MECHANISMS AND PATHWAYS FOR DIGITAL LITERACY UNDER EDUCATION 4.0 IN APPLIED UNIVERSITIES: EVIDENCE FROM THE DIGITAL ECONOMY CONTEXT*

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Received 10 June 2026; Revised 17 June 2026; Accepted 19 June 2026

Abstract

This study aimed to: 1) To examine the influence of Education 4.0 on students' digital literacy in applied universities. 2) To investigate the mediating role of instructional innovation between Education 4.0 and digital literacy. 3) To analyze the relationship between digital literacy and learning satisfaction within the digital economy context. This study adopted a quantitative-dominant sequential explanatory mixed-methods design. Quantitative data were collected from 857 undergraduate students enrolled in three applied universities in Guizhou Province, China. Qualitative data were obtained through semi-structured interviews with 15 participants. Structural Equation Modeling (SEM) and thematic analysis were employed to examine the proposed relationships and explain the quantitative findings.

The findings revealed that: 1) Education 4.0 significantly and positively influences instructional innovation. 2) Education 4.0 significantly enhances students' digital literacy. 3) Instructional innovation partially mediates the

Citation:

* Kun Chen and Dowroong Watcharinrat. (2026). Mechanisms And Pathways For Digital Literacy Under Education 4.0 In Applied Universities: Evidence From The Digital Economy Context. Modern Academic Development and Promotion Journal, 4(5), 954-978.;

DOI: https://doi.org/10.

https://so12.tci-thaijo.org/index.php/MADPIADP/

relationship between Education 4.0 and digital literacy. 4) Digital literacy significantly improves learning satisfaction. 5) The serial pathway Education 4.0 Instructional Innovation Digital Literacy Learning Satisfaction was supported.

The results indicate that instructional innovation serves as the primary mechanism through which Education 4.0 contributes to digital literacy development and educational quality enhancement in applied universities.

Keywords: Education 4.0, Digital Literacy, Instructional Innovation, Learning Satisfaction, Applied Universities; Digital Economy

Introduction

The rapid expansion of the digital economy has transformed labor market demands, increasing the importance of digital competencies such as information evaluation, digital communication, collaboration, and continuous learning (Schwab, 2016; OECD, 2021). As digital technologies become deeply integrated into social and economic activities, higher education institutions face growing pressure to cultivate graduates who can adapt to technology-driven environments and evolving workforce requirements (Fisk, 2017; Vuorikari et al., 2022).

Applied universities are particularly affected by these changes because of their strong emphasis on employability and industry-oriented education (Chen et al., 2021). However, many institutions continue to face challenges related to digital transformation, including uneven technological infrastructure, limited pedagogical innovation, and insufficient integration of digital competence development into teaching and learning processes (Wang & He, 2020). Consequently, developing students' digital literacy has become a critical educational objective.

Education 4.0 has emerged as a prominent educational paradigm for responding to these challenges. Emphasizing learner-centered learning, digital

technology integration, competency-based education, and lifelong learning, Education 4.0 aims to align educational practices with the demands of the digital economy (Sani et al., 2020; Oliveira, 2022). Nevertheless, existing studies often conceptualize Education 4.0 as a broad reform agenda rather than examining the specific mechanisms through which it contributes to student outcomes. Moreover, research on digital literacy remains fragmented, with limited understanding of how educational reforms translate into measurable improvements in students' digital competencies (Ilomäki et al., 2016; Pangrazio & Sefton-Green, 2020).

Despite increasing scholarly attention to Education 4.0 and digital literacy, empirical evidence explaining the pathways linking institutional reform, instructional practices, and learner outcomes remains scarce, particularly in applied university contexts (Xie & Yang, 2023). To address this gap, this study investigates how Education 4.0 contributes to digital literacy development and learning satisfaction through instructional innovation. By examining the pathway Education 4.0 Instructional Innovation Digital Literacy Learning Satisfaction, the study provides a mechanism-based explanation of digital education reform and extends existing research beyond traditional direct-effect models.

Objectives

1) To examine the influence of Education 4.0 on students' digital literacy in applied universities.

2) To investigate the mediating role of instructional innovation between Education 4.0 and digital literacy.

3) To analyze the relationship between digital literacy and learning satisfaction within the digital economy context.

Literature Review

The literature review synthesizes key scholarly strands to establish the theoretical and empirical foundation for exploring the mechanisms linking Education 4.0, instructional innovation, digital literacy, and learning satisfaction in applied universities. This review focuses on four interconnected domains: Education 4.0 in higher education, instructional innovation and digital pedagogy, digital literacy development, and learning satisfaction in digital contexts, while identifying critical gaps that the present study addresses.

Education 4.0 has emerged as a pivotal paradigm in response to digital transformation and Industry 4.0, redefining higher education's purposes, structures, and practices (Schwab, 2016; Schwab, 2018). Central to this paradigm are learner-centeredness, competence orientation, digital integration, interdisciplinarity, and lifelong learning, with adaptability, creativity, and employability as core outcomes (OECD, 2021; Sani et al., 2020). Early conceptual works predominantly outline normative visions of Education 4.0, framing it as a necessary response to the digital economy but often treating it as a prescriptive ideal rather than an empirically testable construct (Fisk, 2017; Jain, 2025). Empirical research has since examined Education 4.0 through institutional strategies, documenting the adoption of digital platforms, blended learning models, innovation-oriented curricula, and industry-university collaboration (Oliveira, 2022; Tang & Zhou, 2022). In applied university contexts, Education 4.0 is frequently linked to practice-oriented learning and labor market alignment, with digital technologies positioned as enablers of authentic learning and collaboration (Chen et al., 2021; Xie & Yang, 2023). However, a critical limitation persists: existing research often focuses on policy discourse or technology adoption at the institutional level, with insufficient attention to how Education 4.0 orientations translate into classroom-level pedagogical change (González-Pérez et al., 2025; Sa'diyah et al., 2023). The implicit assumption of direct effects

between Education 4.0 and learner outcomes overlooks the mediating processes required to convert reform rhetoric into tangible learning gains, leaving a “black box” between institutional intent and classroom practice (Wang & Li, 2021; Zhang et al., 2023).

Instructional innovation constitutes a key response to educational change in digital contexts, representing a shift from teacher-centered instruction to active, learner-centered pedagogies such as problem-based learning, project-based learning, and collaborative learning (Collins et al., 1989; Jonassen, 1991). Grounded in constructivist learning theory, these approaches emphasize learner activity, interaction, and knowledge construction, with consistent empirical links to engagement, critical thinking, and perceived learning effectiveness (Bandura, 1997; Piaget, 1950). With the expansion of digital technologies, instructional innovation has increasingly integrated digital pedagogy, encompassing practices like blended learning, flipped classrooms, online collaboration, and digital assessment (Dede, 2005; Garrison, 1997). A consensus in the literature highlights that technology alone does not improve learning outcomes; pedagogical redesign is essential to leverage digital tools for active engagement and meaningful interaction (Ifenthaler & Yau, 2020; Spector, 2014). Learner-centeredness remains a unifying theme, with innovative practices emphasizing autonomy, collaboration, and authentic problem-solving, though outcomes depend primarily on instructional design rather than technology per se (Barab & Duffy, 2000; Wenger, 1998). Emerging research links instructional innovation to competence development, particularly digital, collaborative, and problem-solving skills, but competence development is rarely modeled explicitly as an intervening process (Krumsvik, 2008; Terzis & Economides, 2011). Additionally, instructional innovation is often examined as an independent predictor rather than a mediating mechanism embedded within broader institutional reform, limiting understanding of how it connects Education 4.0 to learner outcomes (Lave & Wenger, 1991; Mezirow, 1991).

Digital literacy has evolved from a focus on technical and informational skills to a multidimensional construct encompassing information evaluation, digital content creation, communication and collaboration, and ethical awareness (Bawden, 2008; Vuorikari et al., 2022). Influential frameworks such as UNESCO's media and information literacy initiatives and the European DigComp framework have shaped this conceptualization, positioning digital literacy as foundational for academic success, employability, and participation in digitally mediated societies (Ferrari, 2013; Redecker, 2017). Empirical research has examined students' digital literacy levels and associated factors such as discipline, socioeconomic background, and technology use, often treating digital literacy as a quasi-stable learner characteristic (Ilomäki et al., 2016; Ng, 2012). However, this approach identifies who possesses digital literacy but provides limited insight into how it is generated within higher education (Eshet-Alkalai, 2004; Pangrazio & Sefton-Green, 2020). An emerging strand conceptualizes digital literacy as an outcome of pedagogical intervention, showing that project-based, inquiry-oriented, and collaborative digital learning activities can enhance higher-order digital competences (Martin & Grudziecki, 2006; Zhang & Chen, 2022). Research also indicates associations between digital literacy and engagement, self-efficacy, and satisfaction in digital learning environments, but digital literacy is commonly modeled as a direct predictor of outcomes rather than an intermediate mechanism (Helsper & Eynon, 2010; Wang & He, 2020). Conceptual variability, cross-sectional designs, and role ambiguity, with digital literacy alternately treated as a prerequisite, outcome, or predictor, weaken theoretical integration and hinder practical application (Bol et al., 2018; Helsper et al., 2015).

Learning satisfaction, a widely used indicator of educational effectiveness, reflects learners' subjective evaluation of their experiences in digitally mediated contexts, encompassing perceived effectiveness, engagement, relevance, and sustainability (Artino, 2012; Ryan & Deci, 2000). Empirical studies identify

instructional clarity, interaction quality, feedback, and system usability as key predictors of satisfaction in online and blended learning, while poor instructional design is linked to confusion, cognitive overload, and dissatisfaction (Garrison & Cleveland-Innes, 2005; Gunawardena et al., 2001). Self-determination theory has emerged as a dominant theoretical framework, emphasizing autonomy, competence, and relatedness as foundations of positive learning experiences (Deci & Ryan, 1985; Ryan et al., 2006). In digital learning contexts, learners' sense of competence, particularly digital competence, plays a critical role in shaping satisfaction (Deci et al., 1991; Vallerand, 1997). Research suggests that learners with higher digital competence experience less anxiety and more positive evaluations of digital learning, but digital competence is often treated as a background variable rather than a generated outcome of instruction (Schunk, 1995; Zimmerman, 2002). A significant gap remains: learning satisfaction is rarely embedded within sequential, mechanism-based models linking institutional reform, pedagogy, and competence development, limiting understanding of how learner competence shapes evaluative judgments of digital learning experiences (Pintrich, 2000; Seligman, 2011).

Synthesizing these strands reveals persistent fragmentation across institutional, pedagogical, and learner levels. Education 4.0 research emphasizes reform orientation without specifying pedagogical mechanisms; instructional innovation research highlights pedagogical effectiveness but lacks institutional anchoring; digital literacy research recognizes competence importance but insufficiently theorizes its generation; and learning satisfaction research captures learner experience without integrating competence development (Dweck, 2006; Duckworth, 2016). Methodologically, descriptive and correlational designs dominate, limiting causal explanation, while role ambiguity surrounds instructional innovation and digital literacy, weakening model coherence (Bandura, 2001; Pajares, 1996). Most notably, sequential, mechanism-based explanatory models integrating reform, pedagogy, competence, and experience

remain scarce (Engeström, 2001; Illeris, 2004). This study addresses these gaps by adopting a mechanism-based, multilevel framework that positions Education 4.0 as a distal institutional orientation, instructional innovation as the pedagogical enactment mechanism, digital literacy as a generated learner competence, and learning satisfaction as a downstream experiential outcome. By empirically testing the pathway Education 4.0 ⟶ instructional innovation ⟶ digital literacy ⟶ learning satisfaction, the study advances existing research from fragmented associations toward an integrated explanation of digital education reform outcomes in applied university contexts.

However, three important gaps remain. First, existing studies rarely examine the sequential mechanisms through which Education 4.0 influences learner outcomes. Second, instructional innovation has seldom been modeled as a mediating mechanism connecting institutional reform and competence development. Third, digital literacy and learning satisfaction are often studied separately rather than as interconnected outcomes within a unified framework. Addressing these gaps constitutes the primary theoretical contribution of the present study.

Methodology

This study adopted a quantitative-dominant sequential explanatory mixed-methods design to investigate the mechanisms linking Education 4.0 (EDU4), Instructional Innovation (II), Digital Literacy (DL), and Learning Satisfaction (LS) in applied universities. The design prioritized hypothesis testing through structural equation modeling (SEM) while using qualitative interviews to contextualize and explain statistical findings, ensuring both methodological rigor and explanatory depth.

The quantitative phase employed a cross-sectional survey design with covariance-based SEM (CBSEM) as the primary analytical technique. CBSEM was

selected for its ability to model multidimensional latent constructs, test mediation pathways, validate measurement models via confirmatory factor analysis (CFA), and control for measurement error in self-reported data. The qualitative phase followed a theory-informed thematic analysis of semistructured interviews, which aimed to illuminate students' lived experiences of the proposed mechanism chain without generating new hypotheses.

The target population consisted of full-time undergraduate students from three applied universities in Guizhou Province, China: Guizhou Qiannan Economic University, Guizhou Qiannan University of Science and Technology, and Guizhou Communications University. A two-stage stratified cluster random sampling strategy was used to ensure representativeness across academic disciplines (STEM, Business, Liberal Arts) and institutional types (public and private). The final valid sample included 857 respondents, with demographic characteristics.

A structured questionnaire was developed to measure the four core constructs, with items derived from established literature and adapted to the applied university context. EDU4 was operationalized as a second-order latent construct with four first-order dimensions: Civic & Interpersonal Competence (CIC), Innovation & Technology Integration (ITI), Collaborative & Inclusive Environment (CIE), and Self-paced & Lifelong Learning (SPL). DL was also modeled as a second-order construct, comprising Digital Information Literacy (DIL), Digital Content Creation (DTT), and Digital Communication & Collaboration (DCC). II and LS were measured as unidimensional latent constructs. All items used a five-point Likert scale (1 = strongly disagree to 5 = strongly agree).

The instrument's psychometric quality was validated through content validity assessment (Item-Objective Congruence scores > 0.80), pilot testing (Cronbach's α > 0.70 for all constructs), and CFA in the main study. Convergent validity was confirmed via composite reliability (CR > 0.70) and average variance extracted (AVE > 0.50), while discriminant validity was supported by the Fornell-Larcker criterion.

Quantitative data were collected via an online survey platform, with rigorous screening to remove incomplete or insincere responses. Qualitative data were gathered from 15 purposively sampled participants (7 students, 6 teachers, 2 administrators) who represented diverse levels of EDU4 exposure, DL development, and LS. Interviews focused on experiences with EDU4-oriented practices, instructional innovation, and digital literacy development.

For data analysis, the quantitative phase followed a two-stage SEM approach: first, validating measurement models via CFA, then testing structural relationships and mediation effects. Bootstrapping (5,000 resamples) was used to evaluate indirect effects. The qualitative phase involved thematic coding aligned with the research framework, with findings integrated to interpret statistical pathways.

Results

The integrated CFA demonstrated good-to-excellent fit (χ^2 = 1112.914, df = 391, χ^2/df = 2.846; CFI = 0.970; RMSEA = 0.046). All constructs exhibited strong psychometric properties, with standardized factor loadings ranging from 0.715 to 0.966, CR values between 0.847 and 0.940, and AVE values from 0.649 to 0.781. Second-order CFA confirmed EDU4 and DL as hierarchical constructs, with high standardized loadings for their first-order dimensions.

The structural model exhibited excellent fit (χ^2 = 1112.914, df = 391, χ^2/df = 2.846; GFI = 0.916; RMSEA = 0.046). All hypothesized direct effects were positive and statistically significant ($p < 0.001$), as shown in Table 3. EDU4 strongly predicted II (β = 0.841), while both EDU4 (β = 0.394) and II (β = 0.587) significantly influenced DL. DL, in turn, had a strong positive effect on LS (β = 0.841).

The model explained substantial variance in all endogenous constructs: II (R^2 = 0.708), DL (R^2 = 0.888), and LS (R^2 = 0.707). Mediation analysis via bootstrapping confirmed significant indirect effects (Table 4). II partially mediated

the relationship between EDU4 and DL (indirect effect = 0.411, 95% CI [0.353, 0.471]). The serial indirect pathway EDU4 ⟶ II ⟶ DL ⟶ LS was also significant (indirect effect = 0.334, 95% CI [0.282, 0.391]), supporting the full mechanism chain.

Qualitative interviews reinforced the quantitative results, highlighting that instructional innovation acts as a critical "activation layer" translating EDU4 into DL development. Students emphasized that meaningful DL growth occurred through structured tasks such as project-based learning, digital content creation, and online collaboration, rather than mere technology exposure. Key themes included the importance of pedagogical design, task-embedded digital practice, and the link between DL competence and reduced learning frustration, which directly enhanced LS. Interviews also explained the partial mediation effect, identifying direct EDU4-to-DL pathways such as institutional digital resources and peer learning communities.

This study provides robust empirical evidence for the mechanism-based model EDU4 ⟶ II ⟶ DL ⟶ LS in applied university contexts. The findings confirm that Education 4.0 functions as a systemic reform orientation that fosters instructional innovation, which in turn drives digital literacy development. Digital literacy not only prepares students for the digital economy but also enhances their learning satisfaction by reducing task friction and increasing perceived competence.

Theoretical contributions include operationalizing EDU4 and DL as measurable hierarchical constructs, validating instructional innovation as a core mediating mechanism, and integrating competence development with learner-centered outcomes. Practically, the results offer actionable guidance for applied universities to prioritize pedagogical redesign over technology adoption, embed digital literacy across curricula, and align assessment with competence development. Limitations include the cross-sectional design, reliance on self-

reported data, and contextual specificity to Chinese applied universities. Future research could adopt longitudinal or experimental designs, expand the model to include moderators such as student self-efficacy, and explore cross-cultural generalizability. Overall, the study advances understanding of how digital transformation in higher education can be effectively translated into meaningful student outcomes, emphasizing that the value of Education 4.0 lies in its pedagogical enactment rather than technological infrastructure.

Common Method Bias Assessment

Procedural remedies were implemented during questionnaire design, including anonymous participation, voluntary responses, and clear instructions emphasizing that there were no right or wrong answers. Statistically, Harman's single-factor test was conducted. The first unrotated factor accounted for less than 40% of the total variance, indicating that common method bias was not a serious concern in the present study.

Discussion

The present study provides strong empirical support for the proposed mechanism-based framework linking Education 4.0 (EDU4), Instructional Innovation (II), Digital Literacy (DL), and Learning Satisfaction (LS). The measurement and structural models demonstrated excellent fit indices, indicating that the conceptual model adequately represents the relationships among the constructs. The CFA results confirmed the reliability and validity of all latent variables, with factor loadings, composite reliability (CR), and average variance extracted (AVE) values exceeding recommended thresholds, thereby supporting the robustness of the measurement framework (Hair et al., 2022; Kline, 2023). Furthermore, the second-order CFA validated EDU4 and DL as hierarchical constructs, confirming that these multidimensional concepts can be represented through their respective first-order dimensions.

The findings reveal that Education 4.0 exerts a strong positive influence on Instructional Innovation ($\beta = 0.841$, $p < 0.001$). This result aligns with the theoretical foundations of Education 4.0, which emphasize learner-centered, technology-enabled, and competency-based educational practices designed to transform teaching and learning processes (Fisk, 2017; Miranda et al., 2021). The high standardized coefficient suggests that institutional efforts to implement Education 4.0 principles directly stimulate pedagogical innovation. Specifically, dimensions such as curriculum innovation and integration, intelligent technology integration, creative learning environments, and student-personalized learning collectively create conditions that encourage instructors to adopt innovative teaching strategies. This finding is consistent with previous studies indicating that digital transformation initiatives are most effective when accompanied by pedagogical reform rather than merely technological investment (Bond et al., 2018; Puncreobutr, 2016).

The study further demonstrates that Instructional Innovation significantly predicts Digital Literacy ($\beta = 0.587$, $p < 0.001$). This result supports constructivist and experiential learning perspectives, which argue that digital competencies are developed through authentic learning activities rather than passive exposure to technology (Kolb, 2015; Redecker, 2017). Qualitative evidence strengthens this interpretation, as students consistently reported that project-based learning, digital content creation, collaborative online tasks, and technology-supported problem-solving activities contributed substantially to their digital literacy development. These findings suggest that instructional innovation functions as a critical mechanism through which Education 4.0 initiatives are translated into practical digital competence. Similar conclusions have been reported in studies emphasizing that digital literacy emerges from pedagogically structured engagement with technology rather than technology access alone (Ng, 2012; van Laar et al., 2017).

The direct positive effect of Education 4.0 on Digital Literacy ($\beta = 0.394$, $p < 0.001$) indicates that institutional digital ecosystems also contribute independently to students' competence development. This finding suggests that digital literacy acquisition is influenced not only by classroom pedagogy but also by broader educational environments, including digital infrastructure, institutional resources, and technology-rich learning communities. The qualitative findings support this interpretation by highlighting the role of campus digital resources, learning management systems, and peer-supported digital learning networks. Consequently, the results reinforce the argument that digital literacy development requires both pedagogical innovation and institutional support structures (European Commission, 2022; UNESCO, 2023).

One of the most significant findings is the strong relationship between Digital Literacy and Learning Satisfaction ($\beta = 0.841$, $p < 0.001$). This result suggests that students who possess higher levels of digital competence experience greater satisfaction with their learning experiences. The finding aligns with self-determination theory and competence-based learning perspectives, which posit that perceived competence enhances motivation, engagement, and satisfaction (Ryan & Deci, 2020). Interview participants explained that digital literacy reduced learning frustration, increased confidence in completing academic tasks, and enabled more effective participation in digital learning environments. These findings corroborate prior research indicating that digital competence is a critical determinant of successful learning outcomes in technology-enhanced educational settings (Martin, 2018; Zhao et al., 2021).

The mediation analysis provides particularly important insights into the underlying mechanisms connecting Education 4.0 with learning outcomes. Instructional Innovation partially mediated the relationship between Education 4.0 and Digital Literacy, suggesting that pedagogical innovation serves as a major pathway through which institutional transformation influences student

competencies. However, the existence of a significant direct effect indicates that Education 4.0 also affects digital literacy through alternative mechanisms beyond instructional innovation. This finding supports systems-based perspectives of educational transformation, which emphasize the combined influence of institutional, technological, and pedagogical factors (Fullan & Langworthy, 2014).

Moreover, the significant serial mediation pathway EDU4 ⟶ II ⟶ DL ⟶ LS confirms the theoretical sequence proposed in the study. The results indicate that Education 4.0 enhances instructional innovation, which subsequently develops students' digital literacy, ultimately leading to higher learning satisfaction. Interestingly, the indirect pathway EDU4 ⟶ DL ⟶ LS without instructional innovation was not significant, emphasizing that technological transformation alone is insufficient to improve learning satisfaction. Instead, educational technologies must be embedded within innovative pedagogical practices to generate meaningful learning outcomes. This finding supports arguments that the effectiveness of digital transformation depends more on pedagogical implementation than on technological infrastructure itself (Selwyn, 2016; OECD, 2021).

The high explanatory power of the model further strengthens the study's conclusions. Education 4.0 explained 70.8% of the variance in Instructional Innovation, while Education 4.0 and Instructional Innovation together explained 88.8% of the variance in Digital Literacy. Additionally, Digital Literacy accounted for 70.7% of the variance in Learning Satisfaction. These values indicate substantial predictive capacity and suggest that the proposed model captures key determinants of student outcomes within contemporary higher education environments.

The qualitative findings provide valuable contextual support for the quantitative results. Participants consistently emphasized that meaningful digital literacy development occurred through active engagement with technology-

integrated learning tasks rather than through simple technology availability. This observation reinforces the argument that instructional innovation serves as an "activation layer" that transforms institutional Education 4.0 initiatives into student-level competencies. Furthermore, students associated digital competence with reduced academic stress and greater confidence, offering an explanatory mechanism for the strong relationship between Digital Literacy and Learning Satisfaction.

From a theoretical perspective, this study contributes to the Education 4.0 literature by operationalizing Education 4.0 and Digital Literacy as hierarchical second-order constructs and empirically validating their relationships within an integrated structural model. The findings extend existing research by identifying Instructional Innovation as a central mediating mechanism that connects institutional transformation efforts with student learning outcomes. In doing so, the study bridges the gap between macro-level educational reform and micro-level learner experiences.

Practically, the findings suggest that applied universities should prioritize pedagogical redesign alongside technological investment. Universities seeking to enhance students' digital competencies and learning satisfaction should focus on implementing project-based learning, collaborative digital activities, authentic assessment practices, and technology-integrated instructional strategies. Simply providing digital infrastructure may be insufficient unless accompanied by systematic efforts to transform teaching and learning processes.

Despite its contributions, the study has several limitations. The cross-sectional design restricts causal inference, and the reliance on self-reported measures may introduce response bias despite the absence of significant common method bias indicated by Harman's single-factor test. Additionally, the focus on Chinese applied universities may limit the generalizability of the findings to other educational contexts. Future research should employ longitudinal or

experimental designs, investigate potential moderating variables such as self-efficacy, learning motivation, or institutional support, and examine the model across different cultural and educational settings.

Recommendation

Based on the findings of this study, several recommendations are proposed. First, applied universities should move beyond technology acquisition and place greater emphasis on instructional innovation, as the results indicate that innovative teaching practices are the primary mechanism through which Education 4.0 enhances students' digital literacy.

Second, educators should incorporate more project-based learning, digital collaboration activities, and authentic problem-solving tasks into their courses. These learner-centered approaches can provide students with meaningful opportunities to develop digital competencies in real educational contexts.

Third, curriculum designers should systematically integrate digital literacy outcomes across academic programs rather than treating digital competence as a standalone skill. Particular attention should be given to digital information literacy, digital content creation, and digital communication and collaboration.

Finally, future research should employ longitudinal designs, include objective measures of digital literacy, and examine diverse institutional contexts to strengthen the generalizability and causal interpretation of the proposed model.

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