usefulness and personal attitude, and (3) the serial mediation pathway linking ease of use to sustainable use through perceived usefulness and attitude. By focusing on undergraduate students in Bangladesh, this study provides context-sensitive evidence regarding the determinants of sustainable mobile learning behavior in a developing-country setting.

This study contributes to the literature in three important ways. First, it shifts the analytical focus from short-term behavioral intention to long-term sustainable use, thereby extending established acceptance models toward sustainability outcomes. Second, it validates a comprehensive mediation and serial mediation framework that clarifies the cognitive–affective processes underlying sustained engagement in mobile learning. Third, by situating the analysis in Bangladesh, the study responds to calls for greater contextualization of technology adoption models in emerging economies, where infrastructural, cultural, and institutional conditions may shape technology use differently from those in technologically mature contexts.

By integrating theoretical rigor with contextual relevance, this research advances understanding of how mobile learning can transition from temporary adoption to sustained educational practice. Such insights are essential for policymakers, universities, and stakeholders seeking to leverage mobile technologies for long-term, equitable, and sustainable higher education development.

Literature review and hypotheses development

Theoretical foundation

This study is grounded primarily in the Technology Acceptance Model (TAM) (Davis, 1989), complemented by insights from the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003, 2012) and sustainability-oriented mobile learning research. TAM explains users' acceptance of technology through two core beliefs, perceived ease of use and perceived usefulness, which shape attitudes and subsequent behavioral intentions. In mobile learning contexts, these cognitive beliefs interact with affective responses (personal attitudes) and long-term behavioral intentions, such as sustainable use, which refers to continued, consistent use over time rather than short-term adoption (Alanazi et al., 2024; Chowdhury et al., 2019). Integrating TAM with sustainability perspectives is particularly relevant in developing-country contexts such as Bangladesh, where resource constraints make the long-term, effective use of educational technologies essential.

Ease of use and perceived usefulness

Perceived ease of use (EOU) refers to the extent to which individuals believe that using a system requires minimal effort (Davis, 1989). In mobile learning environments, ease of use is

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especially critical due to factors such as small screen sizes, interface complexity, and varying levels of digital literacy. Prior studies consistently report that systems perceived as easy to use are more likely to be judged as useful for learning activities (Al-Rahmi et al., 2021; Roy, 2022). When students can easily navigate mobile learning platforms, access materials, and interact with content, they are more likely to perceive these systems as enhancing their academic performance. In the Bangladeshi higher education context, where students often rely on smartphones as their primary learning device, usability becomes a key determinant of perceived usefulness. Therefore, ease of use is expected to have a significant positive effect on perceived usefulness.

H1: Ease of use significantly affects undergraduates' perceived usefulness for mobile learning.

Ease of use and personal attitude

Personal attitude (PA) reflects an individual's overall evaluative judgment regarding the use of a particular technology. TAM posits that ease of use directly influences attitude, as users tend to develop favorable feelings toward systems that are simple and convenient to operate (Davis, 1989). Empirical research in mobile learning confirms that students who perceive mobile learning platforms as user-friendly are more likely to hold positive attitudes toward their use (Alghazi et al., 2021). In Bangladesh, where students frequently juggle academic, familial, and sometimes work responsibilities, technologies that reduce cognitive and operational burden are more likely to be viewed positively (Roy, 2023a). Hence, ease of use is expected to foster a favorable personal attitude toward mobile learning.

H2: Ease of use significantly affects undergraduates' personal attitude toward mobile learning.

Ease of use and sustainable use

Sustainable use (SU) in mobile learning refers to students' intention to continue using mobile learning technologies consistently over time. Beyond initial adoption, long-term use depends heavily on whether systems are perceived as effortless and convenient. Prior studies suggest that technologies perceived as complex or difficult are often abandoned even after initial adoption (Venkatesh et al., 2012; Voicu & Muntean, 2023). In contrast, easy-to-use mobile learning platforms encourage habitual engagement and long-term reliance. In the Bangladeshi context, where infrastructure and technical support may vary across institutions, ease of use is even more critical for sustaining use. Thus, ease of use is expected to directly influence sustainable use.

H3: Ease of use significantly affects undergraduates' sustainable use of mobile learning.

Perceived usefulness and personal attitude

Perceived usefulness (PU) is defined as the degree to which individuals believe that using a system enhances their performance (Davis, 1989). Numerous studies identify PU as a strong antecedent of attitude toward technology use, particularly in educational settings (Al-Rahmi et al., 2021; Zhou et al., 2025). When students perceive mobile learning as beneficial for understanding course content, improving grades, or increasing learning efficiency, they are more likely to develop a positive attitude toward its use. In performance-oriented higher education systems such as Bangladesh's, students are especially sensitive to technologies that offer clear academic value. Therefore, perceived usefulness is expected to positively influence personal attitude toward mobile learning.

H4: Perceived usefulness significantly affects undergraduates' personal attitude toward mobile learning.

Perceived usefulness and sustainable use

Extant research consistently demonstrates that perceived usefulness is one of the strongest predictors of continued technology use (Venkatesh et al., 2012). In mobile learning contexts, students are more likely to continue using platforms that demonstrably support their learning goals, such as exam preparation, content accessibility, and time efficiency. For sustainable mobile learning initiatives in Bangladesh, perceived usefulness is particularly important, as students may discontinue use if the technology does not provide clear academic benefits (Ahsan, 2025; Roy et al., 2025). Consequently, perceived usefulness is expected to have a direct, positive effect on sustainable use.

H5: Perceived usefulness significantly affects undergraduates' sustainable use of mobile learning.

Personal attitude and sustainable use

Personal attitude plays a central role in shaping long-term behavioral intentions. According to TAM and related behavioral theories, individuals with positive attitudes toward a technology are more likely to continue using it over time (Davis, 1989; Venkatesh et al., 2003). In mobile learning research, favorable attitudes have been linked to higher levels of continuance intention and habitual use (Al-Rahmi et al., 2021; Voicu & Muntean, 2023). In Bangladesh, where mobile learning is increasingly integrated into blended and hybrid education models, students' attitudes toward these systems are crucial for ensuring their sustainable use. Thus, a positive personal attitude is expected to enhance sustainable use.

H6: Personal attitude significantly affects undergraduates' sustainable use of mobile learning.

Mediating role of perceived usefulness

TAM suggests that ease of use influences behavioral outcomes indirectly through perceived usefulness (Davis, 1989). In mobile learning contexts, ease of use enhances perceived usefulness by reducing effort and increasing efficiency, thereby shaping attitudes and long-term usage intentions. Empirical studies support the mediating role of perceived usefulness in technology adoption and continuance models (Al-Rahmi et al., 2021). Accordingly, perceived usefulness is expected to mediate the relationships between ease of use and personal attitude, as well as between ease of use and sustainable use.

H7: Perceived usefulness mediates the relationship between ease of use and undergraduate students' attitudes toward mobile learning.

H8: Perceived usefulness mediates the relationship between ease of use and undergraduate students' sustainable use of mobile learning.

Mediating role of personal attitude

Personal attitude represents an affective mechanism through which cognitive beliefs translate into long-term behavior. Prior research indicates that attitude often mediates the effects of system characteristics and perceived benefits on continuance intention (Alghazi et al., 2021; Chowdhury & Roy, 2015; Venkatesh et al., 2012). In the context of mobile learning, ease of use and perceived

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usefulness are likely to foster positive attitudes, thereby encouraging sustained use (Abdelwahed & Soomro, 2023). Therefore, personal attitude is expected to mediate the relationships between ease of use and sustainable use, as well as between perceived usefulness and sustainable use.

H9: Personal attitude mediates the relationship between ease of use and undergraduate students' sustainable use of mobile learning.

H10: Personal attitude mediates the relationship between perceived usefulness and undergraduate students' sustainable use of mobile learning.

Serial mediation of perceived usefulness and personal attitude

Building on TAM's causal chain, ease of use influences perceived usefulness, which then shapes personal attitude and ultimately leads to sustained behavior. Recent studies in mobile learning and educational sustainability emphasize the importance of such sequential mechanisms for explaining long-term technology use (Al-Rahmi et al., 2021; Voicu & Muntean, 2023). In resource-constrained settings such as Bangladesh, this sequential process is particularly relevant, as students are more likely to sustain mobile learning use when systems are easy to use, perceived as useful, and evaluated positively (Akour et al., 2021; Roy & Ahmed, 2016). Hence, perceived usefulness and personal attitude are expected to mediate the relationship between ease of use and sustainable use in a serial manner.

H11: Perceived usefulness and personal attitude serially mediate the relationship between ease of use and undergraduate students' sustainable use of mobile learning.

Integrative research framework

The integrative research framework, illustrated in Figure 1, synthesizes core constructs drawn from the Technology Acceptance Model (TAM) and sustainability-oriented technology adoption literature to explain learners' sustainable use of mobile learning systems. As depicted in the figure, perceived usefulness and perceived ease of use are fundamental cognitive beliefs that shape learners' attitudes toward mobile learning, which, in turn, influence their intentions to use sustainably and their continued usage behavior. These constructs are modeled to have both direct and indirect effects on sustainable use via attitudinal pathways, consistent with the proposed hypotheses. By visually integrating individual perceptions, system characteristics, and sustainability outcomes, the framework presented in Figure 1 provides a coherent structure for hypothesis testing and offers a comprehensive explanation of how mobile learning adoption can be sustained over time in resource-constrained educational environments (Al-Emran et al., 2016; Davis, 1989; Roy et al., 2021; Venkatesh et al., 2003).

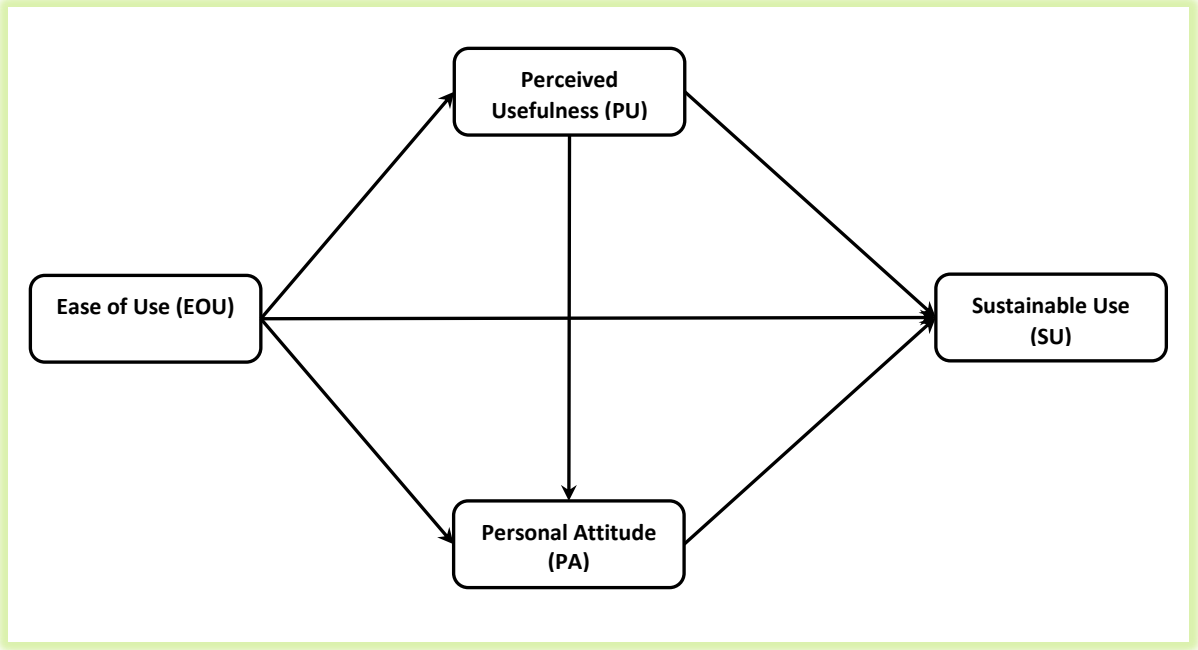

Figure 1: Proposed conceptual framework

Research methodology

Participants

This study utilized primary data to ensure methodological rigor and enhance the robustness of the empirical findings. Data were collected using a systematically designed questionnaire administered to undergraduate students enrolled at higher education institutions in Dhaka, Bangladesh. Dhaka was selected as the research context because of its dense concentration of public and private universities and the widespread use of smartphones and mobile internet services among students, making it a suitable setting for investigating mobile learning intentions. The target population comprised undergraduate students from diverse academic disciplines, allowing for broad representation of learning contexts and levels of technological engagement. Participation was voluntary, and respondents were informed of their right to withdraw from the study at any stage. Following data screening and the removal of incomplete responses, a total of 322 valid questionnaires were retained for subsequent statistical analysis.

Sampling Technique

A non-probability sampling strategy integrating convenience and purposive sampling techniques was employed to recruit participants. This approach was adopted due to its efficiency in terms of time and cost, which is particularly suitable for technology-related behavioral studies conducted within academic settings in Bangladesh (Roy & Islam, 2023; Roy & Khatun, 2023). Convenience sampling enabled timely access to undergraduate respondents, while purposive sampling ensured that all participants

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had prior experience with mobile learning systems, a necessary condition for examining sustainable use behavior. To establish the clarity and reliability of the survey instrument, a pilot study was conducted with 50 undergraduate students, leading to minor revisions based on participant feedback. The finalized questionnaire was then administered online using widely used mobile communication platforms, including Messenger and WhatsApp, which are extensively adopted by Bangladeshi university students. Following data screening and the removal of incomplete or invalid responses, 322 valid questionnaires were retained for statistical analysis. While this combined sampling strategy improved accessibility and ensured relevance to the research objective, the potential limitations inherent in non-probability sampling, such as self-selection bias, are acknowledged and discussed in the limitations section.

Sample Size

The adequacy of the sample size was assessed using both statistical power analysis and established methodological criteria. The minimum required sample size was determined using G*Power software (version 3.1.9.4). In line with prior methodological recommendations, an effect size of 0.05 and a desired statistical power of 0.95 were specified, resulting in a minimum sample requirement of 262 respondents. The final sample consisted of 322 participants, which exceeded this threshold and thus provided sufficient statistical power to identify meaningful effects. Moreover, the sample size is appropriate given the complexity of the proposed research framework, which comprises four latent constructs and multiple structural relationships. According to PLS-SEM guidelines, a minimum sample size should be at least ten times the largest number of structural paths directed toward any endogenous construct. In the present model, the maximum number of direct paths is four, indicating a minimum requirement of 40 cases, which is substantially lower than the achieved sample size. Therefore, the obtained sample size strengthens the robustness, reliability, and internal validity of the results and supports the generalizability of the findings within the Bangladeshi undergraduate context and comparable higher education settings in developing economies.

Measurement instrument

The present study examines four latent constructs: ease of use (EOU), perceived usefulness (PU), personal attitude (PA), and sustainable use (SU). Sustainable use is conceptualized as an individual's intention to continue using mobile learning technologies over time in a consistent and enduring manner, reflecting long-term behavioral sustainability rather than short-term or trial-based adoption. This conceptualization aligns with behavioral sustainability theory, which emphasizes the maintenance of behavior through ongoing perceived value, habitual engagement, and positive attitudinal reinforcement. The measurement items were primarily adapted from well-established and empirically validated scales widely employed in mobile learning and technology adoption research. To ensure contextual relevance and clarity for undergraduate students in Bangladeshi higher education institutions, minor wording adjustments were made without altering the underlying theoretical meaning of the items. Specifically, five items measuring PA, EOU, SU, and PU were adapted from the validated instrument developed by Al-Rahmi et al. (2021). All constructs were measured using a seven-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree), where higher scores indicate stronger agreement with the respective statements and higher levels of the latent constructs. The use of a seven-point Likert scale is consistent with best practices in structural equation modeling and mobile learning research, as it enhances response sensitivity and supports robust estimation of long-term behavioral intentions.

Sample Characteristics

The final sample consisted of 322 undergraduate students drawn from higher education institutions in Bangladesh. The age distribution of respondents ranged from 19 to 26 years. The majority of participants were between 23 and 24 years of age, accounting for 24.5% (n = 79) and 29.8% (n = 96) of the sample, respectively. Participants aged 21 and 22 years each represented 16.1% (n = 52) of the sample, while smaller proportions were observed for those aged 19 (0.6%, n = 2), 20 (2.5%, n = 8), 25 (8.1%, n = 26), and 26 years (2.2%, n = 7). This distribution reflects a predominantly early-adult undergraduate population, consistent with the typical age profile of students enrolled in Bangladeshi universities.

Regarding prior experience with mobile learning, respondents reported varying levels of usage experience. Approximately one-third of the sample reported three years of experience (31.7%, n = 102), followed by those with two years (26.1%, n = 84) and one year (16.5%, n = 53) of experience. Smaller proportions indicated four years (14.3%, n = 46), five years (8.1%, n = 26), and six years (3.4%, n = 11) of experience. This indicates that most participants possessed moderate to substantial familiarity with mobile learning technologies, supporting the suitability of the sample for examining sustainable use behavior.

In terms of gender composition, the sample included a higher proportion of male respondents (59.3%, n = 191) compared to female respondents (40.7%, n = 131), reflecting the gender distribution commonly observed in technology-focused studies within the Bangladeshi higher education context. With respect to academic standing, more than half of the respondents were in their third year of study (51.2%, n = 165), followed by second-year students (17.1%, n = 55), fourth-year students (16.8%, n = 54), and first-year students (14.9%, n = 48). This composition ensures adequate representation across different stages of undergraduate study, thereby enhancing the generalizability of the findings within the Bangladeshi undergraduate population. Check Table 1.

Table 1

Sample Characteristics.

Constructs	Categories	Frequency	Percent
Age (in years)	19	2	0.60
	20	8	2.50
	21	52	16.10
	22	52	16.10
	23	79	24.50
	24	96	29.80
	25	26	8.10
	26	7	2.20
Experience (in years)	1	53	16.50
	2	84	26.10

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	3	102	31.70
	4	46	14.30
	5	26	8.10
	6	11	3.40
Gender	Male	191	59.30
	Female	131	40.70
Academic year	1st year	48	14.90
	2nd year	55	17.10
	3rd year	165	51.20
	4th year	54	16.80
	Total	322	100.00

Data Analysis Method

This study employed partial least squares structural equation modeling (PLS-SEM) to analyze the proposed research model, using SmartPLS software (v-4.1.0.8), in accordance with established methodological recommendations (Ringle et al., 2015; Roy, 2023d-f). PLS-SEM was selected over covariance-based SEM approaches (e.g., AMOS) due to its suitability for complex, prediction-oriented research frameworks that aim to explain key behavioral outcomes (Hair & Sarstedt, 2019). This approach is particularly appropriate for the present study, which investigates sustainable use (SU) of mobile learning systems as the primary dependent construct influenced by multiple interrelated latent variables.

Given the study's central objective of predicting sustainable use behavior, PLS-SEM was adopted for its strong capability to maximize explained variance (R^2) in endogenous constructs and to estimate predictive relationships among latent variables (Roy et al., 2025; Sharma et al., 2021). This feature is especially relevant when examining sustained behavioral outcomes, as SU reflects long-term continuance rather than short-term adoption intentions. Moreover, PLS-SEM does not require strict distributional assumptions, such as multivariate normality, making it well-suited for analyzing Likert-scale survey data commonly used to capture sustained technology use perceptions and attitudes in educational research (Hair et al., 2019).

An additional methodological strength of PLS-SEM lies in its ability to assess predictive effects on sustainable use while explicitly accounting for measurement error. This capability addresses limitations inherent in regression-based and factor-based SEM techniques, including PROCESS macro analyses, which typically estimate structural relationships in isolation and do not fully integrate measurement model evaluation, potentially leading to biased estimates of sustained behavioral effects (Nitzl et al., 2016; Hussain & Papastathopoulos, 2022). In contrast, PLS-SEM simultaneously evaluates both the measurement and structural components of the model, providing more reliable estimates of the determinants of sustainable use and offering greater flexibility in model specification (Roy, 2023g; Sarstedt et al., 2020).

Accordingly, a two-stage analytical procedure was followed. First, the measurement model was assessed to establish the reliability and validity of all constructs, including sustainable use. Second, the structural model was evaluated to test the hypothesized relationships and to determine the predictive power of the antecedent constructs in explaining sustainable use behavior. This analytical strategy is consistent with best-practice guidelines for PLS-SEM and is well-suited for examining long-term technology use outcomes in higher education contexts (Hair & Sarstedt, 2019; Roy et al., 2021).

Data analysis and results

Evaluation of normality

The outcomes of the Shapiro–Wilk normality test, as reported in Table 2, reveal that the assumption of univariate normality was not met for any of the measurement items. In line with these results, the evaluation of multivariate normality using Mardia's skewness and kurtosis measures also resulted in the rejection of the null hypothesis, indicating pronounced departures from multivariate normality. In light of these findings, the use of PLS-SEM is methodologically justified, as this technique does not rely on strict univariate or multivariate normality assumptions and is particularly suitable for the analysis of data that deviates from normal distributional properties.

Table 2

Item-wise descriptive statistics and normality assessment.

Components	Indicators	Shapiro-Wilk Statistic	Mean	Standard deviation
Ease of Use (EOU)	EOU1	0.865***	4.907	1.050
	EOU2	0.836***	5.034	0.937
	EOU3	0.859***	4.981	0.984
	EOU4	0.888***	5.006	1.057
	EOU5	0.873***	4.944	0.973
Perceived Usefulness (PU)	PU1	0.894***	5.009	0.986
	PU2	0.861***	5.059	0.984
	PU3	0.872***	5.109	0.974
	PU4	0.872***	4.941	0.946
	PU5	0.844***	5.047	0.923

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Personal Attitude (PA)	PA1	0.894***	4.885	0.910
	PA2	0.883***	4.913	1.045
	PA3	0.907***	4.888	0.972
	PA4	0.886***	4.963	0.942
	PA5	0.867***	4.944	0.944
Sustainable Use (SU)	SU1	0.850***	5.317	1.139
	SU2	0.831***	5.311	1.093
	SU3	0.877***	5.242	1.133
	SU4	0.812***	5.360	1.095
	SU5	0.893***	5.425	1.113
Multivariate normality assessment				
Mardia's multivariate skewness = 133.4310***				
Mardia's multivariate kurtosis = 815.7208***				
Notes: *p < 0.05; **p < 0.01; ***p < 0.001.				

Assessment of the measurement model

Following recommended measurement evaluation procedures (Hair, 2021), all reflective constructs were examined for reliability and validity. As reported in Table 3, the Cronbach's alpha (α) and composite reliability (CR) values for every construct were above the recommended cutoff of 0.70, indicating acceptable internal consistency and robust construct reliability (Nunnally & Bernstein, 1994). Additionally, all observed indicators displayed standardized outer loadings exceeding 0.708, providing strong evidence of indicator reliability (Hair et al., 2023), as depicted in Figure 2.

Convergent validity was also confirmed, as the average variance extracted (AVE) for each reflective construct surpassed the minimum threshold of 0.50. This finding suggests that the constructs captured a substantial proportion of variance in their respective indicators, thereby satisfying established criteria for convergent validity (Fornell & Larcker, 1981).

Table 3:

Assessment of confirmatory factor analysis.

Factors	Items	Standard loadings	Composite reliability (CR)	Cronbach's alpha (α)	Average variance extracted (AVE)
Ease of Use (EOU)	EOU1	0.710	0.881	0.879	0.592
	EOU2	0.762			
	EOU3	0.754			
	EOU4	0.819			
	EOU5	0.798			
Perceived usefulness (PU)	PU1	0.788	0.897	0.896	0.634
	PU2	0.750			
	PU3	0.780			
	PU4	0.817			
	PU5	0.841			
Personal Attitude (PA)	PA1	0.791	0.890	0.890	0.617
	PA2	0.771			
	PA3	0.770			
	PA4	0.792			
	PA5	0.803			

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Sustainable Use (SU)	SU1	0.837	0.896	0.895	0.630
	SU2	0.773			
	SU3	0.804			
	SU4	0.755			
	SU5	0.797			

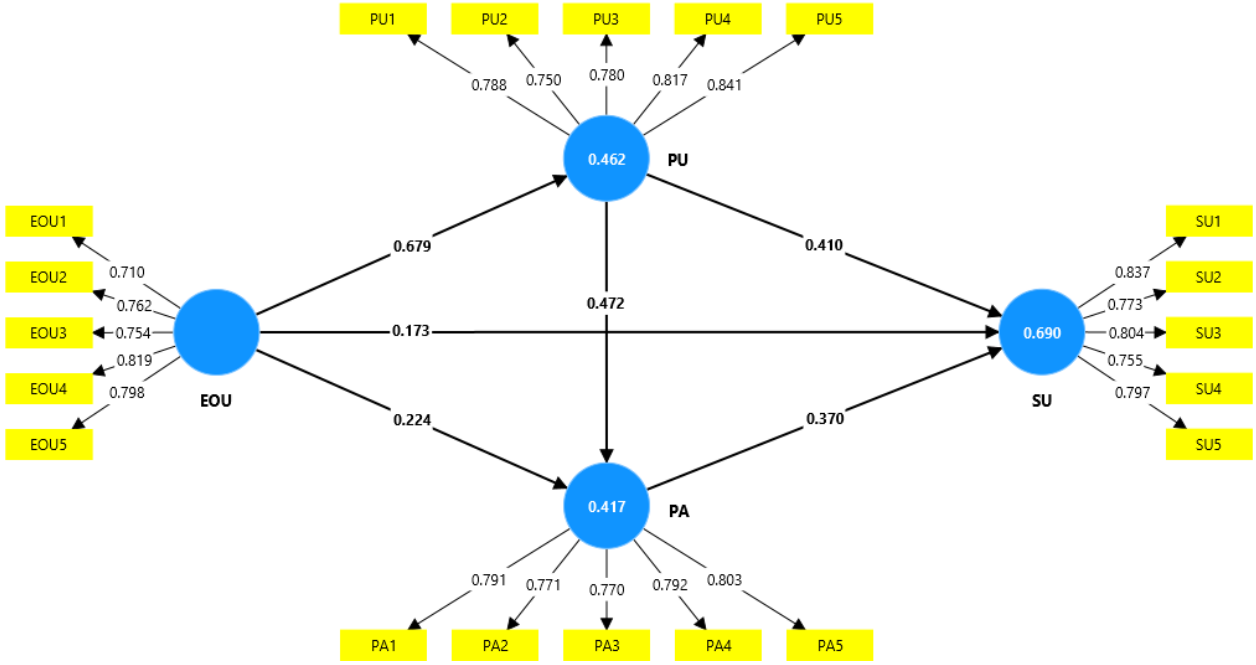

Figure 2: Analysis of the measurement model

Discriminant validity was evaluated using two complementary approaches: the Fornell–Larcker criterion and the heterotrait–monotrait ratio (HTMT), in line with established methodological guidance (Fornell & Larcker, 1981). As reported in Table 4, the square roots of the average variance extracted (AVE), presented along the diagonal, are greater than the corresponding inter-construct correlation coefficients for all reflective constructs, thus meeting the Fornell–Larcker requirement (Farrell, 2010). Furthermore, the HTMT values for all construct pairs fall below the conservative cutoff value of 0.85, providing additional support for discriminant validity and suggesting no significant concerns related to multicollinearity or conceptual overlap among the constructs (Henseler et al., 2016).

Table 4

Evaluation of the discriminant validity

Fornell–Larcker criterion	EOU	PA	PU	SU
EOU	**0.770**			
PA	0.545	**0.786**		
PU	0.679	0.624	**0.796**	
SU	0.653	0.720	0.758	**0.794**
HTMT Ratio	EOU	PA	PU	SU
EOU				
PA	0.541			
PU	0.679	0.623		
SU	0.652	0.719	0.758	

Note: The diagonal values highlighted in bold denote the square roots of the average variance extracted (AVE) for each construct, whereas the off-diagonal entries represent the inter-construct correlation coefficients.

Common method bias (CMB)

Given that the data were collected through self-reported measures, the potential influence of common method bias (CMB) was carefully examined (Malhotra et al., 2006). To mitigate the likelihood of CMB, both procedural and statistical remedies were applied in line with established methodological recommendations (Podsakoff et al., 2003). At the design stage, respondent anonymity

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and confidentiality were ensured by deliberately excluding personally identifiable information from the questionnaire, thereby reducing evaluation apprehension and the risk of socially desirable responses. In addition, a pilot test was conducted with a convenience sample of 40 undergraduate students to evaluate item clarity, content adequacy, and overall questionnaire comprehensibility (Perneger et al., 2015). Feedback from the pilot study led to minor refinements, primarily involving wording adjustments, prior to the administration of the final survey instrument.

To further assess the presence of CMB, several post-hoc statistical diagnostics were performed. First, Harman's single-factor test was applied, indicating that the largest factor accounted for 48.266% of the total variance, which is below the recommended threshold of 50%. This result suggests that common method bias is unlikely to pose a serious threat to the validity of the findings (MacKenzie & Podsakoff, 2012). Moreover, a comprehensive collinearity assessment was conducted using both a random marker variable approach (Kock & Lynn, 2012) and a full collinearity test (Kock, 2015). As reported in Table 5, all variance inflation factor (VIF) values were below the conservative cutoff value of 3.3, providing additional evidence that common method bias does not materially influence the study's results.

Table 5:

Assessment of the collinearity

	Full collinearity test				Full collinearity test with a random variable
	PU	PA	SU		Random
EOU	1.000	1.574	1.654		1.356
PU		1.857	2.240		1.535
PA			1.716		1.658
SU					1.899

Results of the hypothesis testing

The structural model was analyzed to evaluate the proposed hypotheses and to assess the relationships among the latent constructs. In accordance with established methodological guidance, PLS-SEM was used to estimate the predictive effects of the antecedent variables on the sustainable use of mobile learning systems. The assessment of the structural model emphasized both the strength and statistical significance of the standardized path coefficients (β). The analysis demonstrated support for all hypothesized direct paths, and a detailed summary of the structural model outcomes is provided in Table 6.

The results indicate that ease of use (EOU) is positively and significantly associated with perceived usefulness (PU) ($\beta = 0.679$, $p < 0.001$), personal attitude (PA) ($\beta = 0.224$, $p < 0.01$), and sustainable use (SU) ($\beta = 0.173$, $p < 0.05$). These findings provide empirical support for hypotheses H1, H2, and H3. In addition, perceived usefulness exhibits significant positive effects on both personal attitude ($\beta = 0.472$, $p < 0.001$) and sustainable use ($\beta = 0.410$, $p < 0.001$), thereby supporting hypotheses H4 and H5. Furthermore, personal attitude shows a strong and significant influence on sustainable use ($\beta = 0.370$, $p < 0.001$), confirming hypothesis H6. The structural relationships are visually presented in Figure 3.

The mediation analysis further reveals that perceived usefulness serves as a mediator in the relationships between ease of use and personal attitude ($\beta = 0.321$, $p < 0.001$), as well as between ease of use and sustainable use ($\beta = 0.278$, $p < 0.001$), supporting hypotheses H7 and H8. Similarly, personal attitude mediates the relationship between ease of use and sustainable use ($\beta = 0.083$, $p < 0.05$) and between perceived usefulness and sustainable use ($\beta = 0.175$, $p < 0.01$), providing support for hypotheses H9 and H10. Finally, the serial mediation analysis confirms hypothesis H11, indicating that perceived usefulness and personal attitude jointly and sequentially mediate the relationship between ease of use and sustainable use ($\beta = 0.119$, $p < 0.01$).

Table 6:

Assessment of the hypothesis testing.

H	Relationships	Coefficient (β)	T statistics	P values	95% CI	Decision
	Direct paths					
H1	EOU -> PU	0.679	11.002	0.000	[0.523, 0.774]	Supported
H2	EOU -> PA	0.224	2.764	0.006	[0.065, 0.378]	Supported
H3	EOU -> SU	0.173	2.018	0.044	[0.020, 0.327]	Supported
H4	PU -> PA	0.472	6.274	0.000	[0.300, 0.598]	Supported
H5	PU -> SU	0.410	4.457	0.000	[0.225, 0.577]	Supported
H6	PA -> SU	0.370	4.448	0.000	[0.224, 0.551]	Supported
	Mediation paths					
H7	EOU -> PU -> PA	0.321	5.368	0.000	[0.210, 0.438]	Supported

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H8	EOU -> PU -> SU	0.278	4.557	0.000	[0.168, 0.407]	Supported
H9	EOU -> PA -> SU	0.083	2.536	0.012	[0.032, 0.161]	Supported
H10	PU -> PA -> SU	0.175	3.314	0.001	[0.096, 0.311]	Supported
H11	EOU -> PU -> PA -> SU	0.119	3.018	0.003	[0.063, 0.226]	Supported

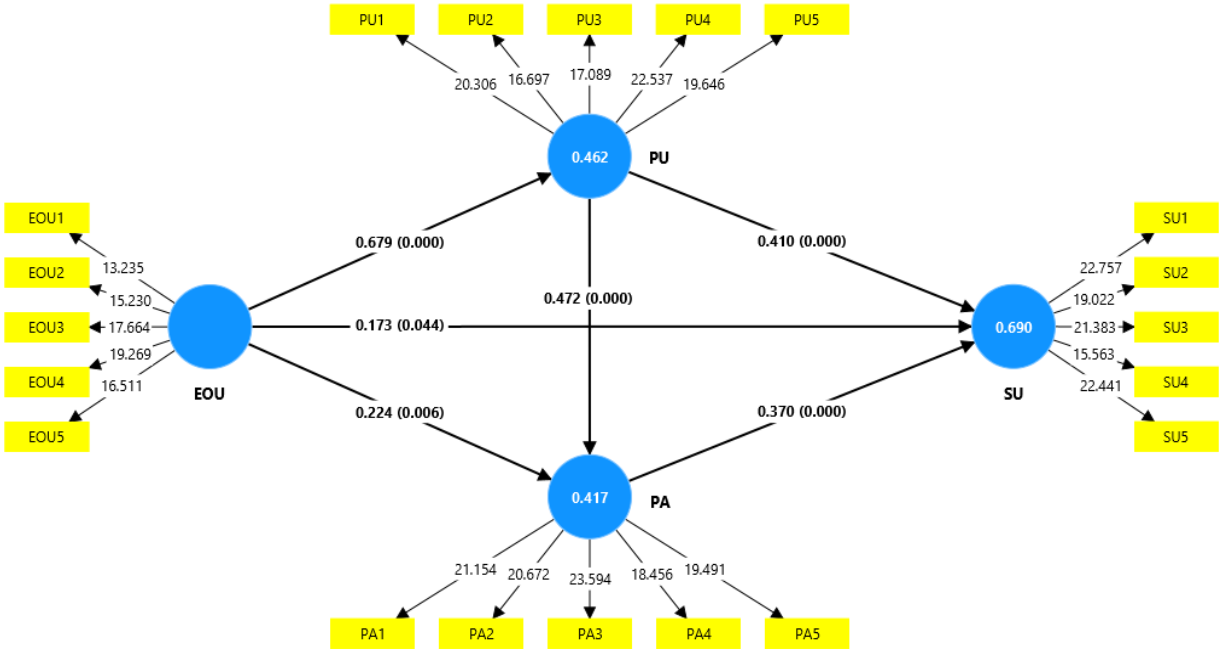

Figure 3: Results of the hypothesis testing.

The explanatory capacity of the structural model was examined using the coefficient of determination (R^2) and effect size (f^2) statistics to determine how effectively the antecedent constructs account for variance in the endogenous variables. As reported in Table 7, the model accounts for 46.2% of the variance in perceived usefulness (PU), 41.7% in personal attitude (PA), and 69.0% in sustainable use (SU). These values indicate strong explanatory power, particularly for sustainable use, which is the primary outcome variable of interest in this study and reflects sustained engagement with mobile learning among Bangladeshi undergraduate students. In accordance with established guidelines, the f^2 statistic was examined to assess the relative contribution of each predictor construct to the explained variance in the endogenous variables (Hair et al., 2020). The results show that most predictors exert small to large yet meaningful effects, consistent with the benchmarks proposed by Cohen (2013), as summarized in Table 7.

Because R^2 and f^2 primarily capture in-sample explanatory performance and do not fully reflect predictive capability beyond the estimation sample, additional procedures were employed to assess predictive relevance. Specifically, Stone–Geisser's Q^2 and PLSpredict were used to evaluate the model's ability to predict sustainable use and its antecedents in an out-of-sample context (Hair, 2021). The blindfolding technique was applied to compute Q^2 values for all endogenous constructs (Chin et al., 2020). As shown in Table 7, the Q^2 values for PU (0.248), PA (0.235), and SU (0.404) are all greater than zero, providing strong evidence of predictive relevance, particularly for sustainable use behavior (Shmueli et al., 2019). Nonetheless, it is acknowledged that Q^2 has inherent limitations, as it integrates both in-sample and out-of-sample elements and does not rely on a holdout sample, which may mask true predictive performance (Shmueli et al., 2016, 2019).

To overcome these limitations and to offer a more stringent evaluation of out-of-sample prediction, PLSpredict was conducted following best-practice recommendations (Shmueli et al., 2016; Hair, 2021). A 10-fold cross-validation procedure was implemented, and predictive accuracy was assessed using the root mean square error (RMSE) criterion. As presented in Table 7, the majority of the indicators produced lower RMSE values than those generated by the naïve linear regression benchmark, thereby demonstrating the model's moderate predictive accuracy and robustness in predicting sustainable use of mobile learning within the Bangladeshi higher education context (Ara & Roy, 2026; Hair et al., 2020).

Table 7:

Assessment of the model's predictive power.

Coefficient of Determination		PLSpredict				
	R^2	Items	PLS-SEM_RMSE	LM_RMSE	Difference	Power
PU	0.462	PA1	0.843	0.847	-0.004	
PA	0.417	PA2	0.968	0.966	0.002	Moderate

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SU	0.690	PA3	0.909	0.906	0.003
		PA4	0.859	0.828	0.031
Predictive Relevance		PA5	0.864	0.867	-0.003
	Q^2	PU1	0.852	0.856	-0.004
PU	0.248	PU2	0.880	0.888	-0.008
PA	0.235	PU3	0.866	0.873	-0.007
SU	0.404	PU4	0.811	0.820	-0.009
		PU5	0.777	0.781	-0.004
Effect sizes		SU1	0.979	0.984	-0.005
	f^2	SU2	0.974	0.980	-0.006
EOU -> PU	0.857	SU3	1.017	1.021	-0.004
EOU -> PA	0.046	SU4	0.982	0.994	-0.012
EOU -> SU	0.049	SU5	0.967	0.972	-0.005
PU -> PA	0.206				
PU -> SU	0.242				
PA -> SU	0.257				

Discussion

This study investigated the determinants of sustainable mobile learning use among undergraduate students in Bangladesh by testing eleven hypotheses grounded in the Technology Acceptance Model and extended through mediating and serial mediation mechanisms. Overall, the findings provide strong empirical support for the proposed framework and offer nuanced insights into how cognitive beliefs and attitudinal factors jointly shape long-term mobile learning behavior in a developing-country context.

The results related to H1 confirm that ease of use significantly influences perceived usefulness, indicating that students are more likely to view mobile learning as beneficial when platforms are intuitive and require minimal effort. This finding is consistent with prior TAM-based studies conducted in mobile and e-learning contexts (Al-Rahmi et al., 2021; Nahar et al., 2023; Zhou et al., 2025). However, in contrast to studies from technologically mature settings where this relationship weakens over time, the strong effect observed here reflects Bangladesh's heterogeneous digital literacy levels and varied device quality. In such contexts, usability remains a persistent driver of perceived value rather than a transitional factor limited to early adoption.

Support for H2 demonstrates that ease of use positively affects personal attitude toward mobile learning. This aligns with earlier empirical evidence suggesting that students develop favorable evaluations of technologies that reduce cognitive and operational burden (Alghazi et al., 2021; Dissanayake & Velananda, 2020). In Bangladesh, where students often balance academic demands with financial or family responsibilities, ease of interaction becomes critical in shaping affective responses. Compared with studies in developed economies, where attitude is often driven more by perceived outcomes than system design, this finding underscores the continued importance of usability in shaping learner perceptions in resource-constrained environments.

The findings also support H3, showing a direct effect of ease of use on sustainable use. While some prior studies report only indirect effects of ease of use through usefulness or attitude (Fan & Wang, 2025; Venkatesh et al., 2012), the present results suggest that usability alone can sustain continued engagement in Bangladesh. This divergence may be attributed to infrastructural variability and limited technical support across institutions, where students are less likely to persist with platforms that are perceived as complex or unstable.

With regard to H4, the study confirms that perceived usefulness significantly enhances personal attitude, consistent with extensive prior research (Al-Rahmi et al., 2021; Islam et al., 2021). Students who perceive mobile learning as improving academic performance, flexibility, and efficiency are more likely to develop positive evaluations. In the Bangladeshi higher education system, which is strongly examination-oriented, this performance-driven perception appears to be particularly salient, reinforcing the central role of usefulness in shaping learner attitudes.

Support for H5 indicates that perceived usefulness has a strong direct effect on sustainable use. This finding aligns with continuance and post-adoption studies emphasizing usefulness as the most robust predictor of long-term technology use (Jabeen et al., 2025; Mohaimen et al., 2025; Venkatesh et al., 2012). Compared with short-term adoption studies, the present findings extend the literature by demonstrating that perceived academic value remains decisive even after initial acceptance, especially in contexts where students are cost-sensitive and outcome-focused.

The results further validate H6, confirming that personal attitude significantly predicts sustainable use. This supports behavioral theories suggesting that affective evaluations are critical in transforming beliefs into enduring behavior (Islam et al., 2025; James et al., 2025). Unlike studies that examine attitude only as a predictor of intention, the current findings empirically link attitude to sustained usage, highlighting its long-term behavioral relevance. In Bangladesh, where institutional mandates alone are insufficient

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to ensure continued technology use, positive student attitudes appear essential for sustaining mobile learning practices.

The mediation analyses provide deeper explanatory insight. Support for H7 and H8 confirms that perceived usefulness mediates the relationships between ease of use and both attitude and sustainable use, consistent with TAM's causal logic (Davis, 1989; Kawser et al., 2023). These findings suggest that usability enhances sustainability primarily by increasing students' perceptions of academic value. This mediation pattern mirrors findings from recent mobile learning studies but is particularly meaningful in Bangladesh, where effort-reducing technologies must also demonstrate clear performance benefits to justify continued use.

Similarly, H9 and H10 are supported, indicating that personal attitude mediates the effects of ease of use and perceived usefulness on sustainable use. This underscores attitude's role as a critical affective mechanism translating cognitive beliefs into long-term behavior. Compared with studies that prioritize direct effects, the present findings highlight that positive feelings toward mobile learning are not merely by-products but essential drivers of sustainability, especially in blended and hybrid learning environments increasingly adopted in Bangladeshi universities (Islam et al., 2025; Khatun & Roy, 2022).

Finally, support for H11 confirms the serial mediating role of perceived usefulness and personal attitude in the relationship between ease of use and sustainable use. This sequential pathway aligns with recent calls to move beyond linear adoption models and examine multi-stage behavioral processes (Khatun et al., 2025; Kumar & Bervell, 2019; Voicu & Muntean, 2023). In the Bangladeshi context, this finding is particularly significant, suggesting that sustainable mobile learning emerges through a cumulative process: systems must first be easy to use, then perceived as useful, then positively evaluated, before sustained engagement can occur.

Taken together, the findings offer strong empirical validation for an extended TAM-based framework focused on sustainability rather than initial adoption. By confirming all eleven hypotheses, the study contributes to the mobile learning literature by clarifying the mechanisms through which usability, usefulness, and attitude interact to shape long-term behavior in a developing-country context. These insights not only reinforce established theories but also demonstrate the necessity of contextualized models when examining educational technology sustainability in countries such as Bangladesh.

Theoretical Implications

This study makes several important theoretical contributions to the literature on mobile learning and technology sustainability. First, by conceptualizing sustainable use as the primary outcome variable rather than behavioral intention or initial adoption, the study extends the traditional Technology Acceptance Model (TAM) beyond its dominant focus on short-term acceptance. While TAM has been widely validated across educational contexts, prior research has been criticized for its limited explanatory power regarding long-term technology engagement. The present findings respond directly to this gap by empirically demonstrating how ease of use, perceived usefulness, and personal attitude jointly explain sustained mobile learning behavior over time.

Second, the study advances TAM by empirically validating multiple mediation and serial mediation mechanisms. The confirmation of perceived usefulness and personal attitude as both independent mediators and sequential mediators provides a more nuanced understanding of the cognitive–affective pathways through which usability translates into sustainable behavior. This layered explanatory structure moves beyond linear cause–and–effect relationships and supports recent theoretical calls for more process-oriented models of educational technology use.

Third, the findings contribute to the growing body of context-sensitive technology adoption research by demonstrating that core TAM relationships operate differently in developing-country settings. Unlike studies conducted in technologically mature environments, where ease of use often shows diminished influence, the present study confirms its sustained theoretical relevance in Bangladesh. This suggests that digital divide factors, such as uneven digital literacy and infrastructural constraints, can prolong the explanatory relevance of usability-related constructs, thereby challenging assumptions of model universality.

Finally, by empirically validating all eleven hypotheses within a single integrative framework, the study strengthens the theoretical robustness of TAM-based models for mobile learning sustainability. It provides evidence that cognitive beliefs (ease of use and usefulness) and affective responses (attitude) should be treated as complementary rather than competing theoretical mechanisms when explaining sustained educational technology use. This integrated perspective offers a stronger theoretical foundation for future research on digital learning sustainability, particularly in emerging economies.

Practical Implications

Implications for Policy Makers

The findings of this study carry important implications for national education and digitalization policies in Bangladesh. First, policy initiatives aimed at promoting mobile learning should move beyond access provision alone and explicitly prioritize usability and pedagogical value. While device distribution and internet expansion remain important, the results indicate that sustainable use depends on students' perceptions that mobile learning platforms are both easy to use and academically beneficial. Therefore, national digital education strategies should include usability standards and learner-centered design guidelines for mobile learning platforms used in higher education.

Second, policymakers should recognize that sustainability requires attitudinal change, not merely technological deployment. Investments in awareness campaigns, digital literacy programs, and learner training can foster positive attitudes toward mobile learning, which in turn promote long-term engagement. This is particularly relevant in Bangladesh, where resistance to non-traditional learning modes still exists in some academic and cultural contexts.

Third, the confirmed serial mediation pathway suggests that fragmented policy interventions are unlikely to yield sustained outcomes. Effective mobile learning policies should adopt a holistic approach, ensuring that platforms are usable, demonstrably useful for academic success, and positively perceived by students. Aligning mobile learning initiatives with national goals related to sustainable development, lifelong learning, and digital inclusion can further enhance their long-term impact.

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Implications for Universities and Higher Education Institutions

For universities, the findings highlight the critical importance of student-centered mobile learning design and implementation. Institutions should prioritize platforms that minimize complexity and cognitive load, as ease of use was shown to influence sustainable use both directly and indirectly. Regular usability testing, student feedback mechanisms, and interface localization (e.g., language and cultural relevance) can significantly enhance students' learning experiences.

Second, universities should clearly communicate and demonstrate the academic usefulness of mobile learning tools. Integrating mobile platforms directly into assessment, course delivery, and academic support services can strengthen students' perceptions of value. When students see tangible benefits, such as improved performance, flexibility, and time efficiency, they are more likely to continue using mobile learning systems beyond compulsory requirements.

Third, the strong role of personal attitude suggests that universities should invest in faculty training and instructional design that promotes positive learner experiences. Instructors play a key role in shaping students' attitudes by how they integrate mobile learning into pedagogy. Supportive teaching practices, consistent platform use across courses, and encouragement of active mobile-based learning can reinforce favorable attitudes and sustained engagement.

Finally, universities in Bangladesh should treat mobile learning not as an emergency or supplementary solution but as a strategic component of long-term educational sustainability. By aligning institutional digital strategies with students' cognitive and attitudinal needs, higher education institutions can foster continuous, meaningful, and equitable mobile learning use.

Limitations and future research directions

Despite its theoretical and empirical contributions, this study has several limitations that should be acknowledged when interpreting the findings. First, the study employed a cross-sectional research design, which restricts the ability to infer causal relationships among the constructs. Although the proposed relationships are grounded in established theory and supported by robust statistical analysis, future studies could adopt longitudinal designs to examine how perceptions of ease of use, usefulness, and attitude evolve over time and how these changes influence sustainable mobile learning use.

Second, the data were collected using self-reported measures, which may be subject to common method bias and social desirability effects. While procedural remedies were applied during survey design, future research could strengthen validity by incorporating objective usage data, system logs, or learning analytics to complement perceptual measures and provide a more comprehensive understanding of sustained mobile learning behavior.

Third, the study focused exclusively on undergraduate students in Bangladesh, which may limit the generalizability of the findings to other educational levels or national contexts. Differences in digital infrastructure, institutional readiness, and cultural attitudes toward technology may influence the strength and direction of the observed relationships. Future research should replicate and extend this model across postgraduate populations, vocational education, and secondary education, as well as in other developing and developed countries, to assess cross-contextual robustness.

Fourth, although the study validated an extended Technology Acceptance Model with multiple mediation pathways, it did not incorporate institutional or pedagogical variables, such as instructor support, course design quality, or assessment integration. These factors may interact with individual perceptions to influence sustainable use. Future studies could integrate TAM with complementary theoretical frameworks, such as self-determination theory or the unified theory of acceptance and use of technology (UTAUT), to capture a broader range of motivational and organizational influences.

Finally, the study operationalized sustainability primarily in terms of continued use behavior, which, while important, represents only one dimension of educational sustainability. Future research could expand this conceptualization by examining outcomes such as learning effectiveness, equity of access, learner well-being, and long-term skill development. Such multidimensional approaches would provide deeper insights into how mobile learning contributes to sustainable education systems in Bangladesh and beyond.

Conclusion

This study investigated the determinants of sustainable mobile learning use in higher education by empirically testing an extended Technology Acceptance Model within the Bangladeshi context. By shifting the focus from initial adoption to long-term sustainability, the study addresses a critical gap in the mobile learning literature. The findings confirm that perceived ease of use, perceived usefulness, and personal attitude are central drivers of sustainable mobile learning, operating through both direct effects and multiple mediation pathways. In particular, the results demonstrate that ease of use enhances sustainability by strengthening learners' perceptions of academic value and fostering positive attitudes toward mobile learning, highlighting the cumulative nature of sustained engagement.

Beyond its empirical contributions, the study provides important theoretical and practical insights for developing-country contexts. The findings underscore that in Bangladesh, where digital literacy and infrastructural conditions vary widely, usability and perceived usefulness remain enduring determinants of continued mobile learning use. By extending established acceptance models toward sustainability outcomes and validating complex mediation mechanisms, the study contributes to theory while offering clear guidance for policymakers and universities. Sustainable mobile learning, as demonstrated, requires more than technological availability; it depends on learner-centered design, demonstrable academic value, and supportive institutional strategies that collectively promote long-term educational transformation.

"Statements and Declarations"

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Declaration of competing interest

The authors declare no conflict of interest.

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Data availability

The data that support the findings of this study are not openly available due to securing the anonymity of the respondents and their institutions. However, anonymized data sets are available from the corresponding author upon reasonable request.

Informed consent

Informed consent was obtained from all participants in this study.

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