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The impact of digital literacy on learning outcomes among college students: the mediating effect of digital atmosphere, self-efficacy for digital technology and digital learning

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Few studies have explored the specific internal mechanisms and links by which digital literacy impacts learning outcomes. This study investigates the complex relationship between digital literacy and learning outcomes among college students, using social cognitive theory (SCT) and structural equation modeling (SEM) as theoretical frameworks. Data were collected from 589 college students in China's northwest region. The results reveal that digital literacy affected learning outcomes indirectly through the digital atmosphere, self-efficacy for digital technology, and digital learning. Specifically, digital atmosphere and digital learning mediate the relationship between digital literacy and learning outcomes. Self-efficacy for digital technology and digital learning jointly mediate the relationship between digital literacy and learning outcomes. Digital literacy has a positive and significant impact on the digital atmosphere and influences students' self-efficacy for digital technology, thereby motivating them to participate in digital learning and ultimately having a positive impact on learning outcomes. Overall, the findings highlight the importance of developing digital literacy, optimizing digital learning atmospheres, and enhancing self-efficacy to fully leverage undergraduates' learning potential in the digital age.

KEYWORDS

digital literacy, learning outcomes, digital atmosphere, self-efficacy for digital technology, mediation analysis

1 Introduction

Over the last few years, the rapid advances in digital technologies have significantly reshaped the concept and method of learning (Hu and Hwang, 2024). In the digital era, digital literacy has become a fundamental and crucial skill needed to adapt to the accelerated digital society, especially for college students who are digital natives (Sunny and Ramasamy, 2025; Thao et al., 2024; Xiaoxia and Kyung Hee, 2022). For instance, being digitally literate can enhance the academic success of college students (Ahmed and Roche, 2021), develop critical thinking for civic engagement (Breakstone et al., 2022), help visual impairment students to overcome certain educational barriers (Arslantas and Gul, 2022), enable college students with reading difficulties to access basic information online (Thao et al., 2024) and other minorities (Cerqueira, 2023; Timmis and Muhuro, 2019).

Learning outcomes are skills, attitudes and knowledge students ought to master through their learning (Biggs and Tang, 2011) and they have received growing emphasis in higher education (Kumpas-Lenk et al., 2018). Emerging studies have indicated that digital literacy is effective in promoting learning outcomes. These studies generally focus on the direct relationship between digital literacy and learning outcomes. Lukitasari et al. (2022) developed and tested the effectiveness of digital literacy instruments on students' learning outcomes, and found that there is a linear relationship between digital literacy and learning outcomes. Brata et al. (2022) analyzed students' digital literacy from the perspective of learning biology material on the digestive system, and found that a positive correlation between digital literacy and learning outcomes. However, the underlying impact mechanisms between digital literacy and learning outcomes among college students remain inconclusive. Additionally, learning outcomes are influenced by students' comprehension of a piece of content or subject matter (Monib et al., 2024), learning environment (Chang et al., 2011; Gui et al., 2023; Guo et al., 2017), self-efficacy (Ngendahayo et al., 2024; Pan et al., 2024; Yang et al., 2025), learning behaviors (Akla Kesuma et al., 2023), especially online learning (Hsiao et al., 2019), e-learning (Pham and Tran, 2020), and microlearning (Gasca-Hurtado et al., 2024). Above all, these studies hold significant value for further investigation on the complex potential relationship between digital literacy and learning outcomes. To our knowledge, few studies have explored the specific internal mechanisms linking digital literacy to learning outcomes. In particular, no research grounded in social cognitive theory (SCT) has examined how digital literacy affects learning outcomes among college students. This study fills this research gap by investigating the underlying mechanisms between digital literacy and learning outcomes within an SCT-based theoretical framework that considers the mediating roles of digital atmosphere, self-efficacy for digital technology, and digital learning.

This study integrates social cognitive theory (SCT) to analyze the impact of digital literacy on learning outcomes among college students by incorporating the relevant factors including digital atmosphere, self-efficacy for digital technology and digital learning. Based on structural equation modeling, the research seeks to answer the following questions: (1) what are the structural relationships between digital literacy and learning outcomes? (2) Are there mediating effects of digital atmosphere, self-efficacy for digital technology and digital learning between digital literacy and learning outcomes among college students? (3) What are the implications for practice to improve college students' learning outcomes in the digital era according to the structural equation model (SEM) analyses?

2 Literature review

2.1 Social cognitive theory (SCT)

Social cognitive theory (SCT) was first put forward by Bandura (1986), which explains that individuals' behavior is not only affected by environmental factors, but also by personal factors, presenting a triadic reciprocal determinism. The theory emphasizes that there is an interactive and interdependent relationship among person, environment and behavior(Hong et al., 2015; Uçar and Sungur, 2017), which is widely used to identify the influencing factors of individual behavior in various specified fields (Chiu and Tsai, 2014; Schunk and DiBenedetto, 2020; Zhou et al., 2020), such as information science (Middleton et al., 2019), career development (Gregory and Penela, 2023), and education (Hust et al., 2017).

The current study included the three factors of SCT model that have been found to be significantly vigorous for predicting learning outcomes, specifically personal factors, environmental factors and behavioral factors. In the learning investigation context, behavioral factors include not only learning styles such as networked learning and digital learning, but also learning outcomes, as they involve the actual activities and actions undertaken by individuals (Lee, 2020). The emergence and development of behavior change are affected by personal factors, for instance, digital literacy and self-efficacy for digital technology, which are activated when individuals possess digital literacy and feel capable of achieving desired behavior (Lee and Tseng, 2024). Moreover, environmental factors play an indispensable and important role in the learning investigation context, which include not only the physical environment, but also the social and learning environment that individuals are in every day. Digital atmosphere, emerging with the digital age, forms a vital part of this learning environment. Thus, we incorporated the combination of personal, environmental and behavioral factors in our study for the purpose of providing a comprehensive framework for understanding the relationship between digital literacy and learning outcomes among college students.

2.2 Digital literacy and digital atmosphere

Digital literacy was first mentioned by Gilster (1997), which was used as "the ability to both understand and use digitized information in multiple formats from a wide range of sources when it is presented via computers." The definition of digital literacy has not yet reached a consensus in academia (Wei, 2024), and there are several perspectives on the definition of digital literacy in the literature. Buckingham (2015) stated that digital literacy refers to various functional issues related to computers and information technology, not just of a functional issue of computers. Polizzi (2020) defined the digital literacy as the ability to access, analyze, evaluate and produce messages in a variety of forms. In a more global context, digital literacy is defined by UNESCO (2018) as the ability to access, manage, understand, integrate, communicate, evaluate and create information safely and appropriately through digital technologies for employment, decent jobs and entrepreneurship, which includes competences that are variously referred to as computer literacy, ICT literacy, information literacy and media literacy. Researchers have established key literacies of digital literacy and the specific literacies identified varied according to the nature of the studies conducted (Falloon, 2020). For instance, Eshet (2004) developed a conceptual framework for digital literacy, which consisted of five literacies, including (1) photo-visual literacy, (2) reproduction literacy, (3) information literacy, (4) branching literacy, and (5) socio-emotional literacy. Based on the work of Eshet (2004), Ng (2012) offered a conceptual framework viewing digital literacy as emerging at the convergence of students' technical, cognitive, and socio-emotional competencies, which focuses on an individual's objective ability to solve practical problems in digital scenarios.

Atmosphere no longer denotes only the envelope of gases around a planet, but in contemporary usage has become a metaphor for the emotional field generated when people engage with particular settings or events (Paschou and Papaioannou, 2023). For instance, digital atmosphere of museums was characterized by the emotions elicited by the integration of digital applications, as well as elements such as content, design, color choices, sound and audio, and the scents and aromas within the physical space (Paschou and Papaioannou, 2023). Visiers-Jiménez et al. (2021) propose that the pedagogical atmosphere on the ward has been identified as part of what constitutes a high-quality clinical learning environment. Virtanen et al. (2022) note that the PE students felt that the learning atmosphere of their final year study module was warm and conversational according to the research results. Tucker and Goodings (2017) report that atmosphere is commonly understood as the feeling or sense of a particular space, and introduce digital atmosphere as a lens to foreground the affective currents that shape how people seek and offer care within social media spaces. In this study, digital atmosphere, born out of the digital age, refers to the perceived feeling or sense that students experience within digital learning spaces, drawing on the concept of learning atmosphere (Virtanen et al., 2022) and educational climate (Krupat et al., 2017) and extending it to digital contexts. Digital atmosphere includes dimensions such as perceived support, interactivity, and emotional tone within digital learning environments. According to the social cognitive theory (SCT), an individual's level of digital literacy may affect their use and perception of digital technology, which in turn influences the digital atmosphere they are in (Steelman et al., 2016). The first hypothesis of the study is as follows:

> *H1*: digital literacy has a positive and significant impact on digital atmosphere.

2.3 Digital learning

With the widespread adoption of digital technology and artificial intelligence in the education landscapes, digital learning has come into being but does not alter the fundamental nature of education (Ismail and Nur, 2024). In the digital age, learners need to not only acquire traditional skills, but also develop a comprehensive ability to comprehend, assess, synthesize, utilize, and generate knowledge by leveraging digital technologies. This is crucial for obtaining professional knowledge, boosting professional competencies, and ensuring the conditions and support necessary for continuous learning, lifelong learning, and innovation. According to the social cognitive theory (SCT), digital atmosphere, as an environmental factor, may impact digital learning behavior of college students. The second hypothesis of the study is formulated as follows:

> *H2*: digital atmosphere has a positive and significant impact on digital learning.

2.4 Self-efficacy for digital technology

Self-efficacy was defined by Bandura (1986) as the belief in one's ability to exert control in a given atmosphere and to produce a desired outcome. This belief is also understood as the confidence in applying one's skills to achieve a specific result (Yang and Du, 2024). Individuals with high perceived self-efficacy are more likely to be motivated to take action and have a greater willingness to tackle challenging tasks (Gerdts-Andresen et al., 2023). Self-efficacy for digital technology refers to one's perception of their ability to perform technological tasks or use digital technology to handle tasks (Yuen-Han Mo et al., 2025), which is a type of "ability belief" that emphasizes an individual's subjective perception of their own abilities, rather than the abilities themselves. In the context of social cognitive theory, the higher an individual's level of digital literacy, the more likely they are to have greater self-efficacy in using digital technology. What's more, perceived self-efficacy for digital technology may influence college students' digital learning. Getenet et al. (2024) found that positive student attitudes and digital literacy significantly contributed to self-efficacy, which, in turn, positively affected the engagement dimensions. Yang and Du (2024) pointed that students with higher perceived self-efficacy for digital technology are more likely to actively use digital tools for learning. Thus, the third and fourth hypotheses of the study are as follows:

> *H3*: digital literacy has a positive and significant impact on self-efficacy for digital technology.
>
> *H4*: self-efficacy for digital technology has a positive and significant impact on digital learning.

2.5 Learning outcomes

The learning and teaching process carried out in educational institutions is reflected in the achievement of optimal learning outcomes. The way students achieve learning outcomes is demonstrated through the lively discussion and interaction conducted by both teachers and students. The learning outcome has become an integral and inseparable aspect for assessing the quality of education (Puniatmaja et al., 2024). Learning outcomes are typically understood as the results that emerge from the interactions that take place during the learning process. Lin et al. (2017) found that digital learning shows better positive effects on learning outcome than traditional teaching does. Hsiao et al. (2019) confirmed that students' online learning behaviors had a significant effect on short-term learning outcomes, and indicated that students with a higher frequency of online learning behaviors obtained a higher GPA grade level. The fifth hypothesis of the study is deduced:

> *H5*: digital learning has a positive and significant impact on learning outcomes.

2.6 The mediating effect of digital atmosphere, self-efficacy for digital technology and digital learning

An individual's level of digital literacy may influence the digital atmosphere they are in Steelman et al. (2016). Additionally, digital atmosphere, as an environmental factor, may impact digital learning behavior of college students. Through digital learning, college students may achieve better learning outcomes by using digital technologies and tools. Therefore, we argue that digital atmosphere, self-efficacy for digital technology and digital learning play mediating roles in the relationship between digital literacy and learning outcomes. The sixth and seventh hypotheses of the study are as follows:

> *H6*: digital atmosphere and digital learning mediate the relationship between digital literacy and learning outcomes.
>
> *H7*: self-efficacy for digital technology and digital learning mediate the relationship between digital literacy and learning outcomes.

3 Methods

3.1 Research model

The relationship description model is designed to clarify the nature of the relationships between two or more variables, as well as the degree of their correlation, while also identifying and quantifying covariance (Karasar, 2012). In this study, we adopt this model and utilize structural equation modeling (SEM) techniques to conduct an in - depth analysis. Specifically, we explore the interplay and correlations among digital literacy (DL), digital atmosphere (DA), self - efficacy for digital technology (SEDT), digital learning (DL'), and learning outcomes (LO) among college students, as depicted in Figure 1.

As illustrated in Figure 1, path H1 represents the direct effect of digital literacy on digital atmosphere; path H2 represents the direct effect of digital atmosphere on digital learning; path H3 represents the direct effect of digital literacy on self - efficacy for digital technology; path H4 represents the direct effect of self - efficacy for digital technology on digital learning; and path H5 represents the direct effect of digital learning on learning outcomes. All analyses were conducted using SPSS 21.0, the PROCESS macro in SPSS, and AMOS 21.0, with statistical significance set at $\alpha = 0.05$.

3.2 Participants and date collection

The present study utilized a questionnaire survey methodology. The survey was administered via the online platform from October to November 2024, targeting college students in universities located in the western region of China. A total of 589 individuals participated in the survey, representing a diverse range of academic disciplines. After excluding invalid questionnaires, a sample size of 538 was retained, comprising 47.96% female participants ($n = 258$) and 52.04% male participants ($n = 280$). In terms of sample size, Maxwell et al. (2008) highlighted the significance of sample size planning in influencing statistical power and the precision of parameter estimates. Lakens and Ravenzwaaij (2022) underscored the necessity of justifying sample size adequacy to ensure the robustness of research findings. Consistent with the recommendations of Schumacker and Lomax (2010), numerous studies have employed sample sizes ranging from 250 to 500 participants, which is deemed sufficient for conducting structural equation modeling (SEM). Given these considerations, the sample size in the current study is deemed adequate.

To ensure data quality and identify inattentive respondents, we incorporated two validity screening measures in the questionnaire design. We included two instructional manipulation checks (IMCs):(1) A simple arithmetic verification item, "What is the answer to 3 + 5?"; (2) A semantic recognition task that asks participants to identify the non-fruit item from a list containing apple, banana, stone, and orange. Additionally, we implemented an automated response time tracking system to record completion durations. Responses that failed either attention check (incorrect answers to verification items) or had implausibly short response times (below 15 s, as determined by pilot testing percentiles) were excluded from analysis. Through this rigorous validation protocol, 51 invalid responses (9.5% of total submissions) were eliminated, resulting in 538 validated questionnaires retained for formal analysis. This validation rate of 90.5% exceeds recommended thresholds for online survey research, ensuring sufficient statistical power for subsequent analyses. Table 1 presents the sample data statistics. 52.04% of the participants were male, and 86.25% of the participants were majoring in liberal arts, science, and engineering.

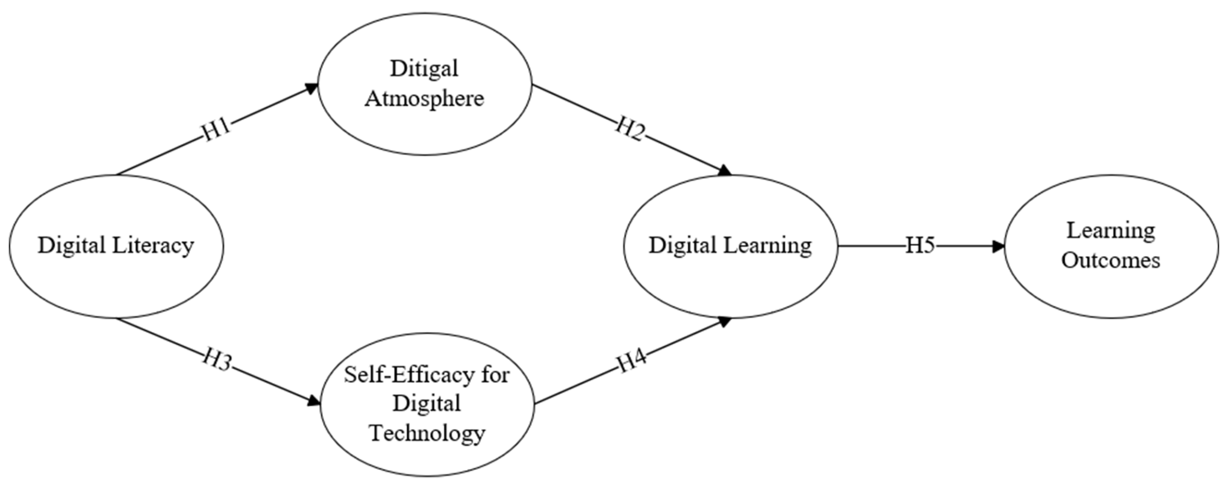

FIGURE 1
Research model.

TABLE 1 Sample data statistics.

Characteristics	Categories	Number of People	Percentage (%)
Gender	Male	280	52.04
	Female	258	47.96
Major	Liberal Arts, Science, and Engineering	464	86.25
	Medicine, Arts, Physical Education, and Other	74	13.75

3.3 Instruments

This study utilizes a 5 - point Likert scale, with options spanning from "strongly agree" to "strongly disagree." It is divided into five dimensions, namely digital literacy, digital atmosphere, self-efficacy for digital technology, digital learning, and learning outcomes. In the process of adapting and designing the scales, we meticulously translated each item into Chinese and subsequently back-translated them into English. This procedure was instrumental in verifying the precision and consistency of the items across both linguistic and cultural spectrums. Beyond this, we were particularly attentive to ensuring the contextual relevance of the items to the Chinese educational landscape. To achieve this, we carefully revised the wording to align with local educational nuances and consulted with Chinese - system - savvy educators. Their insights ensured the adapted scales were linguistically accurate, contextually appropriate, and culturally resonant, thus enhancing their validity and applicability in China.

After the collection of the scale data, we carried out data analysis with the aid of tools of SPSS 21.0 and AMOS 21.0.

3.3.1 Digital literacy

Digital Literacy Scale was adapted from Yesilyurtd and Yuan, which is widely used in the education (Yesilyurt and Vezne, 2023; Yuan et al., 2024). The original scale was composed of dimensions like the tool and technology domain, information domain, and communication domain. After adaptation and revision, this study employed six items. During the development of the scale, reliability and validity tests, such as Cronbach's alpha coefficient analysis and item analysis, were conducted to ensure its reliability and stability.

3.3.2 Digital atmosphere

Digital atmosphere scale was adapted from Krupat et al. (2017). The original scale, which consisted of 8 items, was streamlined to 5 items after modification. The scale utilizes a Likert - type five - point scoring method, with responses ranging from "1 = Completely Disagree" to "5 = Completely Agree." The questionnaire centers on the digital atmosphere as a mediating variable and explores its mechanism of action on the learning outcomes of college students.

3.3.3 Self-efficacy for digital technology

Self-efficacy for digital technology was adapted from Demei et al. (2013). The original scale evaluated this construct, while the modified version includes 5 items on a 5 - point Likert scale ranging from "1 = Completely Disagree" to "5 = Completely Agree." This questionnaire primarily assesses students' confidence and expectations when using digital technology to solve problems.

3.3.4 Digital learning

To assess students' digital learning engagement, researchers employed the online learning Technology Acceptance Scale, originated from Technology Acceptance Model (Davis, 1986). This scale has four dimensions: Perceived Usefulness, Perceived Ease of Use, Attitude Toward Service, and Intention to Continue Use. It uses a 5 - point Likert - type scale, with responses ranging from "1 = Completely Disagree" to "5 = Completely Agree."

3.3.5 Learning outcomes

The dependent variable in this study is learning outcomes. In line with the transition to a digital - learning environment, we have designed a learning - outcomes questionnaire for undergraduates, based on the work of Snell and Lau (2019). For this study, a modified version with 3 items was used. All items were scored using a five - point Likert scale, ranging from "1 = Completely Disagree" to "5 = Completely Agree."

3.4 Data analysis

The data analysis procedure comprised seven sequential steps to ensure methodological rigor. First, we conducted a common method bias assessment using Harman's single-factor test to examine potential homogeneity bias in self-reported measures. Second, reliability analysis was performed through Cronbach's alpha coefficient calculation for all multi-item scales to evaluate internal consistency. Third, competing measurement models were compared using confirmatory factor analysis (CFA) with maximum likelihood estimation to identify the optimal factorial structure. Subsequently, we evaluated the measurement model fit through multiple indices (χ^2/df, CFI, TLI, and RMSEA) and assessed construct validity by examining both convergent validity. Fifth, descriptive statistics (means and standard deviations) were computed for all study variables, followed by bivariate correlation analysis using Pearson's coefficients to establish preliminary relationships among constructs.

Finally, mediation analyses were conducted through bias-corrected bootstrapping procedures (5,000 resamples) to examine indirect effects between key dimensions, controlling for relevant covariates. All analyses were performed using SPSS 21.0 and AMOS 21.0 with statistical significance set at $\alpha = 0.05$.

4 Research results

4.1 Validity and reliability

In the assessment of the measurement model, the fit between observed and latent variables and sample data was analyzed. The measurement model was tested using confirmatory factor analysis

(CFA) to check the validity and reliability of the items explaining the endogenous variables. The goodness of fit of the model was evaluated against several criteria, including X^2/df, CFI, TLI, RMSEA, and SRMR. A measurement model is considered to have an acceptable fit if $X^2/df < 5$, CFI > 0.90, TLI > 0.90, RMSEA < 0.08, and SRMR < 0.08. Based on these criteria, the measurement model of the present study received an acceptable fit ($X^2/df = 3.177$, CFI = 0.929, TLI = 0.920, RMSEA = 0.064, SRMR = 0.037). These results indicate that the measurement model adequately represents the data, with the X^2/df ratio well below 5, CFI and TLI values exceeding 0.90, and RMSEA and SRMR values below the recommended thresholds, suggesting a reasonable approximation of the data by the model.

Moreover, the study also calculated average variance extracted (AVE) and composite reliability (CR) for convergent validity and reliability of all constructs. The recommended limits for AVE and CR are 0.5 (Fornell and Larcker, 1981) and 0.7 (Nunnally and Bernstein, 1994) respectively. The AVE values for all constructs exceeded 0.5, and CR values surpassed 0.7, as shown in Table 2. These results confirm that the majority of variance in the items can be attributed to the underlying constructs, and that the measures are reliable. For instance, the AVE for digital literacy was 0.588, indicating that 58.8% of the variance in the items is explained by the digital literacy construct.

Reliability analysis was performed using Cronbach Alpha and composite reliability (CR) coefficients. Cronbach Alpha and composite reliability coefficients indicate the reliability of the measures, since both should be over 0.70 (Hair et al., 2022). The scales measuring the three variables are found out to be valid and reliable.

Furthermore, the items with weak factor loadings were deleted to improve the AVE and overall fit of the model. A discriminant validity analysis was also conducted, and all values suggested acceptable discriminant validity. The results of the discriminant validity analysis, presented in Table 3, indicate that each construct is empirically distinct from the other constructs in the model. For example, the square root of the AVE for digital literacy (0.767) is greater than its correlations with all other constructs, confirming that digital literacy is distinct from digital atmosphere, self-efficacy for digital technology, digital learning, and learning outcomes.

The AVE and CR values are provided in Table 2, and values obtained as a result of discriminant validity analysis are provided in Table 3. These results collectively demonstrate that the measurement model exhibits sufficient validity and reliability, providing a robust foundation for the subsequent structural equation modeling analysis.

4.2 Pearson correlation analysis

In this study, Pearson correlation analysis was conducted using SPSS 21.0 and AMOS 21.0 to examine the relationships among multiple variables: digital literacy (DL), digital atmosphere (DA), self-efficacy for digital technology (SEDT), digital learning (DL'), and learning outcomes (LO). All scales used were 5-point Likert-type scales. As shown in Table 4, the mean values of these five variables were all above the scale midpoint.

The Pearson correlation analysis revealed significant positive correlations between digital literacy, self-efficacy for digital technology, digital atmosphere, digital learning, and learning outcomes, as indicated in Table 4.

TABLE 2 Convergent validity and reliability analysis.

Constructs	Item	Standardized factor loadings	AVE	CR	α
Digital literacy	Q4	0.742	0.588	0.895	0.894
	Q5	0.810			
	Q6	0.760			
	Q7	0.781			
	Q8	0.782			
	Q9	0.723			
Digital atmosphere	Q10	0.571	0.508	0.836	0.832
	Q11	0.706			
	Q12	0.750			
	Q13	0.701			
	Q14	0.812			
Self-efficacy for digital technology	Q15	0.781	0.621	0.891	0.891
	Q16	0.798			
	Q17	0.814			
	Q18	0.814			
	Q19	0.731			
Digital learning	Q20	0.755	0.525	0.885	0.882
	Q21	0.716			
	Q22	0.626			
	Q23	0.774			
	Q24	0.716			
	Q25	0.779			
	Q26	0.692			
Learning outcomes	Q27	0.710	0.625	0.832	0.829
	Q28	0.793			
	Q29	0.861			

CR, composite reliability; AVE, average variance extract; α, Cronbach alpha.

TABLE 3 Confirmatory factor analysis.

X^2/df	RMSEA	SRMR	GFI	AGFI	CFI	IFI	TLI
3.177	0.064	0.037	0.872	0.845	0.929	0.929	0.920

4.3 Hypothesis testing

All five hypothesized direct relationships in the structural model received empirical support. Specifically, digital literacy exhibited a significant and positive influence on the development of a digital atmosphere ($\beta = 0.589$, $p < 0.001$) and students' self-efficacy for digital technology ($\beta = 0.826$, $p < 0.001$). Additionally, a well-developed digital atmosphere positively impacted digital learning ($\beta = 0.830$, $p < 0.001$), and higher self-efficacy for digital technology significantly enhanced digital learning ($\beta = 0.317$, $p < 0.001$). Digital learning was strongly associated with positive learning outcomes ($\beta = 0.833$, $p < 0.001$). The β coefficients and corresponding bootstrap confidence intervals are presented in Table 5. The structural model with hypothesis testing results is shown in Figure 2.

Moderation analysis was performed using the Bootstrap method at 95% confidence level. 10,000 different indirect effects are calculated

TABLE 4 Pearson correlation analysis among the variables.

Variables	*M*	SD	DL	DA	SEDT	DL'	LO
DL	3.736	0.727	0.767				
DA	3.770	0.699	0.657**	0.713			
SEDT	3.552	0.799	0.683**	0.674**	0.788		
DL'	3.769	0.663	0.691**	0. 781**	0.753**	0.725	
LO	3.822	0.726	0.581**	0.690**	0.581**	0.784**	0.791

Diagonals are the square roots of AVEs, while off-diagonals are correlations. ** Indicates $p < 0.01$.

by selecting 10,000 different samples from the sample in the Bootstrap method. These effects are used to determine the lower and upper limits of the 95% confidence interval (CI). As long as there is no zero (0) value between the lower (LLCI) and upper (ULCI) values, the relationships in the model are significant (Hayes, 2017).

The analysis of indirect pathways confirmed some of the proposed hypotheses (Table 6). Digital literacy exhibited a positive impact on learning outcomes through digital atmosphere and digital learning ($\beta = 0.407$), lending support to Hypothesis 6. Additionally, digital literacy positively influenced learning outcomes via the self-efficacy in digital technology and its subsequent effect on digital learning ($\beta = 0.218$), thereby supporting Hypothesis 7.

5 Conclusion and discussion

This study primarily explores the impact relationship between college students' digital literacy and learning outcomes. Analysis shows that there are some mediating effects between the two variables. Subsequent chain mediation models also confirm this relationship. Based on the data analysis from this study, it appears that our seven hypotheses can be supported.

Firstly, digital literacy, digital atmosphere, self-efficacy for digital technology, and digital learning form a tightly interconnected mediational pathway. Digital literacy encompasses the essential skills required for effective learning and communication in the digital era (Getenet et al., 2024). Individuals with higher digital literacy are more adept at utilizing digital technologies across various processes, including information retrieval, processing, analysis, and innovative application. This proficiency equips individuals with the foundational capabilities necessary to adapt to digital atmosphere and effectively utilize digital resources.

Secondly, a positive digital atmosphere is crucial for stimulating college students' engagement in digital learning and thereby improving learning outcomes. A positive digital learning atmosphere can spark college students' interest and intrinsic motivation, encouraging more active participation in digital learning activities. The creation of such an atmosphere includes an open communication atmosphere, rich digital resources, and supportive technological tools. In this learning atmosphere, college students are more likely to develop a positive perception of digital learning, which includes a clear understanding of learning objectives, active engagement in the learning process, and positive expectations for learning outcomes. The enhancement of cognitive levels helps college students use digital resources more effectively, thereby improving learning efficiency. The strengthening of digital learning directly contributes to the improvement of learning outcomes. When college students have clear goals, actively participate, and effectively utilize resources, they are better able to master knowledge, skills, and abilities, which can lead to enhanced academic achievement (Algouzi and Hazaea, 2023). One of the key findings of this study is that educators and institutions should prioritize the creation of a digital atmosphere when building digital learning atmospheres. By providing supportive technological tools, rich learning resources, and open communication platforms, digital learning can be effectively enhanced, leading to improved learning outcomes. The digital atmosphere is an important factor affecting digital learning and learning outcomes. Optimizing the digital atmosphere can enhance college students' engagement and effectiveness, providing useful insights for educational practice (Al-khresheh and Alkursheh, 2024).

Thirdly, in today's digital era, the developmental path of "digital literacy - self-efficacy for digital technology - digital learning - learning outcomes" holds profound significance for education and learning. Starting with digital literacy, it encompasses the abilities to acquire, understand, evaluate, and use digital information. Individuals with high digital literacy can more freely explore the digital world. As digital literacy improves, digital technical skills also increase. Digital technical skills refer to an individual's self-confidence in using digital technology to complete learning tasks. College students with high self-efficacy for digital technology believe they have the ability to use digital tools to solve learning problems, and this positive self-perception becomes the internal driving force for further action (Mishra and Koehler, 2006). Self-efficacy for digital technology further gives rise to digital learning. When college students are confident in their ability to master digital technology, they actively seek digital learning resources and are more willing to participate in online courses, use learning software, etc. The active participation and positive exploration in the learning process serve as a crucial factor in modern education. The behavior of digital learning directly affects learning achievement. College students with high digital literacy can enhance their digital learning by boosting their self-efficacy for digital technology, which in turn improves their learning outcomes.

The study reveals digital literacy influences digital learning by affecting the digital atmosphere and self-efficacy for digital technology, which then influence learning outcomes. Key approaches to improving college students' digital learning and outcomes include enhancing digital literacy, optimizing the digital atmosphere, and strengthening self - efficacy for digital technology. Their interaction helps students engage more effectively in digital learning and achieve better outcomes (Pagani et al., 2016).

6 Implications for practice

Firstly, to promote the enhancement of digital literacy, it is necessary for educational institutions to conduct digital literacy educational

TABLE 5 Results of direct paths in the structural model.

Hypotheses	Relationships	Path coefficients (*β*)	*t*-value	*p*	Results
H1	DL → DA	0.589	11.457	***	Support
H2	DA → DL'	0.830	10.819	***	Support
H3	DL → SEDT	0.826	14.922	***	Support
H4	SEDT→DL'	0.317	8.616	***	Support
H5	DL' → LO	0.833	15.252	***	Support

*** indicates $p < 0.001$. DL indicates digital literacy; DA indicates digital atmosphere; DL' indicates digital learning; SEDT indicates self-efficacy for digital technology; LO indicates learning outcomes.

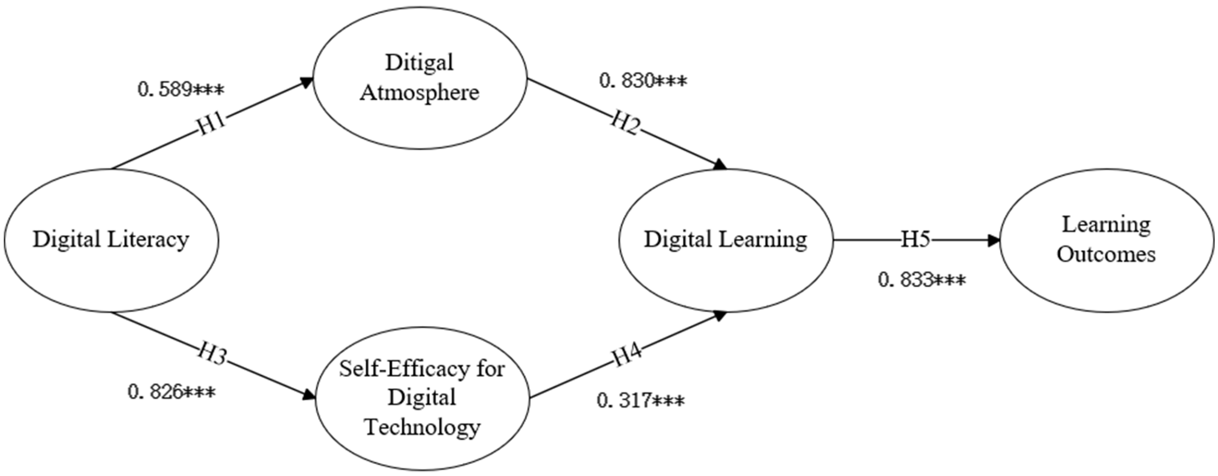

FIGURE 2
Structural model with hypothesis testing results. Model fit: X^2/df = 3.397, RMSEA = 0.067, SRMR = 0.046, GFI = 0.863, AGFI = 0.837, CFI = 0.921, IFI = 0.921, TLI = 0.912.

TABLE 6 Results of indirect paths in the structural model.

Hypotheses	Relationships	Effect	LLCI	ULCI	Results
H6	DL → DA → DL' → LO	0.407***	0.317	0.508	Support
H7	DL → SEDT→DL' → LO	0.218***	0.154	0.300	Support

*** Indicates $p < 0.001$. DL indicates digital literacy; DA indicates digital atmosphere; DL' indicates digital learning; SEDT indicates self-efficacy for digital technology; LO indicates learning outcomes.

activities. Universities should provide key digital literacy courses like "Basic Information Technology Skills," "Network Security Fundamentals," and "Digital Privacy Protection Strategies." Guiding students to use advanced digital tools like Tableau Public can greatly enhance learning efficiency. Jahnke and Liebscher (2020) showed that students proficient in such digital technologies completed assignments significantly faster without sacrificing quality. They should also organize digital literacy competitions and exhibitions to stimulate students' interest and participation in digital learning. Encouraging students to engage in self-directed learning and practice, schools should provide abundant digital learning resources and actively involve students in digital projects and practices, such as programming, web design, animation production, etc., to improve digital literacy and innovation capabilities. At the same time, strengthening digital communication between teachers and students is important. Establishing a digital communication platform for teachers and students facilitates communication and interaction, and further enhances students' learning experience through teachers' use of digital tools for after-class tutoring and answering questions. It is also necessary to educate students on how to correctly screen and evaluate online information to avoid information overload and misinformation. Correctly guiding students to learn how to use digital tools for information retrieval and analysis improves learning efficiency and quality.

Secondly, it is particularly important to emphasize the cultivation of students' digital learning, rather than just enhancing their digital literacy. Universities should deeply integrate digital technology into daily teaching practices, making it an indispensable part of the learning process rather than just an auxiliary tool. For example, specialized courses can be established with specific curricula such as "Digital Learning Strategies" and "Advanced Information Retrieval Techniques" to systematically cultivate students' digital learning and information retrieval abilities, with clearly defined learning objectives and assessment standards. While also strengthening their basic digital operation skills. General education in digital literacy can also be explored, looking into educational models that combine digital literacy with professional courses. Teachers should encourage students to use digital tools in the classroom and provide guidance to help them use these tools effectively to promote learning. In addition, a systematic assessment mechanism should be established to quantify students' progress in digital learning and skills, such as developing a detailed assessment rubric that includes indicators like frequency of digital tool usage, accuracy of information retrieval, and quality of digital content creation, with regular intervals for assessment. This can motivate students to continue improving and allow teachers to use data analysis tools to monitor students' learning progress and engagement, hence adjusting teaching methods and strategies according to individual student needs. In summary, digital learning is the key link connecting digital literacy with learning outcomes. By cultivating and strengthening this awareness, the potential of digital technology in the field of education can be maximized, thereby enhancing overall learning effectiveness (Shu-Sheng et al., 2007).

Thirdly, study findings indicate that enhancing the sense of self-efficacy for digital technology and strengthening the digital learning atmosphere are key factors in promoting digital learning and improving learning outcomes (Rodafinos et al., 2024). Universities should integrate digital technology education into the curriculum, offering training and practical opportunities in cutting-edge technologies to improve students' proficiency and confidence in using digital tools. Meanwhile, universities need to invest in advanced digital teaching facilities, such as high-speed networks, smart classrooms, and online learning platforms, with specific infrastructure development plans like upgrading campus Wi-Fi to ensure coverage in all teaching buildings and dormitories to optimize the digital learning atmosphere and ensure all students have equal access to these resources. Game-based elements and interactive digital activities can create a more engaging and motivating digital atmosphere (Lo and Chan, 2024), which in turn can support the development of self-efficacy for digital technology and encourage more active participation in digital learning. In addition, the structure and design of the learning experience play a direct role in supporting students' emotional regulation, which in turn enhances their self-efficacy as learners. When students experience positive emotional engagement and regulation within these modern classroom settings, their participation and overall performance improve, leading to better learning outcomes and greater competency (Lo, 2023). Universities should build online learning communities with clear functional modules like discussion forums categorized by disciplines and project collaboration tools with version control features, to encourage students to share learning resources, discuss problems, and collaborate on projects, thus enhancing their sense of engagement and belonging, and promoting knowledge sharing and collaborative learning. By implementing these measures, higher education institutions can not only create a supportive and motivating digital learning atmosphere for college students but also, by enhancing their self-efficacy for digital technology, foster their academic achievements and personal development, thus overall improving digital learning and learning outcomes(Qian et al., 2025).

6.1 Limitations

Although this study provides valuable insights for college students and universities in the digital age, it also has several limitations that should be addressed in future research. One limitation is the potential for social desirability bias inherent in survey-based research. Respondents may be influenced by social expectations and choose answers that align with social norms or mainstream opinions rather than reflecting their true thoughts (Rosenthal, 2002). To enhance the representativeness of the sample, future studies could employ a variety of data collection methods to triangulate the results.

Additionally, this study focuses on the impact of digital atmosphere and self-efficacy for digital technology on digital learning and learning outcomes, based on social cognitive theory. However, in the context of digital education, there are likely other influencing factors at play. Future research should explore these additional factors to gain a more comprehensive understanding of the landscape. Conceptually, despite maintained statistical boundaries, the proximity between digital literacy and self-efficacy for digital technology remains a focus for refinement in future iterations. The concept of "digital atmosphere" is relatively new, and there is no consensus on its definition in the academic community. There is potential for further research on this topic in the future.

The generalizability of the results may be limited to the digital infrastructure and educational ecosystem within Chinese higher education. To extend the applicability of these findings, further cross - cultural validation is necessary.

Lastly, the primary subjects of this study are college students, who are primarily in the role of "learners" in the educational process. However, education is a two-way street, and teachers and universities also play crucial roles. To mitigate the limitations of self-report bias and sample homogeneity, future investigations may utilize longitudinal or experimental designs to substantiate causal relationships. Integrating teachers' insights would enhance student-centered approaches and offer a more comprehensive perspective on the digital learning environment. Moreover, examining domain-specific impacts (e.g., STEM versus humanities) or cultural factors influencing digital self-efficacy could significantly enrich the depth of our comprehension in this field.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

Ethical approval was not required for the studies involving humans. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

Author contributions

NY: Writing – original draft, Writing – review & editing. QY: Software, Writing – review & editing. WL: Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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