

PAPER

Fostering Digital Equity via Mobile-Optimized Hypermedia: A Flipped Classroom Model for Resource-Constrained Higher Education

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ABSTRACT

The rapid digitalization of higher education has heightened the need for digital literacy development, particularly for first-year university students in resource-constrained contexts. This study examines the effectiveness of a mobile-optimized hypermedia-based flipped classroom model designed to promote digital equity in higher education. Adopting a Research and Development (R&D) approach guided by the ADDIE framework, the study encompassed needs analysis, expert validation, and an eight-week quasi-experimental field trial involving 60 first-year students. Data were gathered using a multi-method design, including a digital literacy assessment, engagement and satisfaction questionnaires, and learning analytics, as well as qualitative interviews and focus group discussions. The findings show that students in the experimental group achieved substantially greater improvements in digital literacy compared to those in the control group, with a very large pretest–posttest control-group effect size computed using Morris’s (2008) estimator ($d_{ppc2} = 2.41$; bias-corrected $g_{ppc2} = 2.37$) and a moderate-to-high normalized gain (N-Gain = 0.52). Notably, the intervention demonstrated a strong equity-enhancing effect, as students with lower initial digital proficiency exhibited the highest learning gains (N-Gain = 0.61). Qualitative evidence and learning analytics further indicate high levels of engagement, increased learner autonomy, and the emergence of digital resilience, supported by mobile accessibility and offline-enabled hypermedia modules. Overall, these findings highlight the potential of mobile-first, context-sensitive flipped learning models to reduce digital disparities and foster more inclusive digital literacy development in higher education.

KEYWORDS

digital literacy, flipped classroom, hypermedia learning, higher education, mobile learning

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1 INTRODUCTION

The digital transformation of higher education has intensified global demands for advanced digital literacy among university students [1]. As technology-mediated learning becomes deeply embedded in academic environments, first-year university students face the challenge of rapidly developing comprehensive digital competencies to support both academic success and future professional readiness [2]. Digital literacy now extends well beyond basic technical skills to encompass the ability to locate, evaluate, create, and communicate information effectively and ethically using digital technologies. In higher education contexts, this competence integrates cognitive, metacognitive, and socio-emotional dimensions, enabling learners to engage critically, autonomously, and responsibly within digital environments [3], [4], [22].

Recent global analyses further highlight the growing institutional reliance on mobile learning in higher education as part of broader digital transformation initiatives. A PRISMA-guided bibliometric study of mobile learning research between 2007 and 2023 indicates sustained expansion in mobile-based instructional innovation, particularly in university contexts where smartphones serve as primary learning devices [5]. These findings reinforce the relevance of mobile-optimized instructional models in addressing both access and engagement challenges in contemporary higher education environments.

Recent international proceedings on educational technology further emphasize that digital literacy development in higher education is inseparable from broader processes of digital innovation, cloud-based learning environments, and adaptive instructional designs. Studies synthesized in the *Workshop on Cloud Technologies in Education (CTE 2023)* highlight how cloud infrastructures, artificial intelligence (AI)-supported learning platforms, and hybrid learning models reshape students' engagement, autonomy, and digital competencies across diverse educational contexts [6]. These findings reinforce the view that digital literacy should be cultivated through pedagogically structured digital ecosystems rather than assumed as a byproduct of technology exposure. The current research investigates how the mobile-first hypermedia design can enable digital transformation with a focus on equity in higher education with limited resources within the global context of mobile learning expansion and digitally connected ecosystems.

The broader shift toward AI-enhanced educational technologies further underscores the importance of moving beyond simple digitization toward value-added pedagogical innovation. Emerging research emphasizes that AI and socially interactive technologies can reshape learning environments by supporting personalization, engagement, and adaptive feedback mechanisms [7]. While the present study does not implement AI-driven tools directly, it aligns with this trajectory by emphasizing structured, interactive, and equity-oriented technology integration in higher education.

This challenge is further complicated by the persistent "digital native" paradox. Despite frequent exposure to digital technologies in everyday life, many university students lack the advanced digital literacy required for academic and professional contexts [8], [9]. While students often demonstrate fluency in social media and entertainment platforms, empirical evidence shows that they struggle with evaluating the credibility of online information, applying digital ethics, collaborating effectively in virtual learning spaces, and protecting personal data [10], [11]. This gap between perceived and actual competence presents a substantial pedagogical challenge for higher education institutions preparing graduates for an increasingly digitized society.

Evidence from the *3L-Person 2024* workshop further supports this concern by demonstrating that lifelong learning and professional readiness increasingly depend on learners' ability to engage in AI-enhanced, person-oriented digital learning environments. [12] report that many higher education learners exhibit positive attitudes toward digital technologies while simultaneously lacking the higher-order competencies required for critical evaluation, ethical use of AI, and self-regulated learning (SRL) in technology-rich contexts. This reinforces the need for intentional instructional interventions that scaffold digital literacy rather than relying on students' informal digital experiences.

Traditional lecture-based instructional models have been widely criticized for their limited capacity to foster the critical thinking, reflective engagement, and collaborative problem-solving skills required for advanced digital literacy [13], [14]. In response, higher education institutions worldwide have begun to recognize digital literacy as a core graduate attribute and a critical component of 21st-century employability [15]. One pedagogical innovation that has gained considerable attention is the flipped classroom model, which shifts content delivery to pre-class digital learning activities and reserves in-class time for collaborative discussion and problem-solving [16]. Meta-analytic studies report that flipped classrooms can produce small-to-large improvements in academic achievement, student engagement, and satisfaction, depending on instructional design quality [16], [17]. However, the effectiveness of flipped learning remains highly contingent on the pedagogical quality of pre-class learning materials.

Recent research underscores the importance of interactive, multimedia-rich pre-class resources in supporting learner engagement and preparedness in flipped learning environments [18], [19]. Conventional static materials, such as text-heavy readings and linear video lectures, often fail to support deep exploration or personalized learning. Hypermedia technology offers a compelling alternative by enabling non-linear navigation, interactivity, and learner control. When designed according to multimedia learning principles—such as coherence, signaling, and modality—hypermedia environments can reduce extraneous cognitive load and enhance retention and knowledge transfer [20]. Empirical studies further demonstrate that hypermedia-supported learning can improve conceptual understanding, problem-solving skills, and engagement [21]. Despite these advantages, limited research has examined the integration of hypermedia within flipped classroom models specifically to support digital literacy development, particularly in non-Western higher education contexts. This matters because digital literacy is widely conceptualized as a multidimensional construct encompassing information literacy, digital communication, online collaboration, digital safety, and problem-solving, as articulated in frameworks such as DigComp [4] and the UNESCO Global Digital Literacy Framework [23], [24].

First-year university students represent a strategic target group for digital literacy interventions, as they transition from the structured learning environments of secondary education to the autonomous and self-regulated demands of higher education [2], [25]. In Indonesia, this transition is further complicated by disparities in students' technological backgrounds, unequal access to digital infrastructure, and sociocultural factors influencing technology adoption [14]. Such heterogeneity raises significant equity concerns and highlights the need for inclusive, context-sensitive pedagogical approaches in higher education [13], [26]. Although the flipped classroom and hypermedia technologies have each been widely studied, their integrated application to foster digital literacy among Indonesian university students remains underexplored, with most existing studies conducted in Western contexts.

Accordingly, this study aims to develop and empirically evaluate a theoretically grounded hypermedia-based flipped classroom model to enhance the digital literacy of first-year university students in Indonesia. Specifically, the objectives are to: (1) design and validate the proposed learning model through expert evaluation; (2) assess its effectiveness across multiple dimensions of digital literacy; (3) examine patterns of student engagement and learning behavior; and (4) investigate its equity effects in mitigating disparities associated with students' prior digital experiences. In this study, the term "hypercontent" is used to describe hypermedia-based materials that integrate structured content, multimedia resources, and QR-linked LMS activities within a cohesive instructional design.

2 RESEARCH METHODS

2.1 Research design

This study employed a R&D design guided by the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) framework [27], [28]. A sequential mixed-methods approach was adopted to comprehensively evaluate the developed hypermedia-based flipped classroom model [29]. The quantitative phase aimed to objectively measure the effectiveness of the model, while the subsequent qualitative phase provided in-depth insights into students' learning experiences and implementation nuances. This design supported a systematic and iterative development process, enabling refinements based on formative evaluations conducted at each stage of the ADDIE cycle. The study was conducted from January to September 2025.

2.2 Participants and setting

The study was conducted with first-year undergraduate students enrolled in the Physical Education program at Universitas Setia Budi Rangkasbitung during the 2024/2025 academic year. The focus on first-semester students in the Physical Education program was aligned with the developmental objective of strengthening foundational digital literacy competencies at the early stage of higher education. This population was considered appropriate for instructional model development and refinement within an R&D framework [30], [31]. During the needs analysis phase, 45 students completed a survey to identify baseline digital literacy levels and key competency gaps, ensuring that model development was grounded in learners' actual characteristics and needs [30]. The expert validation phase involved eight experts—three content experts, three instructional media experts, and two educational technology experts—who evaluated content validity, pedagogical alignment, and media appropriateness, consistent with standard practices in instructional design research [31], [32].

The formative evaluation phase consisted of one-to-one trials ($n = 5$) and small-group trials ($n = 15$) to assess usability, instructional clarity, and learner engagement, as recommended in systematic instructional design models [31]. Finally, the field-testing phase employed a quasi-experimental design with an experimental group ($n = 30$) and a control group ($n = 30$), an approach commonly used in authentic educational settings where random assignment is impractical [33]. Group equivalence

was confirmed through pre-test measures of digital literacy and demographic characteristics, with no significant baseline differences observed ($p > 0.05$), indicating comparable initial conditions [32].

2.3 Research procedure

The research procedure followed the ADDIE instructional design framework, which provides a systematic and iterative structure for developing, implementing, and evaluating instructional innovations [27], [28]. As summarized in Table 1, the **analysis stage** involved a comprehensive needs analysis to identify gaps in students' digital literacy competencies, a critical step in R&D studies to ensure learning objectives are grounded in empirical learner data [30].

During the **design and development stage**, hypercontent modules were developed in both printed and digital formats to ensure flexibility and accessibility. The printed version served as structured classroom reference material, while the digital version was embedded within the university's learning management system (LMS) at lms.usb.ac.id. The LMS integration enabled organized content delivery, monitoring of student participation, and access to interactive formative assessments.

In this study, the term "hypercontent" refers to structured hypermedia learning materials integrating text, multimedia elements, QR-based assessments, and LMS-embedded activities within a connected learning ecosystem. The modules incorporated non-linear navigation through QR codes and hyperlinks directing students to supplementary videos, illustrative materials, and formative exercises. Each module contained QR codes linking to short formative multiple-choice assessments hosted within the LMS. These quizzes were designed primarily for self-assessment and metacognitive monitoring rather than summative grading. Immediate answer keys were provided to allow students to evaluate their understanding and identify misconceptions independently. This approach supported learner autonomy and reflective learning processes within the flipped classroom structure.

The core instructional content was provided in PDF format and embedded within the LMS environment, enabling both downloadable offline access and interactive QR-linked extensions. The PDF format was selected deliberately to ensure low bandwidth consumption, cross-device compatibility, and stable offline usability in contexts characterized by intermittent internet connectivity.

To ensure genuine mobile usability rather than simple document portability, the hypercontent modules were designed using a mobile-first UX approach. Pages were formatted in a single-column layout with reduced horizontal width, increased spacing, and enlarged headings to minimize zooming on 6-inch smartphone screens. Content was segmented into short micro-units to reduce scrolling fatigue. Interactive elements were presented as large tap-based buttons and clearly separated QR codes to improve touchscreen accuracy. This design prioritized vertical scrolling behavior typical of smartphone use. While less dynamic than a fully native mobile application, this low-tech but robust design was strategically chosen to increase reliability, ensure continuity of learning, and promote access equity in resource-constrained environments.

The **formative evaluation and validation stage** involved expert review by content, media, and educational technology specialists using a 60-criteria analytical rubric to assess instructional design, media quality, and content accuracy.

Expert validation is a standard procedure for establishing content validity and instructional feasibility prior to implementation [31]. The results indicated consistently high ratings across expert groups, accompanied by constructive feedback that informed subsequent revisions.

Finally, the **implementation and summative evaluation stage** consisted of an eight-week field trial. The experimental group engaged in pre-class self-paced study using the hypermedia modules, followed by in-class collaborative discussions and problem-solving activities, consistent with flipped classroom principles [16]. The control group received traditional lecture-based instruction on the same content, delivered over an equivalent duration and by the same instructors, ensuring the instructional model functioned as the primary independent variable and strengthening internal validity in the quasi-experimental design [33].

Table 1. Research stages and key activities

Stage	Key Activities	Participants	Primary Objective
Analysis	Needs analysis, literature review, formulation of learning objectives	45 students	To identify target digital literacy competencies and learner needs based on empirical data [30]
Design & Development	Storyboarding, hypermedia module development, LMS integration, instrument preparation	Research team	To design and develop the instructional model and aligned evaluation instruments following systematic instructional design principles (Branch, 2009 [27]; Alessi & Trollip, 2015)
Formative Evaluation	Expert validation using a 60-item analytical rubric, one-to-one trials (n = 5), small-group trials (n = 15)	3 experts, 20 students	To establish content validity, usability, and practicality prior to large-scale implementation [31]
Implementation & Evaluation	Quasi-experimental field trial (8-week intervention)	60 students (30 experimental, 30 control)	To examine the effectiveness of the learning model and explore student learning experiences under authentic classroom conditions [33]

2.4 Instruments and measures

A multi-method data collection strategy was employed to enhance methodological rigor and enable triangulation across quantitative and qualitative sources, in line with mixed-methods research principles [29]. The primary quantitative instrument was a researcher-developed Digital Literacy Assessment Scale (DLAS) consisting of 50 items (KR-20 = 0.92) measuring six domains: information search, source evaluation, digital communication, online collaboration, digital ethics, and digital safety. These domains were derived from established international frameworks, including DigComp 2.2 and the UNESCO Global Digital Literacy Framework, which conceptualize digital literacy as a multidimensional construct [4, 24]. The KR-20 value indicates strong internal consistency and meets recommended psychometric standards [32].

Student engagement was assessed using a 25-item scale (Cronbach's $\alpha = 0.91$) adapted from validated multidimensional engagement instruments encompassing behavioral, cognitive, and emotional components [34], [35]. The instrument was

contextualized for flipped and technology-enhanced learning environments, consistent with prior research in digital and blended learning contexts [36]. Students' satisfaction with the learning model and instructional content was measured using a 30-item questionnaire ($\alpha = 0.94$), reflecting established practices in evaluating technology-enhanced and flipped learning experiences [16], [37].

To ensure content validity and instructional feasibility, a 60-criteria expert validation rubric was employed during the development phase to evaluate instructional design quality, media presentation, and content accuracy, following accepted procedures in instructional design research [30], [31]. Qualitative data were collected through semi-structured interviews ($n = 24$) and focus group discussions (four FGDs, $n = 15$) to capture in-depth insights into students' perceptions, learning behaviors, and implementation challenges. These methods are well suited for exploring complex educational experiences and contextual factors [33], [38]. Finally, learning analytics data from the LMS—including module completion rates, time-on-task, and interaction patterns—were analyzed to triangulate self-reported measures and capture observable learning behaviors in digital environments [39], [40].

2.5 Data analysis

Quantitative data were analyzed using IBM SPSS Statistics (Version 28), which is widely employed in educational research for hypothesis testing and group comparisons [41]. Prior to analysis, assumptions of normality and homogeneity of variance were examined to confirm the suitability of parametric tests. Paired-samples t-tests were used to compare pre-test and post-test digital literacy scores within each group, while independent-samples t-tests were conducted to compare post-test gains between the experimental and control groups, consistent with quasi-experimental pretest–posttest designs [33]. To examine differential intervention effects across initial digital proficiency levels (low, medium, high), a one-way ANOVA was performed in accordance with best practices in educational intervention research [41].

The practical significance of the findings was assessed using effect size and learning gain indices. Effect size was computed using Morris's (2008) pretest–posttest control-group standardized mean difference (d_{ppc2}), which standardizes the between-group difference in gain scores using the pooled pretest standard deviation. This estimator is recommended for quasi-experimental pretest–posttest designs because it anchors standardization to baseline variability and avoids inflation due to post-intervention variance changes. All effect-size calculations were recomputed directly from the raw pretest–posttest dataset. Using this procedure, the study yielded $d_{ppc2} = 2.41$, with a bias-corrected Hedges' estimate of $g_{ppc2} = 2.37$. In addition, normalized gain (N-Gain) was calculated to quantify improvement relative to students' initial performance levels.

Qualitative data were analyzed using reflexive thematic analysis, following the updated framework proposed by [43]. This involved iterative phases of familiarization, coding, theme construction, review, and reporting, emphasizing reflexivity and analytic transparency [43]. Finally, data triangulation was conducted by integrating quantitative results, qualitative themes, and learning analytics data to strengthen the credibility and trustworthiness of the mixed-methods findings [29]. The overall research flow is presented in Figure 1.

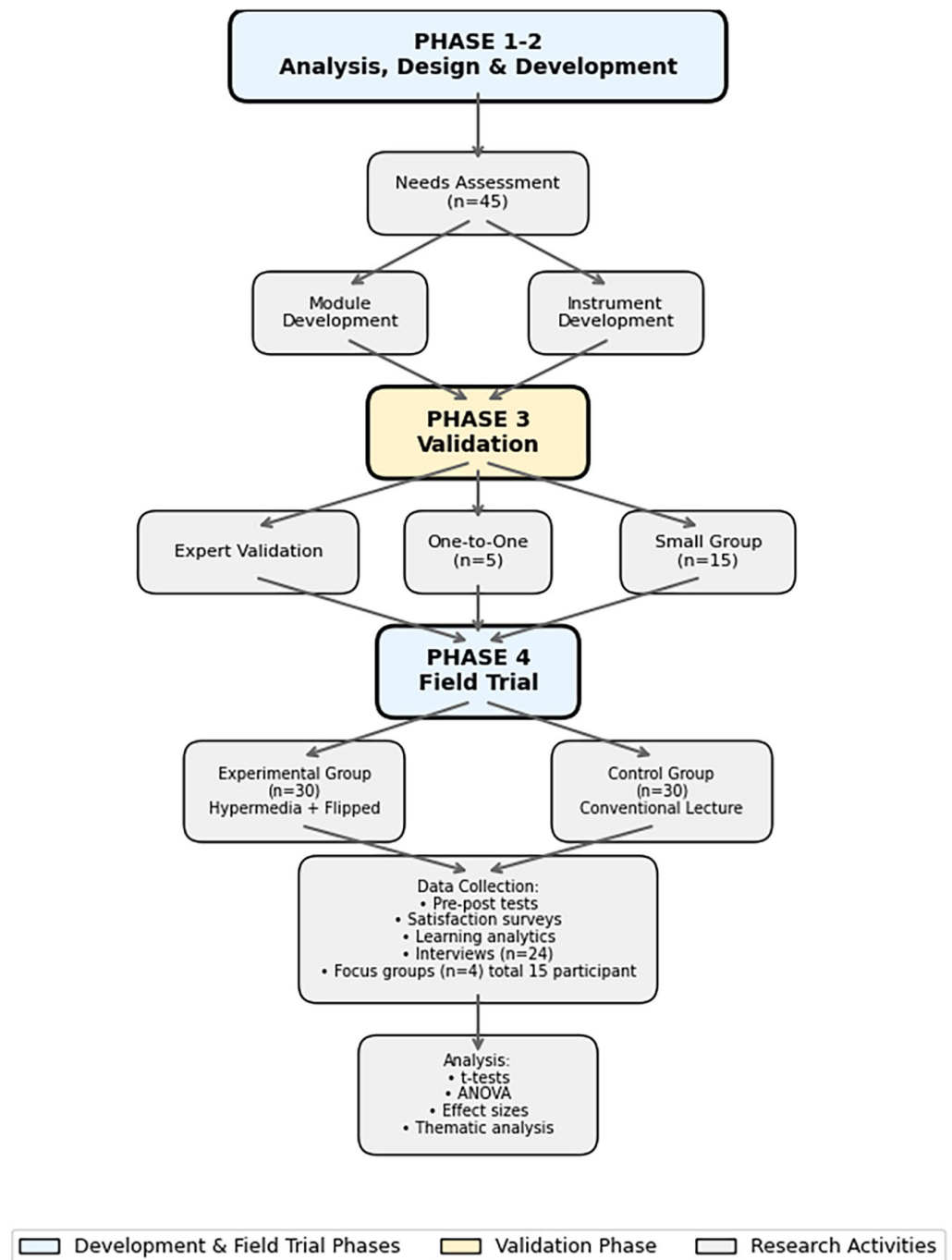


Fig. 1. Research flow diagram

2.6 AI tools

Declaration of Generative AI and AI-assisted technologies in the writing process: During the preparation of this work, the author(s) used Grammarly in order to improve the quality of our writing, addressing grammatical issues, correcting spelling and punctuation errors, and adjusting the tone to align with the formal academic context. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

3 RESULTS AND DISCUSSION

3.1 Needs analysis: identifying the digital literacy gap and contextual onstraints

A needs analysis with 45 first-semester undergraduate students showed a wide range of digital literacy skills. At first, data were collected using a survey-based digital literacy tool with high internal consistency (Cronbach's $\alpha = 0.89$). Later, a more detailed 50-item Digital Literacy Assessment test (KR-20 = 0.92) was used for more precise measurement. Figure 2 shows that 32% of students had low digital literacy (scores 40–59), 44% had medium (60–74), and 24% had high (75–100).

The marked diversity in students' digital literacy levels makes it clear that a "one-size-fits-all" instructional design is inadequate and underscores the need for adaptive and differentiated learning designs. These results are in line with previous empirical studies that have shown that the digital competencies of students are highly determined by their disciplinary background, previous digital technological exposure, and socio-economic conditions and that this is especially evident in diverse contexts of higher education institutions [44], [45].

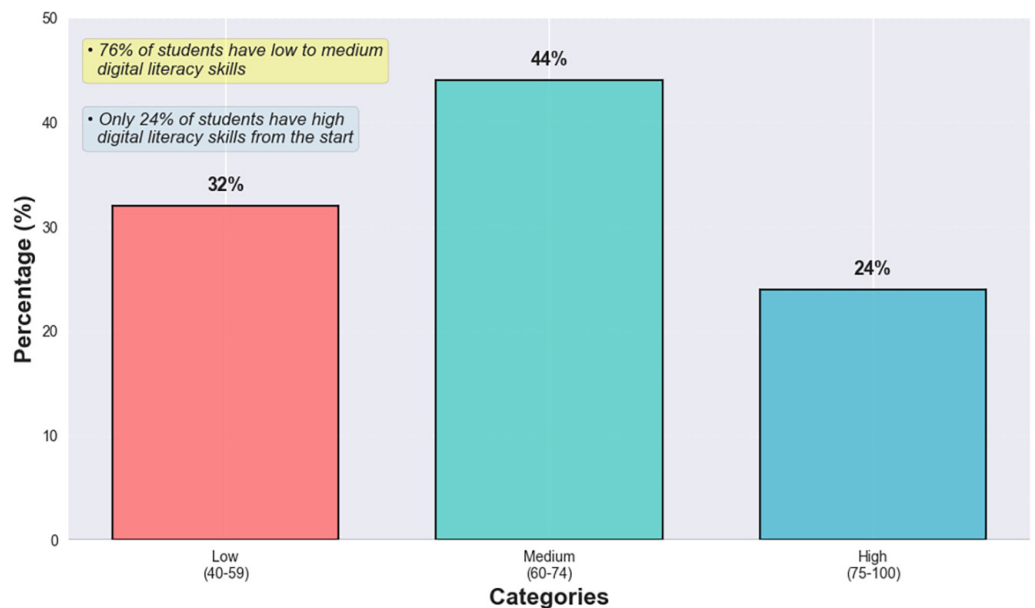


Fig. 2. Distribution of initial digital literacy skills among first-semester students ($n = 45$)

Focus group interviews and semi-structured interviews helped shed light on students' learning preferences and contextual barriers. A vast majority of participants preferred experiential and participatory learning over traditional lecture-based learning (82%). This finding is consistent with current empirical evidence showing that the use of active learning strategies can enhance student motivation, engagement, and learning in post-secondary contexts. Additionally, most students (i.e., 89%) reported that a significant, self-paced process requires them to access learning materials through a flexible, multi-device-compatible interface, while traditional materials generated low satisfaction among students ($M = 2.1$, on a scale of five). The discrepancy between students' desire for interactive multimedia learning and the overreliance on traditional materials for their learning resources (i.e., 93% of the materials were in the form of PDF documents and PowerPoint slides) suggests

the importance of more technology-enhanced and interactive instructional designs to match students' expectations and learning processes [17], [46].

An infrastructure assessment revealed a dueling digital world. While several facilitators were identified, including widespread ownership of smartphones (96%) and the presence of an institutional LMS, critical barriers were also noted, including unstable internet connectivity (33% of students), bandwidth limitations during peak usage, and limited signal mobility in certain campus areas. This and similar mixed digital landscapes are common in many emerging countries, where the launch of higher education digital transformation strategies must be carefully calibrated to existing infrastructural limitations [47], [48].

In consequence of these contextual realities, a hypermedia-based flipped classroom model was designed. The model was purposefully designed to exploit hypermedia affordances such as non-linear navigation, learner control, and multimedia integration to promote interactivity and flexibility in learning while reducing reliance on persistent high-bandwidth connectivity [20]. Meanwhile, face-to-face learning activities would be designed to support collaborative, hands-on learning activities to which students explicitly indicated a preference, consistent with evidence of active learning in the flipped classroom to be more effective [49]. Futures to address infrastructural limitations included feasible design modifications, such as offline materials, media compression, and adaptive scheduling of learning activities, to support equitable access and learner engagement despite connectivity constraints.

3.2 Development and validation of the hypermedia module

The hypermedia-based flipped classroom module was subject to expert validation with content experts ($n = 3$), media design experts ($n = 3$), and educational technology experts ($n = 2$). Expert validation is a commonly used quality guarantee procedure in the areas of instructional design and R&D to ensure content validity, pedagogical coherence, and technical viability before the actual field test [30], [31]. The validation results should therefore be understood as indicating a consistently high quality on many aspects and as encompassing recommendations for improvement, which represent a realistic and credible evaluation outcome rather than an indication of perfect error-free working conditions.

Content validation. Content experts consistently rated the module's overall quality in terms of content accuracy, completeness, and didactic value (mean score = 4.38 out of 5). Content experts perceived the module as most aligned with the learning objectives and suitable for first-year university students. The findings suggest that our educational product was perceived as having high content validity [32]. In line with the quantitative evaluation, content experts provided qualitative feedback. They indicated that the module's content was well presented, with good coherence and well-structured information. Content experts particularly appreciated that all five domains of a contemporary multidimensional digital literacy model were included in the module [4], [24]. Content experts suggested—albeit only slightly—that more examples be formulated in a local context to be more contextually relevant. Content experts also suggested that the assessment rubrics could be improved to explicitly state the criteria for both critical and creative knowledge.

Media and hypermedia validation. The overall mean score was 4.31 based on the media experts' evaluation. The module showed excellent performance in its visual design, navigational consistency, and multimedia integration, as well as interactivity. The media experts recognized the module's ease of use and intuitive navigation interface, as well as the sophisticated multimedia implementation to facilitate

learning and promote learner autonomy. The results are consistent with the multimedia learning theory, which suggests that the appropriate combination of text, visuals, and interactive elements can aid cognitive processing while reducing extraneous cognitive load [20]. Despite the high overall usability score, the experts suggested optimizing video loading times under low-bandwidth conditions and minor adjustments for mobile responsiveness for smaller screens, which is particularly pertinent for developing-country settings [47].

Educational technology and instructional strategy validation. Validation by educational technology experts yielded the highest overall mean score (4.43), particularly for alignment with flipped classroom principles and the design of pre-class and in-class learning activities. Experts noted that the module effectively operationalized constructivist learning principles by ensuring that pre-class hypermedia activities adequately prepared students for in-class collaborative discussions, problem-solving, and group work. This sequencing reflects best practices in flipped classroom pedagogy, where out-of-class content delivery is strategically used to maximize active learning during face-to-face sessions [16], [49]. Feedback further indicated that the transition between online and face-to-face components was smooth and pedagogically coherent, requiring no substantial structural revision.

Overall, the expert validation results confirm that the hypermedia module demonstrates strong theoretical grounding, pedagogical coherence, and technical reliability, with mean scores consistently exceeding 4.30 across all expert groups. Importantly, the qualitative feedback generated targeted and feasible recommendations, all of which were addressed prior to field implementation. This multi-perspective validation process provides a robust foundation of quality assurance, supporting the module's readiness for experimental testing and reinforcing its potential effectiveness in authentic instructional settings [31].

3.3 Mobile-first equity design as a pedagogical strategy

This paper redefines mobile optimization as an equity-based pedagogical approach rather than a technological upgrade. In much of higher education in the developing world, a student's main computer is a smartphone, not a laptop. Yet, mobile learning environments are still configured as a miniature desktop rather than as an intentionally designed smartphone.

We incorporated mobile-first design principles from the very beginning of the intervention design phase. All aspects of content hierarchy, visual hierarchy, segmentation, tap targeting, QR-based navigation, and offline accessibility were all deliberately designed with consideration to "reading on a handhelds" and bandwidth constraints. The decision to embed the PDF-based hypercontent in the LMS and use QR-based internal hyperlinking to link the content with formative assessment was not a technical limitation but a deliberate choice to make the content more readily accessible to participants, to lower data costs, and to increase learning continuity during unstable connectivity.

This approach redesigns the notion of "low-tech" by positioning it as context-sensitive mobile innovation rather than limited choice. Instead of privileging high-interactivity native applications that systematically exclude low-connectivity or low-device-computing learners, design for robustness, inclusivity, and sustainability. In this context, mobile optimization serves the purpose of limiting digital inequality, rather than the perfection of the user interface. This paper introduces a model that integrates hypermedia structure, LMS embedding, QR-linked assessment, and mobile-first layout design to adapt an existing ICT-based design for interactive

mobile technologies to under-resourced settings without compromising pedagogical integrity. The model contributes to the conversation on equity-oriented educational technology implementation. The decision supports the ideas of frugal innovation and appropriate technology, putting affordable, strong, and fit-for-context access to learning before bandwidth-heavy sophistication in resource-strapped higher education.

3.4 Field implementation and empirical effectiveness

The field trial demonstrated substantial improvements in digital literacy among students in the experimental group compared to the control group. This pattern was reflected by a moderate-to-high normalized gain ($N\text{-Gain} = 0.52$) and a very large pretest–posttest control-group effect size computed using Morris’s (2008) estimator ($d_{ppc2} = 2.41$; bias-corrected $g_{ppc2} = 2.37$). These findings indicate that the hypermedia-based flipped classroom model produced markedly greater learning gains than conventional lecture-based instruction. Access to the hypermedia modules, QR-linked assessments, or mobile-optimized LMS materials was not provided to the control group. Instruction was delivered exclusively via face-to-face lectures and conventional printed materials. These effect sizes exceed typical benchmarks for flipped and technology-enhanced learning interventions in higher education [16], reinforcing the alignment between the model’s design—integrating flipped pedagogy, multimedia principles, and hypermedia interactivity—and its educational impact (see Figure 3) for a comparison of digital literacy improvements between the experimental and control groups.

High expert validation scores during the development phase translated into effective real-world implementation, evidenced by strong learner engagement (91.7% pre-class completion, 94.2% attendance) and significantly greater self-reported learner autonomy in the experimental group ($M = 4.25$ vs. 3.41; $p < 0.001$). These outcomes affirm the model’s pedagogical coherence and the importance of instructional media quality [50].

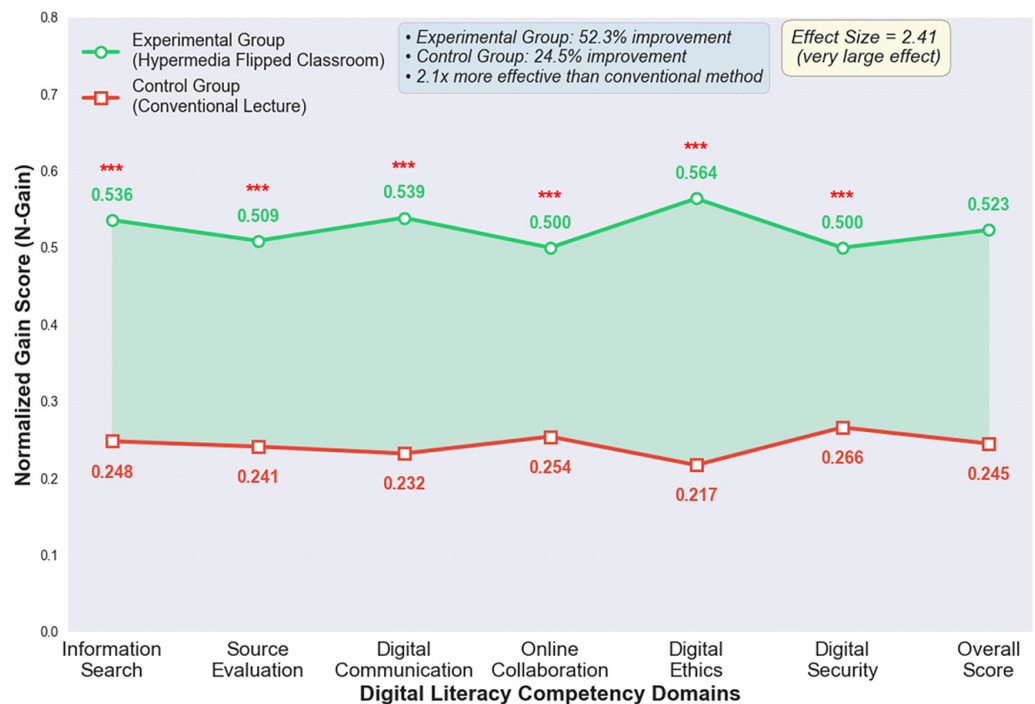


Fig. 3. Comparison of digital literacy improvement between experimental group (Hypermedia Flipped Classroom) and the control group (Conventional Lecture)

Learning analytics further corroborated the model’s effectiveness. Experimental group students displayed sustained engagement through longer time-on-task, increased interaction with hypermedia content, and more active participation in online forums—behavioral metrics that validated self-reported engagement and demonstrated the model’s capacity to foster deep, autonomous learning [20], [40], [46] (see Figure 4) for learning analytics data illustrating comparative engagement patterns.

To enhance accessibility in mobile learning contexts, the model adopted a mobile-first design. With smartphone ownership at 96%, mobile optimization was achieved through responsive layouts, simplified navigation, and segmented multimedia. The integration of offline-accessible PDF modules with embedded links and QR codes enabled continued engagement during periods of poor connectivity, addressing infrastructural constraints common in developing contexts. This design directly supports mobile learning principles, particularly in promoting digital equity and flexible access in resource-limited environments.

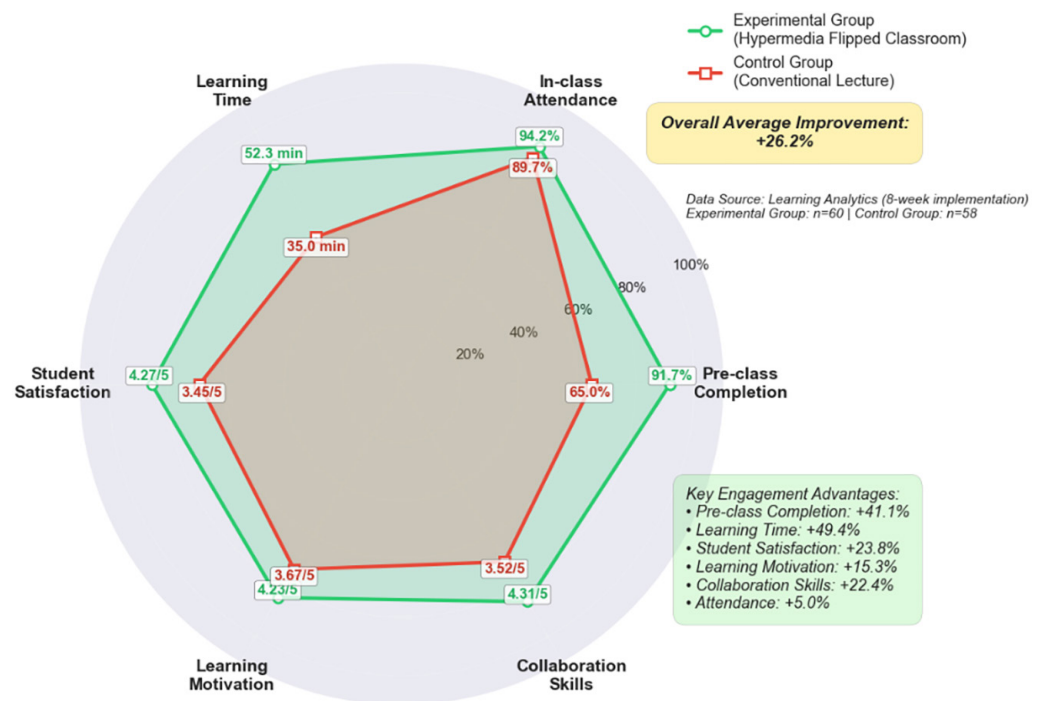


Fig. 4. Student engagement and learning analytics: Hypermedia flipped classroom vs. conventional approach

3.5 The equity-promoting effect and practical challenges

A key finding of this study is the equity-promoting effect of the hypermedia-based flipped classroom model. Students with low initial digital proficiency demonstrated the highest learning gains (N-Gain = 0.61), significantly outperforming their high-proficiency peers (N-Gain = 0.39; $p = 0.001$), indicating the model’s capacity to narrow pre-existing digital skill disparities—an outcome particularly relevant in developing higher education contexts marked by persistent digital inequality [51] (see Figure 5).

The above-mentioned positive differential effect can mainly be explained by the model’s inclusive design, which integrates offline and online resources, a well-structured learning trajectory, and scaffolding embedded in the hypermedia content. These aspects align with the Universal Design for Learning (UDL) framework, which recommends strategies for engagement, representation, and action to support all

learners [52]. Previous research also supports the idea that UDL-based digital learning environments can minimize differences in participation and learning outcomes between students with varying degrees of prior technology experience [53].

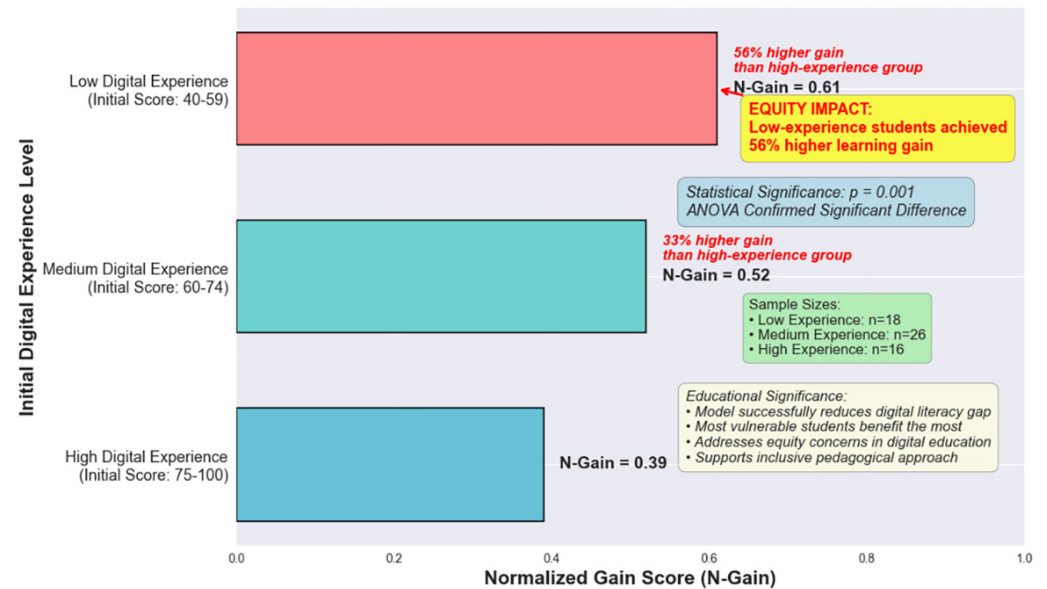


Fig. 5. Equity-promoting effect of the hypermedia flipped classroom model

Despite the model's overall effectiveness, qualitative data revealed notable implementation challenges. Students reported varying levels of perceived usability ($SD = 0.73$) and struggled with time management, particularly in balancing self-paced pre-class learning with other academic commitments. These challenges highlight the critical need for iterative, learner-centered usability testing to complement expert validation, ensuring that issues related to workload and interface design are addressed early [20], [31]. Addressing such concerns is vital to maintain the pedagogical integrity and long-term sustainability of equity-focused instructional innovations.

3.6 Thematic analysis: student perceptions and lived experiences

A thematic analysis of in-depth interviews ($n = 24$) and focus group discussions (four FGDs, $n = 15$) yielded rich insights into students' lived experiences with the hypermedia-based flipped classroom model. Five overarching themes emerged, capturing both the transformative potential of the intervention and the practical challenges encountered during implementation (see Figure 6).

Theme 1: from digital anxiety to digital confidence. A central theme was the transformation from digital anxiety to growing digital confidence among students with initially low digital proficiency. As articulated by participant EKS-023, "Honestly, I was very afraid at first... but it turned out the module was very user-friendly," this narrative reflects a typical technology acceptance trajectory in educational contexts. Such shifts are supported by research showing that well-designed, learner-centered digital environments can foster digital resilience and reduce anxiety over time [54].

This evolution can be understood through self-efficacy theory, which highlights how mastery experiences and supportive contexts enhance learners' belief in their digital capabilities [55], [56]. As students progressed through scaffolded hypermedia tasks, their perceived competence improved, contributing to higher academic

self-efficacy—a key predictor of engagement and success in online and blended learning [57]. This theme is especially relevant in Indonesia, where students from rural or under-resourced areas often report heightened digital insecurity. Context-sensitive interventions such as this can play a crucial role in supporting their transition into technology-rich academic environments.

Theme 2: awakening to contextual digital literacy. Another key theme was a conceptual shift in students' understanding of digital literacy, particularly the distinction between everyday digital fluency and the academic digital competencies required in higher education. As articulated by participant EKS-011, *"I thought I was already proficient with technology ... it turns out digital literacy for entertainment and for academics is different,"* this reflection captures a process of conceptual awakening toward contextual digital literacy—a realization echoed across interviews and focus groups.

This insight directly challenges the widely held yet increasingly disputed "digital native" assumption, which posits that frequent digital exposure automatically translates into academic digital competence. In contrast, recent studies show that students often lack advanced skills in evaluating sources, practicing digital ethics, and engaging in scholarly communication [2], [8]. Digital literacy, as current scholarship affirms, is a situated and domain-specific capability, varying by purpose and context [45].

These findings underscore the need for explicit digital literacy instruction in higher education, moving beyond assumptions of innate student proficiency. Leading frameworks advocate for integrating targeted learning tasks focused on information searching, critical evaluation, synthesis, and ethical digital practice [4], [58]. In the Indonesian context, this theme aligns with national priorities outlined in the *Kurikulum Merdeka*, which promotes the development of contextualized digital competencies to support inquiry, critical thinking, and innovation in higher education [59].

Theme 3: the double-edged sword of flexibility. Students expressed appreciation for the flexibility offered by self-paced learning while also acknowledging its challenges—particularly around time management and self-discipline. As participant EKS-055 noted, *"Because it's flexible, sometimes I procrastinate. But after creating my own study schedule, it became more organized,"* this statement reflects a gradual development of metacognitive regulation in navigating autonomous learning contexts. Other students echoed similar sentiments in group discussions, valuing the non-judgmental nature of asynchronous review but recognizing the risk of disengagement.

This duality highlights the complexity of SRL in flipped and digital environments, where learner autonomy can foster deeper engagement or lead to procrastination without appropriate support structures [60], [61]. Research on SRL emphasizes the need for scaffolding mechanisms—such as goal-setting tools, progress tracking, and time management prompts—to guide learners toward productive autonomy [62].

In the Indonesian higher education context, where students may be transitioning from teacher-directed instruction to self-directed learning cultures, these findings underscore the importance of "structured flexibility." This approach balances learner freedom with clear guidance and accountability measures, which have been shown to be particularly effective in supporting student persistence and self-regulation [62].

Theme 4: peer collaboration as social scaffolding. A prominent theme emerging from the qualitative data was the spontaneous formation of peer support networks, which played a critical role in addressing technical challenges and clarifying content-related questions. As one participant shared, *"If there were technical problems, my friends would help,"* this highlights how peer-assisted learning acted as a form of social scaffolding, allowing students to progress collaboratively through digital and academic tasks.

Such peer interactions are central to sociocultural learning theories, which emphasize the importance of distributed expertise in technology-enhanced environments [63]. Peer support extended beyond troubleshooting to include collaborative learning strategies, as reflected in EKS-025’s comment: “When there was a group assignment, I suggested using Google Docs so we could work together online. My friends also became more productive.” These behaviors exemplify distributed digital competence, where literacy is enacted collectively rather than individually [64].

In the Indonesian context, peer-based scaffolding resonates with prevailing collectivist cultural norms, particularly the emphasis on mutual assistance and communal learning. These values naturally foster a learning environment where students are inclined to collaborate and support one another, both socially and academically. Within such a context, structured peer collaboration in hypermedia-based flipped classrooms holds particular promise—not only in enhancing learning outcomes but also in reinforcing pedagogical approaches that are congruent with local educational philosophies. This alignment potentially strengthens student motivation and engagement, especially among those who may face challenges in digital learning environments.

Theme 5: developing digital resilience. Thematic analysis revealed clear manifestations of digital resilience among students, particularly in their ability to adapt learning strategies in response to infrastructural constraints such as unstable internet connectivity. As illustrated by participant EKS-025, who stated, “The biggest challenge is the internet connection. I live in an area with a sometimes weak signal. But luckily the module could be downloaded, so I downloaded it first while on campus, then studied offline at home,” students demonstrated proactive and resourceful behaviors in navigating digital barriers.

Rather than functioning merely as short-term coping mechanisms, these agentic responses reflect core dimensions of digital resilience, understood as learners’ capacity to anticipate, adapt to, and recover from digital disruptions while sustaining meaningful engagement in learning activities [65]. Strategic practices such as pre-downloading hypermedia materials enabled students to maintain learning continuity despite limited access, aligning with evidence that adaptive digital behaviors are critical for academic persistence in resource-constrained contexts [66]. From an equity-oriented pedagogical perspective, such resilience highlights how learners actively negotiate structural limitations, positioning digital resilience not only as an outcome of instructional design but also as an essential graduate attribute for participation in increasingly digitalized educational environments.

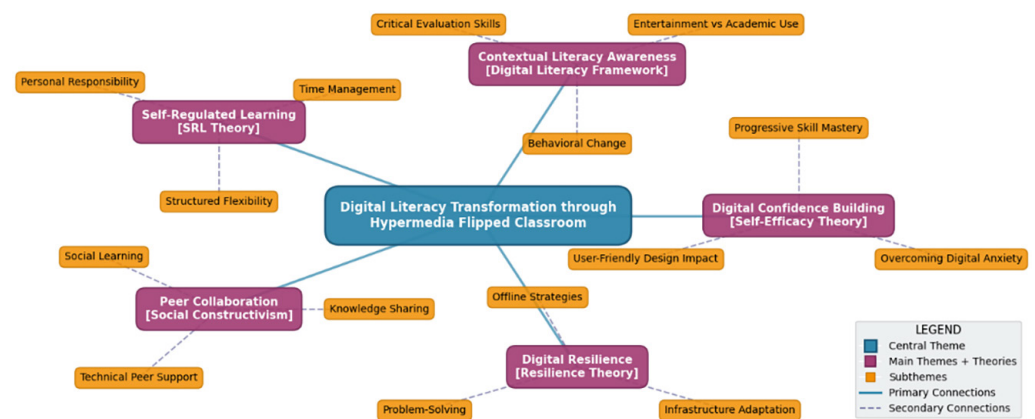


Fig. 6. Thematic map of student experiences with the hypermedia flipped classroom model

3.7 Methodological implications and synthesis

One of the particular strengths of the study is the triangulation of quantitative learning outcomes, learning analytics, and learning behavior with qualitative data to provide converging evidence on the effectiveness of the hypermedia-based flipped classroom model and the associated benefits to teacher learning in technology-enhanced learning contexts. The alignment across multiple data sources strengthens the validity of findings and reflects best practices in mixed-methods research [29].

The phased R&D approach—spanning needs analysis, expert validation, and mixed-methods field testing—enabled the creation of a theoretically grounded and contextually responsive intervention [30], [67]. Qualitative insights reinforced the initial needs analysis and confirmed that key design features—such as flexibility, multimedia scaffolding, and support for digital diversity—were both pedagogically effective and student-endorsed. Moreover, challenges related to self-regulation that emerged during implementation were anticipated in the design phase, justifying the inclusion of structured support mechanisms. This alignment between predicted needs, design responses, and empirical validation underscores the strength of the iterative development process.

The study also offers a scalable framework for institutions in non-Western contexts seeking to reduce digital literacy disparities through pedagogically informed, equity-driven technology integration. Its methodological contribution lies in the integration of Morris's (2008) pretest–posttest control-group effect size estimator (d_{ppc2}), normalized gain analysis, behavioral learning analytics, and thematic inquiry [42]. The magnitude of the effect size is partly attributable to relatively low baseline variance in digital literacy scores, which increases standardized gain differences when pooled pretest standard deviation is used for scaling, as recommended by Morris [42]. This multidimensional evaluation approach allows for more nuanced and equity-sensitive insights than single-method studies, particularly when assessing impact across heterogeneous student populations [40], [46].

3.8 Limitation

The present study utilized a relatively small sample ($n = 60$; 30 per group) obtained from a single study program at a single institution of higher education in Indonesia. This sample size was appropriate for the pilot implementation of a quasi-experimental design; however, it substantially limited the statistical power of the current study and thereby constrained the generalizability of the results to the broader Indonesian higher education landscape. Therefore, the results of the current study can best be seen as evidence of effectiveness at the individual institution. The study also employed a quasi-experimental design that used intact groups rather than random assignment, which potentially introduces contextual effects, despite achieving equivalence at baseline. Future work should extend this pilot implementation with larger, multi-site sample populations that span multiple institutional contexts and, where possible, stronger experimental controls in order to replicate the observed equity effects.

The remarkably high effect size ($d_{ppc2} = 2.41$) should also be interpreted with some methodological caution. Although calculated with Morris's [42] recommended estimator for pretest–posttest control-group designs, the magnitude of the effect may be partially a function of the relatively low degree of baseline variance in the

sampled population ($SD_{pre} \approx 4.36$ on a 100-point scale). When baseline pooled pretest standard deviations are low, standardized gain differences can appear inflated compared to studies conducted in more heterogeneous populations. Thus, while the results indicate strong instructional impact in this context, the magnitude of the effect size should not be interpreted as indicative of universally large effects across broader or more diverse higher education contexts.

Another drawback is the use of PDF-based hypercontent rather than a complete native mobile application. Despite the modules being developed with a mobile-first layout in mind and embedded into the LMS, the interaction was not as fluid as many app- and web-app-based solutions. Future work may investigate adaptive mobile interfaces or lightweight web applications that are as robust offline as the PDFs above but offer better interaction.

4 CONCLUSION AND IMPLICATIONS

This study offers robust empirical support for the effectiveness of a hypermedia-based flipped classroom model in enhancing digital literacy among first-year university students in Indonesia. The intervention yielded significant improvements, evidenced by a very large pretest–posttest control-group effect size ([42]; $d_{ppc2} = 2.41$; bias-corrected $g_{ppc2} = 2.37$) and a moderate-to-high normalized gain (N-Gain = 0.52), with the strongest gains observed among students with initially low digital proficiency (N-Gain = 0.61), underscoring its equity-promoting potential. Qualitative data revealed a shift in the psychological and conceptual mindsets of learners from digital anxiety to self-efficacy and from recreational to academic forms of digital literacy. These changes were guided by three design pillars: design process with expert validation, multimedia and hypermedia learning principles, and a mobile and context-sensitive framework within infrastructural constraints.

The study contributes both theoretically and practically to the field of educational technology. Theoretically, it advances understanding of how flipped pedagogy, hypermedia learning, and culturally responsive design converge to generate cognitive and equity-focused outcomes. Practically, it provides a validated framework for implementing digital literacy interventions in resource-constrained settings, emphasizing the importance of pedagogical adaptation over technological determinism. Conceptually, the study demonstrates that mobile-first equity design can function as a viable alternative to high-bandwidth app-based solutions in contexts characterized by infrastructural constraints. Future research should examine the long-term retention of digital competencies, test the model's transferability across disciplines and institutions, and develop more nuanced indicators for assessing equity and inclusion in technology-mediated education—particularly in under-resourced and diverse higher education environments.

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7 APPENDIX

Effect Size Calculation (Morris, 2008)

Summary Statistics

Group	n	M_pre	SD_pre	M_post	Gain
Control	30	63.9733	4.3232	72.7933	8.8200
Experimental	30	63.0400	4.3943	82.3433	19.3033

Pooled Pretest *SD*

$$SD_{pre,pooled} = \sqrt{\frac{(n_E - 1)SD_E^2 + (n_C - 1)SD_C^2}{n_E + n_C - 2}} = 4.3589$$




Morris (2018) d_{ppc2}

$$d_{ppc2} = \frac{(19.3033 - 8.8200)}{4.3589} = 2.405 \approx 2.41$$




Bias-Corrected Hedges' *g*




$$g_{ppc2} = 0.987 \times 2.405 = 2.37$$

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