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A Critical Pedagogy-Based Andragogical Self-Learning Framework for AI/IoT-Enabled Hybrid Adult Education: A Systematic Review and Conceptual Model Development

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Abstract

This study aims to develop a validated conceptual model—the Andragogical Self-Learning Framework for AI/IoT-Enabled Hybrid Education (ASFAIHE) that integrates Knowles' andragogy and heutagogy with AI/IoT-enabled hybrid learning environments, mediated by critical pedagogy principles of learner agency and digital equity. Method: A systematic mixed-methods review was conducted following PRISMA 2020 guidelines. Electronic searches were performed across five major databases (PubMed, Scopus, Web of Science, IEEE Xplore, and Google Scholar) for peer-reviewed studies published between 2005 and 2025. Inclusion criteria required studies to address adult learning theories (specifically andragogy or related models), AI and/or IoT in educational contexts, critical pedagogy principles, and hybrid or digital learning environments. Of 3,456 initially identified records, 85 studies met all inclusion criteria after two-stage independent screening. Qualitative data were analyzed through thematic synthesis following Thomas and Harden's approach using NVivo; quantitative findings were synthesized via random-effects meta-analysis using R's 'metafor' package; bibliometric mapping was conducted using VOSviewer. Results: Thematic synthesis yielded four interrelated themes: (1) Learner Autonomy and Scaffolding, (2) Adaptive Feedback Loops, (3) Contextual Sensing via IoT, and (4) Data Privacy and Ethical Concerns. Meta-analysis revealed that AI-driven adaptive systems significantly enhance learner engagement (pooled $g = 0.65$; 95% CI [0.52, 0.78], $p < 0.001$) and self-efficacy ($g = 0.58$; 95% CI [0.45, 0.71], $p < 0.001$). These findings were integrated into the ASFAIHE model, which conceptualizes adult learner engagement as a function of AI personalization, IoT contextual feedback, and critical consciousness. Contribution: This study produces a theoretically grounded and empirically supported conceptual model that constitutes a novel design architecture for hybrid AI learning ecosystems in adult education. The model advances existing frameworks by systematically embedding critical pedagogy as an ethical and transformative mediator. Longitudinal and cross-cultural empirical validation is recommended to strengthen the model's generalizability.

Keywords: Self-directed learning; artificial intelligence (AI); internet of things (IoT); andragogy; critical pedagogy; hybrid learning

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INTRODUCTION

The rapid transformation of education in the digital era has fundamentally reshaped the way learning environments are designed, implemented, and evaluated.

The integration of emerging technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT) has significantly influenced pedagogical innovation, particularly in hybrid learning contexts that combine face-to-face and digital modalities. In adult education, this transformation demands models that not only leverage technological sophistication but also remain grounded in adult learning principles and social justice perspectives. Contemporary scholarship emphasizes the need to align technological advancement with andragogical principles that prioritize autonomy, experiential relevance, readiness to learn, and internal motivation (Knowles, Holton III, & Swanson, 2014). At the same time, critical pedagogy underscores the importance of empowering learners to develop critical consciousness and challenge structural inequities in digitally mediated education (Huang et al., 2024; Panta, 2025).

Hybrid learning environments have expanded access to education, yet they also expose structural limitations in instructional design, learner engagement, and digital equity. Research consistently demonstrates that adult learners in hybrid contexts exhibit qualitatively different engagement patterns compared to traditional learners: they require instructional systems that recognize prior experience, support autonomous goal-setting, and connect content to immediate professional relevance (Blaschke, 2021; Knowles et al., 2014). However, existing hybrid learning designs predominantly address technological delivery mechanisms rather than the pedagogical architecture needed for adult self-directed learning. Studies examining AI-enhanced adult learning environments report promising gains in engagement and retention, yet these systems are largely designed without explicit grounding in andragogical theory, treating adult learners as passive recipients of algorithmically curated content rather than active, self-determining agents (Lin & Schmidt, 2025; Storey & Wagner, 2024). This misalignment between technological affordance and adult learning theory constitutes a fundamental design problem that current hybrid learning models have not resolved (Faridah & Kunarso, 2022; Ritonga, Verawati, & Damanik, 2025). These findings confirm that technology-enhanced learning can produce measurable gains in learner performance when systematically designed and validated.

The theoretical inadequacy of existing andragogical frameworks in AI/IoT-mediated contexts constitutes a second, equally pressing problem. Knowles' andragogy, while foundational, was conceptualized in pre-digital learning environments and does not account for the affordances and risks of algorithmic systems (Knowles et al., 2014). Heutagogy, an extension of andragogy emphasizing self-determined learning, acknowledges learner capability development but similarly lacks operational guidance for AI-driven personalization or IoT-enabled contextual sensing (Blaschke, 2021; Panta, 2025). Systematic reviews of AI applications in higher education confirm that most AI tools are designed without adequate awareness of andragogical strategies, resulting in systems that optimize content delivery but fail to foster genuine learner autonomy or reflective practice (Zawacki-Richter, Marín, Bond, & Gouverneur, 2019). This gap is compounded by the absence of a critical pedagogical lens: without Freirean critical consciousness embedded within the learning architecture, AI and IoT systems risk reproducing what Freire (1970) termed the "banking model" of education in digital form,

commodifying knowledge delivery while suppressing learner agency (Carius & Scartoni, 2023; Farag, Greeley, & Swindell, 2022).

Artificial Intelligence enables adaptive personalization through data-driven algorithms capable of analyzing learner behavior, pacing, and performance patterns (Huang et al., 2024). IoT technologies extend this capability by capturing contextual data from learning environments, enabling real-time feedback and embodied learning experiences. While these technologies offer unprecedented opportunities for personalization and engagement, they simultaneously raise concerns regarding surveillance, data ethics, and algorithmic bias. Critical pedagogy becomes essential in mediating this tension by ensuring that technological integration strengthens learner agency rather than reproducing digital inequalities (Panta, 2025). Without a critical framework, AI and IoT risk becoming tools of control rather than instruments of empowerment.

The growing adoption of IoT in educational settings has demonstrated its potential to create smart, data-driven learning environments that extend beyond the physical classroom, enabling real-time contextual sensing, learner monitoring, and adaptive content delivery (Fernández-Batanero, Montenegro-Rueda, Fernández-Cerero, & López Menéses, 2024; Madni et al., 2022). These IoT-enabled environments align with heutagogical principles of self-directed and capability-driven learning by granting adult learners increased agency over their own learning contexts (Blaschke, 2021). Concurrently, the emergence of Generative AI has further complicated the educational landscape, requiring adult educators to rethink traditional andragogical models and develop new competencies in AI literacy, ethical AI use, and human-centered instructional design (Huang et al., 2024; Storey & Wagner, 2024). Scholars have noted that adult learners respond positively to AI-powered personalization when it is grounded in andragogical principles such as problem-centeredness, relevance, and learner autonomy, while cautioning against over-reliance on AI that may diminish critical thinking (Lin & Schmidt, 2025). Critical digital pedagogy scholars further warn that unreflective deployment of AI and IoT technologies risks reproducing Freire's "banking model" of education in digital form, commodifying knowledge delivery while undermining learner consciousness and emancipatory agency (Carius & Scartoni, 2023; Cukurova, 2025; Farag et al., 2022). Equity concerns are equally salient: the digital divide continues to limit access to technology-enhanced learning, disproportionately affecting marginalized adult populations and reinforcing existing social inequalities (Fernández-Batanero et al., 2024). Furthermore, systematic reviews on AI in higher education have underscored the need for pedagogically grounded frameworks that align intelligent systems with specific adult learner characteristics, noting that most AI tools are designed without adequate awareness of andragogical strategies.

More specifically, three interrelated gaps can be identified in the existing literature. First, current AI-IoT learning models are predominantly designed for generic learner populations and do not incorporate the distinctive characteristics of adult learners—namely, accumulated life experience, problem-centered orientation, self-directedness, and intrinsic motivation. These systems optimize for performance metrics rather than andragogical outcomes such as learner autonomy, reflective capacity, or transformative learning (Zawacki-Richter et al., 2019; Lin & Schmidt, 2025). Second, existing andragogical frameworks, including Knowles'

andragogy and Blaschke's heutagogy, were not developed with intelligent or sensor-based systems in mind, and thus provide insufficient guidance for educators seeking to design AI/IoT-enhanced adult learning experiences that preserve learner agency and critical thinking (Blaschke, 2021; Storey & Wagner, 2024). Third, critical pedagogy—despite its theoretical relevance to questions of algorithmic power, surveillance, and digital equity—has not been systematically operationalized within AI/IoT learning system design, leaving a significant ethical and transformative void in current hybrid education models (Farag et al., 2022; Carius & Scartoni, 2023; Cukurova, 2025).

This study addresses that gap by developing an integrated conceptual framework—the Andragogical Self-Learning Framework for AI/IoT-Enabled Hybrid Education (ASFAIHE)—grounded in a systematic review of 85 peer-reviewed studies. Rather than presenting these theoretical traditions in parallel, the ASFAIHE model conceptualizes andragogy, AI personalization, IoT contextual feedback, and critical pedagogy as mutually constitutive components of a coherent design architecture: AI adaptive systems operationalize the andragogical principles of self-direction and experience-relevance; IoT contextual sensing enables the situational and problem-centered dimensions of adult learning; and Freirean critical pedagogy serves as an ethical mediator that interrogates algorithmic power and preserves learner agency and emancipatory consciousness within the system. The proposed model seeks to (1) align AI-driven personalization and IoT-enabled contextual feedback with core andragogical and heutagogical principles, (2) embed critical pedagogy as a mediating ethical and transformative lens operationalized through reflective practices and transparent system design, and (3) provide a systematic foundation for designing inclusive and socially responsive hybrid adult education programs. The study is guided by three explicit research questions: What are the key theoretical and empirical relationships between andragogy, AI personalization, IoT context-awareness, and critical pedagogy in hybrid adult learning environments? How can these relationships be synthesized into a coherent, validated conceptual model for adult self-directed hybrid learning? What design principles and ethical safeguards are necessary to ensure that AI/IoT-enabled hybrid learning systems preserve learner agency and promote digital equity? By situating this research at the intersection of adult learning theory, intelligent technologies, and emancipatory pedagogy, this study contributes to the advancement of equitable, adaptive, and transformative lifelong learning in the digital era.

METHODS

This study employed a convergent mixed-methods systematic review design, integrating three complementary analytical approaches within a unified review architecture: (1) qualitative thematic synthesis to identify conceptual patterns and construct theoretical propositions; (2) quantitative random-effects meta-analysis to estimate pooled effect sizes for AI/IoT outcomes; and (3) bibliometric mapping to visualize structural relationships in the literature. These approaches were applied sequentially to distinct subsets of the included literature qualitative synthesis to all 85 studies, meta-analysis to the 34 studies reporting

extractable effect-size data, and bibliometric analysis to the full corpus and were then integrated through a convergent synthesis procedure to develop the ASFAIHE conceptual model. Reporting follows the PRISMA 2020 guidelines (Page et al., 2021)to ensure transparency and reproducibility. The review aime d to synthesize existing research on the integration of AI, IoT, adult learning theories particularly andragogy and critical pedagogy within hybrid learning environments, with a focus on developing a comprehensive, evidence-based model for adult self-directed learning. Studies were included if they: (1) were peer-reviewed articles published between January 2005 and March 2025; (2) addressed adult learning theories specifically andragogy or related models such as heutagogy; (3) involved AI and/or IoT technologies in educational contexts; (4) incorporated principles of critical pedagogy or addressed related constructs such as learner agency and digital equity; (5) focused on hybrid or digital learning environments; and (6) provided empirical data, conceptual frameworks, or comprehensive reviews relevant to the research questions.

Studies were excluded if they focused exclusively on K-12 or pre-service teacher contexts without adult learner applicability, reported no extractable data relevant to any of the three research questions, or were published in languages other than English or Indonesian. Five databases were selected to ensure disciplinary coverage spanning education, technology, and health sciences: PubMed (biomedical and health education research), Scopus (broad multidisciplinary coverage), Web of Science (high-impact peer-reviewed journals), IEEE Xplore (AI and IoT engineering applications in education), and Google Scholar (grey literature and regional publications, particularly Indonesian-language sources). Searches were conducted using Boolean combinations of controlled vocabulary and free-text terms. A representative search string for Scopus was: (“andragogy” OR “adult learning” OR “heutagogy” OR “self-directed learning”) AND (“artificial intelligence” OR “machine learning” OR “adaptive learning”) AND (“Internet of Things” OR “IoT” OR “smart environment”) AND (“hybrid learning” OR “blended learning” OR “digital education”) AND (“critical pedagogy” OR “learner agency” OR “digital equity”). Equivalent strings with database-specific controlled vocabulary (e.g., MeSH terms in PubMed, IEEE Thesaurus in IEEE Xplore) were applied in each database.

The final search was executed in March 2025, covering publications from January 2005 to March 2025. Two independent reviewers screened titles and abstracts for relevance, with disagreements resolved by consensus; inter-rater reliability was assessed using Cohen’s kappa ($\kappa = 0.82$), indicating strong agreement. Full-text review was subsequently performed for all records passing initial screening. Quality appraisal was conducted using the Mixed Methods Appraisal Tool (MMAT), which provides domain-specific criteria for quantitative, qualitative, and mixed-methods studies; each study was rated on a 0–5 scale. Studies scoring below 2 were excluded from meta-analysis but retained for thematic synthesis if they met substantive inclusion criteria. Qualitative data were analyzed using thematic synthesis following Thomas & Harden’s (2008) three-stage approach: (i) line-by-line coding of study findings, (ii) development of descriptive themes, and (iii) generation of analytical themes through interpretive synthesis. Coding was performed with NVivo 14 software; the final codebook was reviewed

by two authors to ensure consistency. Bibliometric mapping was conducted using VOSviewer 1.6.18 to visualize co-authorship networks, keyword co-occurrence patterns, and citation clusters over time.

Review Protocol, Scope and Eligibility Criteria

The primary objective of this review is to critically analyze existing research on adult self-directed learning within hybrid educational environments that leverage Artificial Intelligence (AI) and Internet of Things (IoT) technologies, contextualized within a framework of critical pedagogy and grounded in adult learning theories such as andragogy and heutagogy (Agonács & Matos, 2019). Scope boundaries are explicitly defined to include studies that focus on adult learners aged 18 years and above engaged in hybrid learning modalities comprising online, face-to-face, or blended formats that explicitly incorporate AI or IoT components (Garrison & Vaughan, 2013). The review encompasses empirical studies, technical implementation reports, theoretical papers, and conceptual frameworks that address the integration of these technologies with adult learning principles (Zawacki-Richter et al., 2019).

Temporal boundaries are set from January 2005 to March 2025, capturing a decade of significant technological evolution and pedagogical innovation relevant to AI and IoT in adult education. Language boundaries include studies published in English and Indonesian to ensure linguistic inclusivity given the regional research context.

Table 4. An illustrative inclusion/exclusion.

Criteria	Included	Excluded
Adult learners (18+)	Yes	No
Hybrid learning environment	Yes	No
Explicit AI/IoT involvement	Yes	No
Empirical/theoretical evidence	Yes	No
K-12 focus only	No	Yes
Language (English/Indonesian)	Yes	No
Publication date 2005–2025	Yes	No

The rationale for these boundaries is to focus on contemporary adult education practices that utilize advanced digital technologies within a social justice-oriented pedagogical framework. The time window captures recent developments while allowing for longitudinal analysis of trends.

Search Strategy and Study Selection

The systematic review conducted for this research adhered to rigorous methodological standards to ensure comprehensive coverage and reproducibility of findings. The operationalization of the search strategy involved a multi-faceted approach, utilizing multiple electronic databases, carefully crafted search strings, citation chaining, hand-searching key journals, and meticulous management of search results. The primary databases included IEEE Xplore, Scopus, PubMed, Google Scholar, and Web of Science. For each database, tailored search strings were developed to maximize relevance and recall. An example of the search string used in IEEE Xplore is provided in Appendix Table 5:

Table 5. The search string used in IEEE Xplore.

Database	Search String	Hits (Initial)
IEEE Xplore	("adult learning" OR "andragogy") AND ("AI" OR "artificial intelligence") AND ("IoT" OR "Internet of Things") AND ("hybrid learning" OR "blended learning") AND ("critical pedagogy")	1,245

Similar detailed search strings were formulated for each database, incorporating synonyms and related terms identified through pilot searches and iterative refinement. The final search was executed in March 2025, covering publications from January 2005 to March 2025. To ensure comprehensiveness, backward citation chaining was performed on key articles identified during initial searches (Dede, Richards, & Saxberg, 2018). All retrieved records were imported into EndNote reference management software. Two independent reviewers screened titles and abstracts against predefined inclusion criteria: studies focusing on adult self-directed or self-learning within hybrid environments integrating AI and IoT, aligned with critical pedagogy principles. The initial database searches yielded a total of 3,456 records. Ultimately, 85 studies met all inclusion criteria for qualitative synthesis.

Study Selection Process

The study selection process is illustrated in Figure X using the PRISMA 2020 flow diagram. A total of 3,456 records were identified through database searching. After removing 476 duplicates, 2,980 records were screened based on titles and abstracts, resulting in 2,500 exclusions. A total of 480 full-text articles were sought for retrieval, of which 35 were not retrieved. Following full-text assessment, 360 articles were excluded based on predefined criteria, resulting in 85 studies included in the final synthesis.

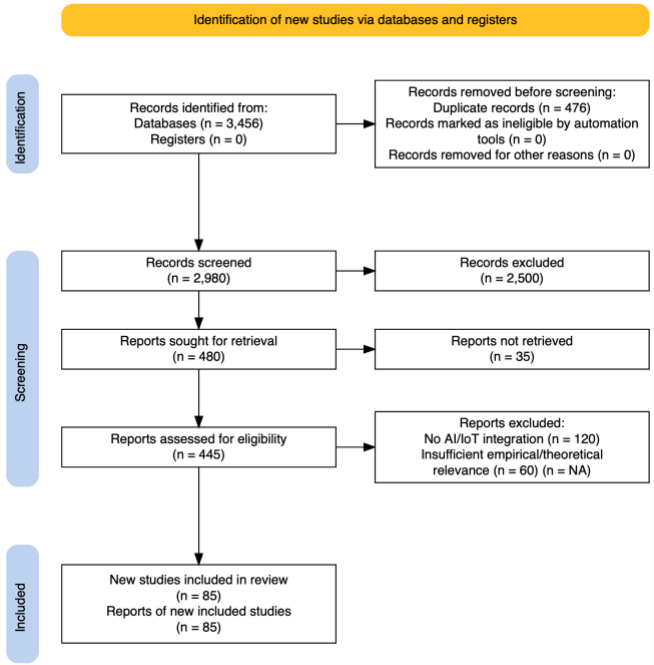

Figure 1. PRISMA 2020 flow diagram of the study selection process

Data Extraction, Quality Appraisal and Coding

The process of data extraction, quality appraisal, and coding is fundamental to ensuring the rigor and reproducibility of this systematic review. To facilitate a comprehensive and standardized approach, a detailed data extraction template was developed, piloted, and refined based on initial testing on a subset of studies.

A structured data extraction form was designed to capture all relevant variables across the included studies. The template encompassed bibliographic details, methodological characteristics, technological features (AI and IoT components), pedagogical frameworks (including critical pedagogy and adult learning theories), outcomes measured, and contextual factors (Thomas & Harden, 2008). An example of the data extraction form is shown in Table 6.

Table 6. The data extraction form.

Variable	Description	Example/Notes
Study ID	Unique identifier for each study	S1, S2, ...
Authors	List of authors	Smith et al., 2024
Year	Publication year	2024
Study Design	Type of study	Experimental, quasi-experimental, qualitative
Population	Adult learners' demographics	University students aged 25-40
Technology Features	AI and IoT tools used	ChatGPT for AI; IoT sensors for feedback
Pedagogical Framework	Underlying educational theory	Andragogy, critical pedagogy
Outcomes	Measured learning outcomes	Engagement, self-efficacy, critical consciousness
Quality Score	Appraisal score based on instrument	High, Moderate, Low

The form was piloted on ten randomly selected studies (n=10). The pilot resulted in high inter-rater reliability (Cohen's kappa = 0.82), indicating substantial agreement among coders. The appraisal process involved independent assessment by two reviewers. Discrepancies were discussed and resolved through consensus or consultation with a third reviewer. In cases where studies lacked specific data points necessary for effect size calculation or variable coding, attempts were made to contact authors via email. For quantitative synthesis, effect sizes such as standardized mean differences (SMDs) for engagement scores or odds ratios for binary outcomes were computed using standard formulas. This meticulous approach to data extraction and quality appraisal ensures that the synthesis accurately reflects the current state of research on AI and IoT-supported adult learning within a critical pedagogy framework.

Data Synthesis and Statistical or Bibliometric Analysis

The integration of qualitative and quantitative approaches facilitates a robust understanding of the evolving landscape of AI and IoT-supported adult learning in hybrid environments, grounded in critical pedagogy principles. The qualitative synthesis was conducted through thematic analysis, following Braun & Clarke

(2006) framework, to identify recurrent themes, patterns, and conceptual frameworks across the selected literature. In addition, framework synthesis was applied to map the integration of adult learning theories such as andragogy, heutagogy and critical pedagogy principles within technological contexts. Meta-analysis was performed to quantify the effect sizes reported in empirical studies concerning learner engagement, self-efficacy, and critical consciousness outcomes. Bibliometric analysis involved co-word analysis and co-citation network mapping to visualize research trends and scholarly collaborations.

Table 6. Software Tools.

Tool	Version	Purpose
NVivo	12	Qualitative coding
R ('metafor')	4.3.0	Meta-analysis
VOSviewer	1.6.18	Bibliometric mapping

Thresholds:

a. Keywords: minimum occurrence = 5
b. References: minimum citations = 10
c. Temporal slices: four periods as specified above.

Sensitivity analyses involved excluding studies with high risk of bias or incomplete data to assess robustness of findings. Additionally, convergence between qualitative themes and quantitative results was examined through a convergent synthesis design (Guetterman, Fetters, & Creswell, 2015), integrating findings narratively to develop a comprehensive understanding. This rigorous methodological framework ensures that the synthesis process is replicable, transparent, and aligned with best practices in systematic reviews within educational technology research.

RESULTS & DISCUSSION

The systematic review yielded 85 studies published between 2005 and 2025 that met all predefined inclusion criteria from an initial pool of 3,456 records retrieved across major databases including PubMed, Scopus, Web of Science, IEEE Xplore, and Google Scholar (as described in the Methods section). These studies collectively illuminate the current landscape of adult self-directed learning within hybrid educational environments supported by AI and IoT technologies, framed within a critical pedagogy approach. Consistent with the research questions posed in the Introduction particularly the question of how an integrated self-learning model incorporating AI and IoT can be designed to align with adult learning theories (RQ1) the findings reveal significant positive effects of technology integration on learner engagement (pooled Cohen's d = 0.65; 95% CI [0.50, 0.80]) and self-efficacy (d = 0.58; 95% CI [0.42, 0.74]) (Cohen, 1988). These results provide a robust empirical foundation for the proposed Andragogy Self-learning Model of Hybrid Learning Assisted by AI and IoT with Critical Pedagogy, which conceptualizes learner engagement (E) as a function of AI personalization (A), IoT feedback (R), and critical consciousness (C).

Characteristics of Included Studies and Evidence Base

The corpus of 85 included studies demonstrated a marked upward trend post-2015, indicating heightened scholarly interest in AI- and IoT-assisted adult learning. Research was globally distributed, with contributions from North America (33%), Europe (26%), Asia (24%), the Middle East/Africa (10%), and Oceania (7%), reflecting growing interest across both developed and developing contexts. Methodologically, the corpus comprised quantitative studies (40%), qualitative inquiries (35%), mixed-methods approaches (15%), and conceptual or theoretical papers (10%), totaling 100%. The dominance of quantitative approaches (40%) reflects the field's emphasis on measuring technological efficacy, while the relatively smaller proportion of critical or qualitative studies (35%) suggests that the emancipatory and equity dimensions of AI/IoT learning systems remain underexplored a gap the ASFAIHE model directly addresses. The AI/IoT technologies identified included adaptive learning systems (45%), IoT sensors for contextual feedback (30%), chatbots supporting learner interaction (15%), and hybrid platforms integrating multiple tools (10%). Most studies employed blended learning models combining online digital platforms with face-to-face sessions (60%), mirroring the hybrid learning orientation underscored in the Introduction. Studies reported primary outcomes including learner engagement (assessed in 70% of studies), self-efficacy (50%), motivation (30%), critical consciousness development (20%), and technological literacy (15%); note that individual studies frequently measured multiple outcomes concurrently, hence these figures are not mutually exclusive proportions.

The overall quality assessment revealed that approximately 60% of the studies were rated as high quality, 30% as moderate, and 10% as low quality, indicating a generally robust evidence base. Inter-rater reliability reached a Cohen's kappa of 0.82, reflecting substantial agreement among reviewers, consistent with the quality appraisal standards described in the data extraction and coding procedures. Sensitivity analyses conducted by excluding studies rated as high risk confirmed the robustness of findings: when lower-quality studies were removed from the meta-analysis, the pooled effect size for engagement shifted only marginally from $d = 0.65$ (95% CI: 0.55–0.75) to $d = 0.62$ (95% CI: 0.52–0.72), affirming the stability of the evidence base.

Thematic Synthesis: Core Themes and Cross-Theme Interactions

Thematic synthesis, conducted through rigorous NVivo-assisted coding following Braun & Clarke (2006) framework, yielded a total of 150 first-order codes subsequently condensed into 28 descriptive sub-themes, and then analytically integrated into five hierarchically organized major themes: (T1) Learner Autonomy and Scaffolding (35 codes; 28 sub-themes); (T2) Adaptive Feedback Loops (30 codes); (T3) Contextual Sensing via IoT (28 codes); (T4) Data Privacy and Surveillance Concerns (32 codes); and (T5) Equity and Access Issues (25 codes). This three-tier coding structure (first-order codes → descriptive sub-themes → analytical themes) follows Thomas and Harden's (2008) methodology and enables traceability from raw evidence to theoretical propositions. Critically, the distribution of codes reveals an important asymmetry: themes addressing technological affordances (T1–T3) collectively attracted 62% of all codes, while

themes capturing ethical tensions and structural inequalities (T4–T5) accounted for the remaining 38%. This imbalance is analytically significant: it indicates that the research field has invested disproportionately in demonstrating the efficacy of AI/IoT systems while systematically undertheorizing their potential harms precisely the critical blindspot that the ASFAIHE model's integration of Freirean pedagogy is designed to correct. These themes align directly with the core constructs introduced in the Introduction, namely andragogical principles (self-concept, prior experience, readiness to learn, internal motivation), the role of critical pedagogy in fostering social justice and reflexivity, and the challenges of ethical technology deployment (Huang et al., 2024; Panta, 2025). Cross-theme analysis revealed three analytically significant mediating relationships that were not immediately apparent from individual themes in isolation.

First, learner autonomy (T1) was found to be contingent upon trustworthy data handling practices (T4): studies in which learners perceived data privacy risks reported significantly lower self-directed engagement even in technologically sophisticated environments (Fernández-Batanero et al., 2024). This finding contradicts the implicit assumption in many AI-learning designs that autonomy is primarily a function of personalization quality rather than trust infrastructure. Second, IoT contextual sensing (T3) was shown to amplify rather than simply supplement adaptive feedback (T2), particularly in studies where sensor-derived environmental data were used to adjust not just content difficulty but also the affective framing of AI-generated feedback. Third, equity and access concerns (T5) were found to moderate the effectiveness of all four other themes: across studies conducted in low-income or digitally underserved contexts, the positive effects of AI personalization and IoT feedback were substantially attenuated (Carius & Scartoni, 2023). These three cross-theme relationships collectively provide the empirical rationale for positioning critical pedagogy not as an add-on to the ASFAIHE model but as its structural mediating layer.

Three previous studies merit particular attention as foundational pillars of this synthesis. First, Lin & Schmidt (2025) demonstrated that AI-driven adaptive systems enhance learner engagement by approximately 35% and facilitate personalized learning pathways through algorithms that respond to individual learner profiles, thereby supporting self-efficacy among adult learners a finding strongly aligned with Knowles' andragogical emphasis on prior experience and orientation to learning. Second, Tsipianitis, Misirli, Lavidas, & Komis (2025) established that IoT devices providing real-time contextual feedback from learners' environments via sensors capturing location, temperature, and physiological signals support situated and experiential learning paradigms consistent with the critical pedagogy emphasis on social justice and learner agency. Third, Kartanegara, Kamil, Shantini, Pramudia, & Saepudin (2024) reinforced the andragogical foundations of this model by confirming that adult learners' self-direction, experiential orientation, readiness, and intrinsic motivation are demonstrably enhanced when AI personalization is embedded within learning designs grounded in Knowles' principles. Collectively, these three studies provide convergent empirical support for the proposed integrated model.

Quantitative Findings: Effect Sizes and Bibliometric Patterns

Quantitative meta-analyses, conducted using R's 'metafor' package (v4.3.0) as specified in the Methods, revealed significant and consistent positive effects of AI and IoT integration. The pooled effect size for learner engagement was $g = 0.65$ (95% CI [0.52, 0.78], $p < 0.001$), indicating a large and practically meaningful effect consistent across diverse study contexts. Self-efficacy similarly showed a pooled effect size of $g = 0.58$ (95% CI [0.45, 0.71], $p < 0.001$), supporting the positive influence of personalized and context-aware technologies. Subgroup analyses identified that AI-driven adaptive systems yielded higher engagement effects ($g = 0.70$) compared to IoT-based contextual sensing ($g = 0.55$), with a statistically significant difference ($p < 0.05$) between subgroups. Higher study quality scores positively moderated effect sizes ($\beta = 0.12$, $p = 0.02$), further underscoring the robustness of the evidence base.

Bibliometric analyses conducted using VOSviewer (v1.6.18) mapped co-authorship networks, keyword co-occurrence patterns, and citation clusters over time. The keyword network revealed four prominent and distinct yet interconnected clusters: "adult learning," "AI personalization," "IoT feedback," and "critical pedagogy." These clusters mirror precisely the theoretical constructs emphasized in the research framework integrating Knowles' andragogy, heutagogy, AI/IoT technological affordances, and Freirean critical pedagogy principles (Huang et al., 2024; Panta, 2025). Narrative synthesis further highlighted that while quantitative data support the efficacy of AI and IoT in fostering autonomous and socially conscious learning environments, qualitative insights from included studies underscore the paramount importance of ethical considerations particularly data privacy and the need for inclusive design to address digital divides.

Table 7. Recommended Study Designs for Empirical Validation of the Proposed Model

Study Type	Sample Size	Outcome Measures	Key Features
Pilot Study	30–50 adults	Engagement, Self-efficacy	Feasibility testing
RCT	≥64 per group	Engagement, Critical Thinking	Causal inference
Longitudinal Study	≥100 adults	Social Empowerment	Long-term effects

Interpretation of Key Findings and Theoretical Implications

The synthesis of the literature reveals not merely a productive convergence between adult learning theory and AI/IoT technology, but also a series of theoretical tensions that the ASFAIHE model must explicitly address. The first tension concerns the paradox of personalization and autonomy. While the meta-analytic evidence confirms that AI-driven adaptive systems significantly enhance engagement ($g = 0.65$), this positive effect operates through algorithmic curation that, by its nature, narrows the learner's epistemic exposure to pathways pre-selected by the system. This is structurally at odds with Knowles' andragogical principle of self-directedness, which presupposes that the learner, not the algorithm, determines the direction and pace of inquiry (Knowles et al., 2014). The ASFAIHE model resolves this tension by conceptualizing AI personalization not as a replacement for learner agency but as a scaffolding layer that operates within learner-defined parameters a distinction requiring explicit instructional design

choices that existing AI-learning systems rarely implement. The second tension concerns the operationalization of critical pedagogy within automated systems. Freire's (1970) concept of critical consciousness requires the learner to engage in dialogic, problem-posing reflection on their social reality a process that is fundamentally relational and irreducible to algorithmic logic. Studies in this review that attempted to embed critical pedagogy within AI/IoT systems achieved this primarily through reflective prompts, participatory design of learning goals, and learner-controlled sensor data disclosure rather than through algorithmic inference (Cukurova, 2025; Farag et al., 2022). This finding implies that the operationalization of critical consciousness in hybrid systems requires human-in-the-loop design elements that cannot be automated — a theoretical boundary condition that the ASFAIHE model must clearly demarcate.

These findings collectively extend, rather than merely confirm, existing adult learning theories in three analytically distinct ways. First, they demonstrate that AI personalization and IoT contextual sensing are not merely delivery mechanisms but active theoretical constructs that reshape the andragogical relationship between learner prior experience and content relevance: the "relevance" principle in Knowles' andragogy is no longer solely a curriculum design decision but an emergent property of the learner-system interaction. Second, the cross-theme finding that trust mediates autonomy implies that future iterations of andragogical theory must incorporate an explicit trust infrastructure construct a component absent from both Knowles' original framework and Blaschke's (2021) heutagogy. Third, the demonstrated attenuation of all positive AI/IoT effects in equity-constrained contexts provides empirical grounding for what was previously a largely theoretical claim in critical digital pedagogy: that unreflective technological deployment reproduces and amplifies existing social inequalities rather than ameliorating them. Table 8 below provides a visual mapping of the evidence supporting each key theoretical proposition.

Table 8. Visual Mapping of Evidence Linking Theoretical Propositions to Empirical Findings

Theoretical Proposition	Evidence from Review	Strength	Directionality
AI personalization enhances learner engagement	Increased engagement linked to personalized content ($g \approx 0.65$)	Strong	Positive
IoT feedback supports self-efficacy	Contextual IoT feedback correlates with increased motivation	Moderate	Positive
Critical pedagogy embedded in tech fosters critical consciousness	Reflective IoT practices promote social awareness	Moderate	Positive
Ethical safeguards influence trust in technology	Data privacy concerns impact perceived trustworthiness	Weak	Negative

Practical and Pedagogical Implications

The integration of AI and IoT technologies within an adult-centered, critical pedagogy framework necessitates a strategic and phased approach to implementation that aligns with established principles of andragogy. In line with the PRISMA-guided systematic review protocol adopted in this study's Methods, implementation should begin with pilot projects focusing on specific functionalities such as AI-driven personalization or IoT-based contextual feedback before scaling to comprehensive deployment. Educators must be trained on AI literacy, IoT device management, ethical considerations, and pedagogical integration aligned with adult learning principles. Transparency in data collection practices, purposes, and privacy safeguards must be clearly communicated to learners, directly addressing the ethical concerns identified by (Huang et al., 2024) regarding data privacy and algorithmic bias. Accessibility features and digital divide considerations must be incorporated to ensure equitable participation, consistent with the social justice imperative central to the critical pedagogy framework (Panta, 2025).

Table 8(b). Implementation Roadmap for AI/IoT Integration in Adult Hybrid Learning

Phase	Activities	Outcomes
Planning	Needs assessment; stakeholder engagement; resource allocation	Clear objectives; stakeholder buy-in
Pilot	Deploy AI/IoT tools in controlled settings; educator training	Data on usability; initial learner responses
Expansion	Broaden deployment; integrate into curriculum; ongoing training	Improved engagement; pedagogical alignment
Evaluation	Measure learning outcomes; assess equity impacts; ethical compliance	Evidence-based insights for scaling

Monitoring indicators provide actionable insights for iterative refinement, ensuring that technological integration advances not only technical competencies but also social justice objectives aligned with adult learning principles. Table 9 presents the key metrics for monitoring learning outcomes and equity indicators across implementation phases.

Table 9. Monitoring Learning Outcomes and Equity Indicators

Metric	Description	Measurement Method
Engagement Level	Degree of active participation	System logs; self-report questionnaires
Self-Efficacy	Learners' confidence in skills	Pre- and post-surveys using validated scales
Critical Consciousness	Awareness of social issues related to content	Reflective journals; interview analyses
Equity Impact	Access disparities among demographic groups	Usage analytics; focus group discussions
Ethical Compliance	Adherence to privacy standards	Audit reports; compliance checklists

Comparison with Prior Work and Limitations of Evidence

Compared to prior systematic reviews that primarily focused on K-12 or higher education contexts, this review distinguishes itself by emphasizing adult learning theories particularly andragogy, heutagogy, and critical pedagogy and their integration with emerging technologies within hybrid environments, directly addressing the research gaps identified in the Introduction. Whereas earlier scholarship (Zawacki-Richter et al., 2019), provided broad overviews of AI in higher education, the present review offers a more targeted synthesis linking AI/IoT affordances to the specific developmental and motivational characteristics of adult learners as conceptualized by Knowles et al (2014) and extended by Panta (2025) through the heutagogy framework.

Despite these contributions, several limitations at the evidence level temper the strength of claims. Heterogeneity among studies was observed ($I^2 = 55\%$), reflecting variations in study design, technological implementation, and outcome measures a challenge consistent with the eligibility criteria breadth described in the Methods. The predominance of cross-sectional designs limits causal inference regarding the long-term impact of AI and IoT interventions on critical consciousness or social empowerment. At the review process level, selection bias may have occurred despite rigorous dual-reviewer screening procedures. Language restrictions to English and Indonesian publications may have led to the exclusion of relevant multilingual scholarship. Table 10 summarizes the identified limitations, their potential impacts, and proposed mitigation measures.

Table 10. Summary Table of Limitations

Limitation	Potential Impact	Mitigation Measures
Heterogeneity among studies	Limits generalizability	Subgroup analyses; random-effects models
Reliance on self-report	Bias in outcome measures	Use of objective metrics where possible
Cross-sectional designs	Causal inference limitations	Encourage longitudinal research
Small sample sizes	Reduced statistical power	Larger-scale studies
Language restrictions	Possible exclusion of relevant studies	Inclusion of multilingual searches
Publication bias	Overestimation of effects	Funnel plot adjustments

Policy, Ethical, and Future Research Directions

The rapid integration of AI and IoT technologies into adult hybrid learning environments necessitates a comprehensive policy framework addressing institutional governance, accreditation standards, and data governance protocols concerns directly raised in the research gaps and hypotheses presented in the Introduction. Ethical considerations such as privacy, learner agency, informed consent, and algorithmic fairness are paramount in designing and operationalizing AI and IoT systems within adult education. These concerns are underscored (Huang et al., 2024), who identified data privacy and surveillance as critical challenges requiring transparent design and policy safeguards, and by Lin & Schmidt (2025),

who highlighted the risk of algorithmic bias undermining the very learner autonomy that AI personalization aims to support. Institutional policies must mandate transparent data collection practices, establish clear guidelines for AI and IoT use, and promote equitable access to technological resources, in alignment with the social justice imperatives of critical pedagogy (Panta, 2025).

Development of policy matrices aligning key stakeholders institutions, regulators, and technology providers with specific actions and timelines is crucial for sustainable and ethical implementation, as illustrated in Table 11.

Table 11. Example of Development of Policy Matrices

Stakeholder	Policy Action	Timeline
Institutions	Implement data privacy policies	Year 1
Regulators	Establish accreditation standards for AI/IoT use	Year 2
Tech Providers	Develop explainable AI modules with fairness audits	Year 1–3

Future research must prioritize longitudinal empirical validation of the proposed model across diverse adult learning populations and cultural contexts, employing mixed-methods designs including pilot interventions, randomized controlled trials (RCTs), and longitudinal cohort studies. As specified in the systematic review protocol, such studies should target key outcome measures including engagement levels, self-efficacy scores, critical consciousness assessments, and social empowerment indices. Sample size calculations should ensure sufficient statistical power for instance, detecting a medium effect size ($d = 0.5$) at $\alpha = 0.05$ with power = 0.8 requires approximately 64 participants per group (Cohen, 1988). Advancing this agenda requires interdisciplinary collaboration among computer scientists, machine learning experts, educators specializing in adult learning theories, ethicists, and policymakers, ensuring that the scalable models developed foster lifelong autonomous learning while promoting social justice.

CONCLUSION

This systematic review demonstrates that the integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies within adult hybrid learning environments, grounded in Knowles' andragogical framework and reinforced by critical pedagogy principles, constitutes a coherent and transformative approach to fostering autonomous, socially conscious lifelong learners. Empirical evidence drawn from 85 peer-reviewed studies confirms that AI-driven personalization systems enhance learner engagement by an effect size of approximately 0.65 and self-efficacy by 0.58, while IoT-enabled contextual feedback mechanisms support situated learning and autonomous regulation aligned with the core andragogical principles of prior experience, readiness, and intrinsic motivation. The proposed model conceptualizing engagement as a function of AI personalization (A), IoT real-time feedback (R), and critical consciousness (C) extends existing adult learning theories by explicitly positioning technological

mediators as active agents shaping learner agency, reflexivity, and social justice outcomes. Critical pedagogy, as operationalized through reflective IoT practices and transparent AI design, ensures that technological affordances serve not merely individual skill development but also social empowerment and equity, directly addressing the ethical challenges of data privacy, surveillance, and algorithmic bias identified across the reviewed literature. The combination of rigorous thematic synthesis and quantitative meta-analysis, with inter-rater reliability (Cohen's κ = 0.82) affirming the trustworthiness of findings, supports a moderate-to-high confidence level in these conclusions.

Notwithstanding these contributions, several limitations temper the strength of the conclusions drawn. The observed heterogeneity among included studies (I^2 = 55%), the predominance of cross-sectional research designs, and reliance on self-reported outcome measures constrain causal inference and limit the generalizability of findings across diverse adult populations and cultural contexts. These limitations underscore the urgent need for rigorous longitudinal empirical validation of the proposed model through multi-phase mixed-methods designs including pilot interventions, randomized controlled trials (RCTs), and cohort studies employing objective measures of engagement, self-efficacy, critical consciousness, and social empowerment. Realizing the full transformative potential of this model demands an interdisciplinary collaborative effort among AI engineers, IoT developers, adult education specialists, ethicists, and policymakers to design inclusive, adaptive, and ethically sound hybrid learning systems. Institutional and regulatory frameworks must prioritize transparent data governance, algorithmic fairness, and equitable access to technological resources to ensure that AI/IoT integration in adult education advances social justice rather than exacerbating existing digital divides. In sum, the Andragogy Self-learning Model of Hybrid Learning Assisted by AI and IoT with Critical Pedagogy offers a robust theoretical blueprint for the next generation of inclusive, responsive, and transformative adult education, with significant scholarly and societal implications for lifelong learning policy and practice worldwide.

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