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Mobile learning evolution: a decade of developments (2014-2023)

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Abstract. The rapid evolution of mobile technologies has significantly transformed educational landscapes over the past decade. This systematic review examines the development of mobile learning environments from 2014 to 2023, analyzing their conceptual foundations, theoretical frameworks, design principles, implementation strategies, and effectiveness. Building on our earlier taxonomy of learning environments, we propose an expanded framework that accommodates emerging technologies and pedagogical approaches. Through a comprehensive analysis of 97 articles published in peer-reviewed journals, we identify key trends in mobile learning research, including the integration of artificial intelligence, extended reality technologies, and learning analytics. Meta-analytic findings demonstrate moderate to significant positive effects of mobile learning on student outcomes across different educational levels and subject domains. The review further reveals that pedagogical approaches such as project-based learning, collaborative learning, and situated learning significantly enhance the effectiveness of mobile learning environments. We also examine challenges in implementation, including technological barriers, pedagogical integration issues, and concerns about equity and accessibility. The paper concludes with a proposed research agenda and practical guidelines for developing effective, inclusive, and sustainable mobile learning environments in the emerging educational technology landscape.

Keywords: mobile learning, systematic review, theoretical frameworks, effectiveness, emerging technologies, design principles

1. Introduction

The educational landscape has undergone profound transformations in the past decade, driven mainly by the rapid advancement and ubiquitous presence of mobile technologies. Mobile devices have transcended their initial role as communication tools to become powerful educational instruments that can facilitate learning across diverse contexts, unrestricted by traditional spatial and temporal constraints [59]. As Traxler [50] aptly noted, mobile technologies have the potential to fundamentally reshape how we conceptualize and engage with educational content and experiences.

In 2014, we presented a taxonomy of learning environments and explored approaches to developing mobile learning environments, particularly in the context of

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teaching higher mathematics to engineering students [34]. Since then, the field of mobile learning has experienced remarkable growth, characterized by evolving theoretical frameworks, innovative pedagogical approaches, and the integration of emerging technologies such as artificial intelligence, extended reality, and learning analytics. These developments have not only expanded our understanding of mobile learning but also transformed its implementation in educational settings.

The COVID-19 pandemic catalyzed the accelerated adoption of mobile learning across educational levels and contexts [24]. As institutions worldwide rapidly transitioned to remote learning, mobile technologies emerged as essential tools for maintaining educational continuity. This global crisis has prompted researchers and practitioners to reassess the potential of mobile learning and explore novel approaches to overcome persistent challenges.

Building on our previous work, this paper presents a systematic review of developments in mobile learning environments from 2014 to 2023. The following research questions guide the review:

1. How have theoretical frameworks and conceptualizations of mobile learning evolved since 2014?
2. What does recent empirical research reveal about the effectiveness of mobile learning on student outcomes?
3. How are emerging technologies being integrated into mobile learning environments?
4. What design principles and implementation strategies characterize effective mobile learning environments?
5. What challenges persist in implementing mobile learning, and how are they being addressed?
6. What are the emerging trends and future directions in mobile learning research?

2. Methodology

This study employed a systematic review methodology following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure rigour, transparency, and reproducibility. The review process consisted of several stages: defining search parameters, searching electronic databases, screening articles based on inclusion and exclusion criteria, extracting data, and synthesizing findings.

2.1. Search strategy

We conducted a comprehensive search of the literature using Scopus and Web of Science, ERIC, and IEEE Xplore. The search was restricted to articles published between January 2014 and December 2023 to capture developments since our previous work. The following search terms were used in various combinations: “mobile learning”, “m-learning”, and “mobile learning environment”. Additional search terms related to specific aspects of our research questions included “artificial intelligence”, “machine learning”, “virtual reality”, “augmented reality”, “learning analytics”, “educational data mining”, “design principles”, “theoretical framework”, “implementation model”, “effectiveness”, “evaluation”, “challenges”, and “barriers”.

2.2. Inclusion and exclusion criteria

To be included in the review, studies had to meet the following criteria:

- published in peer-reviewed journals or conference proceedings between January 2014 and December 2023;
- written in English;

- focused specifically on mobile learning or mobile learning environments;
- addressed at least one of our research questions;
- presented empirical data, theoretical frameworks, systematic reviews, or meta-analyses.

We excluded articles that were not peer-reviewed, editorials, commentaries, book reviews, or articles that mentioned mobile learning only tangentially without substantive discussion. Studies focusing solely on technical aspects of mobile device development without educational applications were also excluded.

2.3. Screening and selection process

The initial search yielded 2573 articles. After removing duplicates, 1986 articles remained. We then screened titles and abstracts to assess relevance, resulting in 426 potentially eligible articles. A full-text review of these articles led to a final selection of 97 articles that met all inclusion criteria. Figure 1 illustrates the PRISMA flow diagram for the selection process.

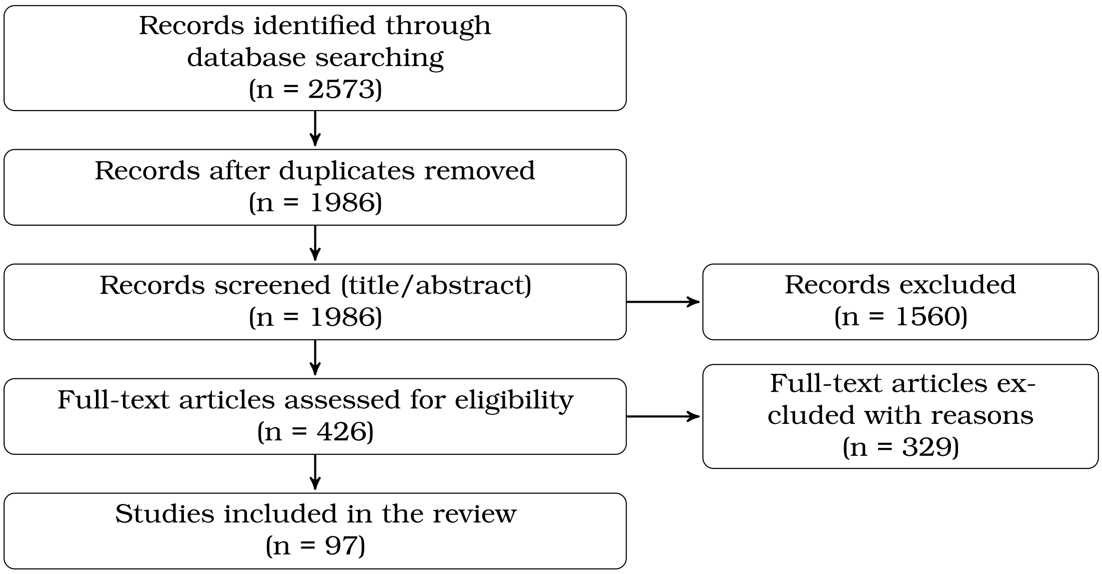

Figure 1: PRISMA flow diagram of the study selection process

2.4. Data extraction and analysis

For each included article, we extracted the following information: bibliographic details, research aims and questions, theoretical framework, methodology, sample characteristics, technologies used, findings, implications, and limitations. Two independent reviewers conducted the data extraction, with a third reviewer resolving any discrepancies.

We performed both quantitative and qualitative analyses of the extracted data. The quantitative analysis involved descriptive statistics on publication trends, methodologies employed, educational contexts, and technologies examined. For articles reporting effect sizes, we recorded this information to identify patterns across studies. Qualitative analysis involved thematic synthesis to identify recurring themes, emerging trends, and conceptual developments in the field.

For meta-analytic findings, we relied on published meta-analyses identified in our search, which provided weighted effect sizes for the impact of mobile learning on various outcomes. This approach allowed us to present robust evidence on the effectiveness of mobile learning while avoiding duplication of existing meta-analytic work.

3. Evolution of mobile learning conceptualizations

The conceptualization of mobile learning has undergone significant evolution since our initial taxonomy in 2014 (figure 2). This section examines this evolution, highlighting shifts in definitions, theoretical frameworks, and taxonomic approaches.

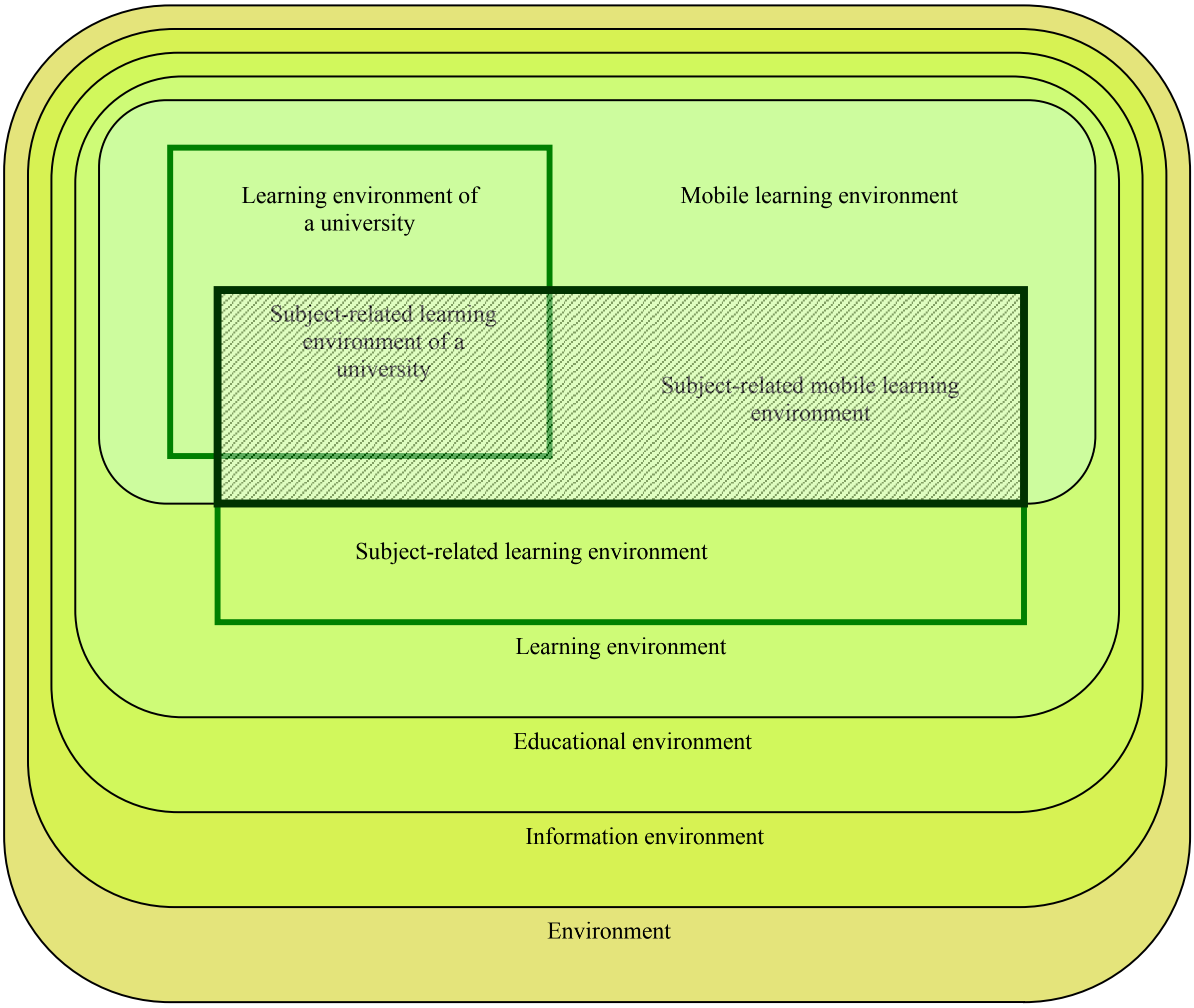

Figure 2: Taxonomy of environments [34].

3.1. Changing definitions of mobile learning

Early definitions of mobile learning typically emphasized the technological aspects, focusing on the mobility of devices rather than the learning experience. As Grant [22] notes, mobile learning was often defined simply as "learning through mobile computational devices". However, recent definitions have shifted towards a more holistic understanding that emphasizes pedagogical aspects and learner experiences.

Wishart [59] provides a representative contemporary definition that has gained significant traction: "Mobile learning is learning across multiple contexts, through social and content interactions, using personal electronic devices". This definition acknowledges the contextual nature of mobile learning and recognizes that it involves more than just technology use.

Another notable shift has been the increased emphasis on ubiquity and seamlessness in mobile learning definitions. Milrad [38] characterizes mobile learning as learning that "occurs across multiple contexts, among people and interactive technologies". This conception underscores that mobile learning transcends traditional boundaries of formal and informal learning settings.

Table 1 presents the evolution of mobile learning definitions over the past decade, illustrating the progressive shift from technology-centered to pedagogy-centered and context-aware conceptualizations.

Table 1
Evolution of mobile learning definitions (2014-2023).

Period	Primary focus	Representative definitions
2014-2016	Technology-centered definitions	"Learning through mobile devices such as smartphones, tablets, or laptops" [26] "E-learning through mobile devices, anywhere, anytime" [61]
2017-2019	Pedagogical process-centred definitions	"A form of e-learning that specifically employs wireless communication devices to deliver content and learning support" [33] "Learning that occurs across multiple contexts, among people and interactive technologies" [38]
2020-2023	Context-aware, experience-centered definitions	"A learning approach that leverages mobile devices to enable learning across contexts through social and content interactions" [21] "The integration of mobile technology into learning experiences to support authentic, situated, and personalized learning across formal and informal contexts" [43]

3.2. Theoretical frameworks in mobile learning

The theoretical underpinnings of mobile learning research have also evolved considerably. While early work often lacked explicit theoretical foundations, recent research has increasingly grounded mobile learning in established learning theories and developed specialized theoretical frameworks.

Parsons et al. [43] conducted a systematic review of mobile learning frameworks published between 2011 and 2022, identifying several key pedagogical approaches and underlying theories of learning. Their analysis revealed that social constructivism, heutagogy, collaborative learning, experiential learning, inquiry-based learning, and student-centred learning were the most frequently mentioned theoretical frameworks in mobile learning research.

The integration of established learning theories with mobile learning has become increasingly sophisticated. For instance, social constructivism has been particularly influential in mobile learning research, emphasizing the social nature of knowledge construction through interactions with peers, instructors, and content [31]. Similarly, connectivist principles have been applied to understand how mobile learning facilitates connections between learners, content, and resources across digital networks [56].

Several specialized frameworks have explicitly emerged for mobile learning. The FRAME (Framework for the Rational Analysis of Mobile Education) model, developed by Koole and Ally [32], conceptualizes mobile learning as occurring at the intersection of device aspects, learner aspects, and social aspects. This model has been widely cited and applied in mobile learning research.

Another influential framework is the Mobile Pedagogy Framework proposed by Tlili et al. [48], which identifies four dimensions of mobile learning pedagogy: technological affordances, learning design, pedagogical approaches, and contextual factors. This framework provides a comprehensive approach to understanding and designing mobile learning experiences.

The SAMR (Substitution, Augmentation, Modification, Redefinition) model has also been applied to understand how mobile technologies transform learning experiences. Tlili et al. [48] found that "redefinition" was the most frequently used pedagogical functionality of technology in mobile learning, indicating that mobile technologies are increasingly being used to create learning experiences that would not be possible without the technology.

3.3. Expanded taxonomy of learning environments

Building on our original taxonomy of learning environments [34], we propose an expanded taxonomy that reflects contemporary developments in the field. This expanded taxonomy acknowledges the increased complexity and diversity of learning environments in the digital age, as illustrated in figure 3.

Figure 3: Expanded taxonomy of contemporary learning environments.

Within mobile learning environments, we further distinguish three subcategories that reflect the evolution of the field:

1. *Device-centric mobile learning* focuses on the use of mobile devices for learning, emphasizing the portability and accessibility of educational content through smartphones, tablets, and other mobile devices.

2. *Context-aware mobile learning* emphasizes the role of context in shaping mobile learning experiences, leveraging location-based services, sensors, and contextual data to provide personalized and situated learning experiences.
3. *AI-enhanced mobile learning* integrates artificial intelligence technologies such as machine learning, natural language processing, and intelligent tutoring systems to create adaptive, personalized, and intelligent mobile learning environments.

This expanded taxonomy acknowledges the increasing complexity and sophistication of mobile learning environments, reflecting both technological advancements and pedagogical innovations in the field.

4. Effectiveness of mobile learning: evidence from meta-analyses

Recent meta-analyses provide robust evidence of the effectiveness of mobile learning across different educational contexts, subject domains, and learner groups. This section synthesizes findings from key meta-analytic studies published between 2020 and 2023.

4.1. Overall effectiveness

Multiple meta-analyses consistently report positive effects of mobile learning on student outcomes. Dong et al. [15] conducted a meta-analysis of 57 effect sizes from 44 studies on mobile learning in science education, finding a large overall effect size (g = 0.857) on students' science achievement. Similarly, Tlili et al. [49] analyzed 70 quantitative studies and reported a large effect (g = 0.93) of pedagogical approaches in mobile learning on students' learning performance.

In mathematics education, Güler et al. [23] found a medium-level positive effect (g = 0.476) of mobile learning on students' mathematics achievement based on 22 studies. For undergraduate students, Bazhenova et al. [11] reported a moderate effect size (d = 0.52) of mobile-based interventions on learning performance.

A second-order meta-analysis by Yang and Xiang [60] synthesizing 22 meta-analyses on mobile learning reported a positive overall effect (g = 0.665) on students' academic achievement compared to traditional learning. This finding is particularly significant as it represents a higher-level synthesis of existing meta-analytic evidence.

Table 2 summarizes the effect sizes reported in recent meta-analyses of mobile learning effectiveness.

Table 2
Effect sizes reported in recent meta-analyses of mobile learning.

Study	Effect size	Number of studies	Context
Dong et al. [15]	g = 0.857	44	Science education in K-12
Tlili et al. [49]	g = 0.93	70	Various educational contexts
Güler et al. [23]	g = 0.476	22	Mathematics education
Bazhenova et al. [11]	d = 0.52	12	Undergraduate education
Yang and Xiang [60]	g = 0.665	22 meta-analyses	Second-order meta-analysis
Zheng et al. [65]	d = 0.91	34	Inquiry-based mobile learning
Wang et al. [55]	g = 0.52	85	Primary and secondary education
Abdullah et al. [1]	g = 0.73	36	Physics education

4.2. Moderating factors

Meta-analyses have identified several factors that moderate the effectiveness of mobile learning. Dong et al. [15] found that the pedagogical approach significantly moderated the effect of mobile learning on science achievement, with inquiry-based and game-based approaches showing larger effects than other approaches. They also found that the subject area within science education moderated the effects, with biology showing larger effects than physics and chemistry.

Tlili et al. [49] reported that project-based learning had the largest effect on learning outcomes (g = 1.78), followed by collaborative learning (g = 1.10), situated learning (g = 0.95), and game-based learning (g = 0.87). They also found that the effect was moderated by the field of education, level of education, learning setting, and mobile device type.

In their analysis of mobile learning in mathematics, Güler et al. [23] found that content area was a significant moderator, while grade level and implementer were not. Wang et al. [55] identified several moderating variables in their meta-analysis, including community type, students' socioeconomic status, the hardware used, student-to-hardware ratio, and teaching method.

Figure 4 illustrates the effect sizes of different pedagogical approaches in mobile learning based on the meta-analysis by Tlili et al. [49].

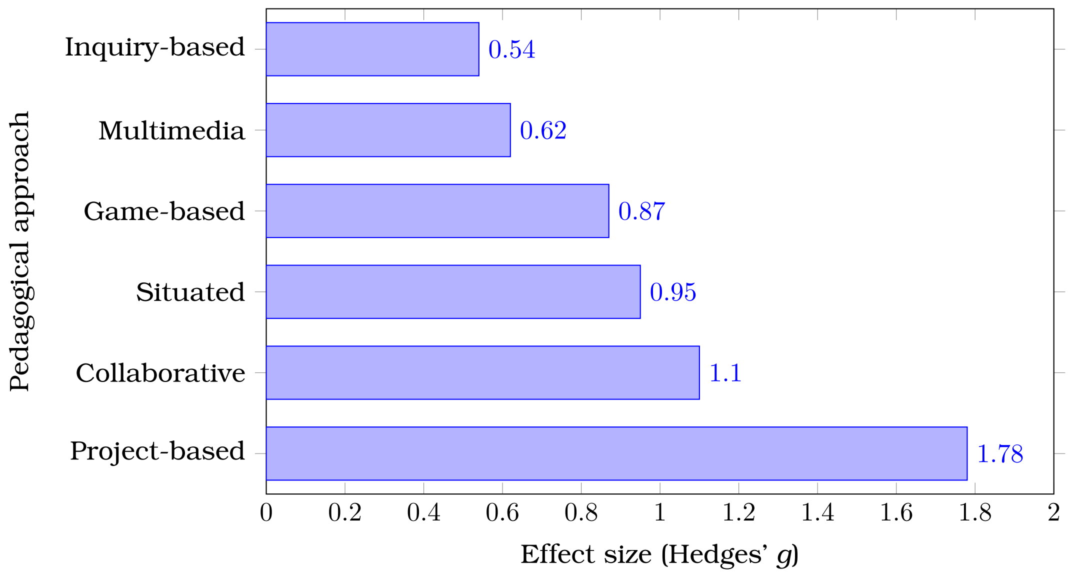

Figure 4: Effect sizes of different pedagogical approaches in mobile learning.

4.3. Domain-specific effectiveness

Meta-analyses have also examined the effectiveness of mobile learning in specific subject domains. In science education, Dong et al. [15] found that mobile learning had a larger effect on biology (g = 1.06) compared to earth and space sciences (g = 0.89), chemistry (g = 0.77), and physics (g = 0.62). Abdullah et al. [1] reported a significant positive effect of mobile learning on student achievement in physics (g = 0.73).

For language learning, Garzón, Lampropoulos and Burgos [20] conducted a meta-analysis of mobile English learning, finding a large effect on students' achievement. The effect was influenced by the pedagogical approach, education level, and control treatment, but not by the learning environment or mobile device.

In mathematics education, Güler et al. [23] found a medium-level positive effect (g = 0.476) of mobile learning on students' mathematics achievement. The effectiveness varied by content area, with some topics showing stronger effects than others.

These domain-specific findings suggest that mobile learning may be particularly effective for certain subjects or topics, potentially due to the alignment between mobile technologies' affordances and the learning requirements of those domains.

5. Integration of emerging technologies in mobile learning

The past decade has witnessed significant advancements in integrating emerging technologies into mobile learning environments. This section examines how artificial intelligence, extended reality, and learning analytics are being incorporated into mobile learning research and practice.

5.1. Artificial intelligence and machine learning

Artificial intelligence (AI) and machine learning (ML) have emerged as powerful tools for enhancing mobile learning experiences. Baba et al. [9] describe an AI-driven personalized educational platform designed for mobile devices that allows instructors to upload information and enables learners to interact with an AI mentor through a chat interface. Their study found that the AI-enhanced mobile learning system significantly improved student engagement, understanding, and academic achievement.

Avanija et al. [7] highlight how intelligent mobile assistants using machine learning are creating new forms of communication in mobile learning. These assistants provide personalized recommendations and adaptive interfaces, enhancing the learning experience by tailoring content and interactions to individual learner needs and preferences.

The integration of AI in mobile learning typically serves several key functions:

1. *Personalization* – AI algorithms analyze learner data to deliver personalized content, recommendations, and learning pathways tailored to individual needs, preferences, and performance.
2. *Intelligent tutoring* – AI-powered tutoring systems provide real-time feedback, guidance, and support to learners, mimicking the role of a human tutor.
3. *Adaptive assessment* – AI enables the development of adaptive assessments that adjust difficulty levels and question types based on learner responses, providing more accurate and informative evaluations.
4. *Natural language processing* – AI-powered chatbots and virtual assistants facilitate natural language interactions, allowing learners to ask questions, seek clarification, and engage in dialogue.

Moya and Camacho [41] propose a framework for AI-powered mobile learning that emphasizes the importance of pedagogically sound integration of AI into mobile learning environments. Their framework addresses key considerations for designing effective AI-enhanced mobile learning experiences, including ethical considerations, transparency, and learner agency.

5.2. Extended reality: AR and VR in mobile learning

Augmented reality (AR) and virtual reality (VR) technologies have been increasingly integrated into mobile learning environments to create immersive and interactive learning experiences. Yen et al. [62] present a conceptual framework for VR/AR applications in mobile learning environments, highlighting how these technologies support portability, accessibility, flexibility, and contextualization of learning experiences.

Sural [46] examines mobile augmented reality applications in education, noting that AR can provide rich contextual learning for individuals. The study identifies various educational applications of mobile AR, including visualization of complex concepts, simulation of real-world experiences, and enhancement of engagement and motivation.

Recent research on AR in mobile learning has focused on specific educational domains. Kanimozhi and Sairamesh [30] describe an interactive learning environment for networking topics based on augmented reality, finding that AR technology enhances comprehension, stimulates motivation, and generates student interest in learning computer networking concepts.

Yusuf et al. [64] review mobile augmented reality in education, highlighting its potential for providing positive, effective, and powerful learning experiences. They identify various software development kits and user interface considerations for developing effective mobile AR applications for educational purposes.

Table 3 summarizes key applications and benefits of AR and VR in mobile learning environments based on recent research.

Table 3
Applications and benefits of AR and VR in mobile learning.

Technology	Educational applications	Benefits
Mobile augmented reality (MAR)	visualization of abstract concepts; interactive simulations; contextual information overlay; virtual laboratory experiments	Enhanced spatial understanding; increased engagement; contextualized learning; visualization of invisible phenomena
Mobile virtual reality (MVR)	Immersive learning environments; virtual field trips; simulation of dangerous or inaccessible environments; role-playing scenarios	Full immersion; enhanced presence; emotional engagement; safe experimentation; perspective-taking
Mixed reality (MR)	Collaborative problem-solving; complex systems modeling; training for procedural tasks; interactive storytelling	Blending physical and virtual elements; collaborative interaction; real-time feedback; spatial awareness

5.3. Learning analytics and educational data mining

Learning analytics and educational data mining have emerged as valuable approaches for understanding and optimizing mobile learning processes. Fulantelli, Taibi and Arrigo [18] propose a task-interaction framework to support educational decision-making in mobile learning based on learning analytics. Their framework analyzes the relationships between different types of interactions in mobile learning activities and pedagogically relevant tasks.

Ahmed [2] developed a framework for learning analytics in smartphone-based blended learning environments, highlighting how analytics can help predict learner performance, identify learning difficulties, and provide meaningful feedback. The four-stage framework guides the setup and improvement of learning analytics workflows in mobile learning contexts.

Aljohani and Davis [4] emphasize that learning analytics in mobile learning can enhance the learning experience by analyzing learner data to improve personalization, engagement, and effectiveness. They propose a Mobile and Ubiquitous Learning Analytics Model (MULAM) for analyzing mobile learners' data based on a five-step model of learning analytics.

Dhankhar and Solanki [14] compare different educational data mining and learning analytics techniques applied in mobile learning, identifying their potential strengths and weaknesses for predicting student performance. The study highlights how these techniques can interpret large datasets from mobile learning environments to optimize learning and teaching strategies.

A framework for implementing learning analytics and educational data mining in traditional learning environments is proposed by Vaidya and Saini [52], emphasizing the role of analytics in predicting learner performance and identifying potential issues.

Although focused on traditional learning environments, many of the principles and approaches can be adapted for mobile learning contexts.

6. Design principles and implementation strategies

Effective design and implementation of mobile learning environments require careful consideration of pedagogical, technological, and contextual factors. This section examines key design principles and implementation strategies identified in recent literature.

6.1. Design principles for mobile learning environments

Several studies have proposed design principles and guidelines for creating effective mobile learning environments. Harpur and de Villiers [26] synthesized a comprehensive set of guidelines for designing and developing mobile learning environments in tertiary education based on empirical research. Their guidelines emphasize user-centered design, iterative evaluation, and alignment with pedagogical objectives.

Harpur and de Villiers [27] identified the following key design principles for mobile learning environments:

1. *User-centered design* – focus on the needs, preferences, and behaviours of learners to ensure usability and engagement.
2. *Contextual relevance* – design for the contexts in which mobile learning will occur, considering physical, social, and cultural factors.
3. *Pedagogical alignment* – ensure that mobile learning activities align with sound pedagogical principles and learning objectives.
4. *Seamless integration* – design for seamless transitions between different learning contexts, devices, and activities.
5. *Accessibility and inclusivity* – ensure that mobile learning environments are accessible to diverse learners, including those with disabilities.

Aziz and Khoukhi [8] proposed a design requirements framework for mobile learning environments that emphasizes five perspectives: generic mobile environment, mobile learning context, learning experience, social learning strategy, and learning objectives. Their framework guides developing mobile learning applications that meet learner needs and educational goals.

For specialized contexts, Ariffin and Dyson [6] identified principles for designing culturally appropriate mobile learning applications, highlighting the importance of local cultural content, aesthetic values, language, and philosophical values in design decisions.

6.2. Implementation models and strategies

Implementation of mobile learning requires thoughtful strategies and models that address institutional, pedagogical, and technological considerations. Moya and Camacho [39] investigated factors affecting the effectiveness of mobile learning implementation, identifying five key dimensions: technological resources, digital literacy, pedagogical factors, behaviour and attitudes, and leadership. Their findings highlight the importance of a holistic approach to implementation that addresses all these dimensions.

Popov, Jiang and So [44] conducted an international Delphi study to identify challenges and solutions for implementing mobile learning across K-12 education, higher education, and industry. They identified four major challenge themes: risk-taking (attitudes toward experimentation), matching technology to use (using technology in pedagogically sound ways), know-how (resources for information), and infrastructure (supporting structures and systems).

Several implementation models have been proposed for specific contexts. Duarte Filho and Barbosa [16] developed a service-oriented reference architecture for mobile learning environments (Ref-mLearning) that contributes to the development, reuse, and interoperability of mobile learning systems. Their architecture aims to increase quality and reduce costs during development through the use of service-oriented architecture principles.

Hamid et al. [25] describe a successful implementation of mobile learning during the COVID-19 pandemic, highlighting the role of academic leadership in facilitating the transition from traditional to online mode of education. Their case study demonstrates how the Active Implementation Frameworks (AIFs) enabled a public-sector women's university to overcome challenges and maintain educational continuity during the pandemic.

Table 4 presents a comparison of different implementation models for mobile learning based on recent literature.

Table 4
Comparison of mobile learning implementation models.

Model	Key components	Focus areas	Contexts
Active implementation frameworks (AIFs)	Implementation teams; implementation drivers; implementation stages	Organizational change; capacity building; sustainability	Higher education during crisis
Service-oriented reference architecture	Modular services; interoperability standards; reusable components	Technical infrastructure; system integration; scalability	Mobile learning systems development
Mobile technology capacity building framework	Agency development; activity-centered design; technology-practice integration	Professional development; workplace learning; capacity building	Workplace learning
FRAME model	Device aspects; learner aspects; social aspects	User experience; technological affordances; social interaction	Cross-context implementation

6.3. Evaluation frameworks for mobile learning

Evaluating the quality and effectiveness of mobile learning environments is essential for continuous improvement and evidence-based decision-making. Recent literature has proposed several evaluation frameworks to guide this process.

Vavoula and Sharples [53] proposed a three-level framework for evaluating mobile learning comprising a micro level concerned with usability, a meso level concerned with the learning experience, and a macro level concerned with integration within existing educational and organizational contexts. Their framework addresses six challenges in evaluating mobile learning: capturing learning across contexts, measuring processes and outcomes, respecting privacy, assessing technology utility and usability, considering organizational context, and assessing formality and informality.

Wei and So [57] developed a holistic evaluation framework for contextual mobile learning with three levels: external (social, cultural, and technical factors), intermedium (content, context, and device), and internal (learner attitudes and experiences). Their analysis of empirical studies revealed that most evaluations focused on the intermedium and internal levels, with limited attention to external factors.

Baloh et al. [10] proposed a quality evaluation framework for mobile learning applications that examines specific quality criteria based on the mentor-learner model of study. They evaluated this framework with respect to given quality criteria on 21 mobile learning applications using correlation analysis to discover relationships between evaluated attributes.

Soad, Duarte Filho and Barbosa [45] established a method for evaluating the quality of mobile learning applications based on a systematic review of quality characteristics. Their method comprises a quality model, metrics, and judgment criteria, providing a comprehensive approach to assessing mobile learning application quality.

7. Challenges and solutions in mobile learning implementation

Despite mobile learning's significant potential, various challenges and barriers can hinder its effective implementation. This section examines key challenges identified in recent literature and explores potential solutions and mitigation strategies.

7.1. Technological challenges

Technological challenges remain significant barriers to mobile learning implementation, particularly in resource-constrained contexts. Benali and Ally [12] conducted a systematic review of mobile learning implementation barriers, identifying several technological challenges including device compatibility, internet connectivity, and infrastructure limitations.

Popov, Jiang and So [44] found that technological challenges were particularly prevalent in industry settings, where concerns about hardware compatibility, software integration, and technical support were common. In educational settings, Hamdan et al. [24] highlighted challenges related to the digital divide, ICT infrastructure readiness, and technical difficulties during the COVID-19 pandemic.

Potential solutions to technological challenges include:

1. *Device-agnostic design* – developing mobile learning applications that work across different devices and operating systems to address compatibility issues.
2. *Offline functionality* – implementing offline access capabilities to mitigate connectivity challenges, allowing learners to download content when connected and access it later without an internet connection.
3. Using *cloud-based solutions* to address storage and processing limitations of mobile devices, as proposed by Yuan [63].
4. Developing *progressive web applications* that combine the benefits of web and native applications, providing a consistent experience across devices with minimal technical requirements.

7.2. Pedagogical challenges

Pedagogical challenges in mobile learning relate to the effective integration of mobile technologies into teaching and learning practices. Benali and Ally [12] identified several pedagogical barriers, including a lack of appropriate instructional design, limited teacher training, and difficulties in aligning mobile learning with existing curricula.

Terras and Ramsay [47] highlighted five key psychological challenges that learners may face in mobile learning: managing limited cognitive resources, determining relevance in complex environments, maintaining coherence across learning contexts, managing metacognition and self-regulation, and reconciling personal and educational technology use.

Solutions to pedagogical challenges include:

1. *Professional development* – providing comprehensive training and ongoing support for educators to enhance their capacity to design and implement effective mobile learning activities, as emphasized by Trede et al. [51].

2. Developing and applying specialized *pedagogical frameworks* for mobile learning that guide instructional design, assessment, and evaluation, such as the mobile pedagogy framework proposed by Tlili et al. [48].
3. Creating *activity design guidelines* for designing effective mobile learning activities, such as the Mobile Lesson Template developed by Vincent-Layton [54], which helps educators create engaging and pedagogically sound mobile learning experiences.
4. Implementing *scaffolding strategies* in mobile learning applications to support learner cognition and self-regulation, as demonstrated by Al Mulhem and Almaiah [3] in their study of educational mobile games with scaffolding learning strategies.

7.3. Equity and accessibility challenges

Ensuring equitable access and inclusive experiences in mobile learning environments is a critical challenge, particularly for learners from disadvantaged backgrounds or with disabilities. Liu [36] highlighted issues of digital divide, equity, and access on a global scale as significant challenges for mobile learning.

Haven [28] identified two key barriers to inclusive mobile learning: rapid technological evolution leading to interface issues with each upgrade and the dependence on smart devices for access to education, which does not address inaccessible course design and delivery of educational content.

Approaches to addressing equity and accessibility challenges include:

1. Applying *universal design for learning* principles to mobile learning design to ensure accessibility for diverse learners, including those with disabilities, as proposed by Cumming and Strnadová [13].
2. Integrating *assistive technologies* and accessibility features into mobile learning applications, such as the accelerometer-based interaction methods for vision-impaired students described by Mehigan [37].
3. Designing mobile learning content and applications that can function effectively in *low-bandwidth environments* to address connectivity disparities.
4. Incorporating *culturally responsive design* principles to ensure that mobile learning environments are relevant and meaningful for learners from diverse cultural backgrounds, as highlighted by Ariffin and Dyson [6].

7.4. Institutional and policy challenges

Institutional and policy challenges can significantly impact the adoption and sustainability of mobile learning initiatives. Gannod and Bachman [19] identified key policy issues related to mobile learning adoption, including concerns about cost, technology selection, and institutional support.

Wishart [58] highlighted institutional and cultural barriers to mobile learning in workplace settings, noting that the challenge is “much less a technical challenge than one requiring institutional and cultural innovation in permissions and behaviours within these settings”.

Addressing institutional and policy challenges requires:

1. Developing *comprehensive strategic plans* for mobile learning implementation that align with institutional goals and priorities, as emphasized by Alkhodhair et al. [5].
2. Establishing *clear policies and guidelines* for mobile learning that address issues such as device usage, data privacy, and intellectual property rights.
3. Involving *key stakeholders* including administrators, educators, students, and IT staff in the planning and implementation of mobile learning initiatives to build buy-in and address concerns.

4. Developing *sustainable funding models* for mobile learning initiatives that ensure long-term viability beyond initial implementation stages.

Figure 5 illustrates the interrelationships between different types of challenges in mobile learning implementation and potential solutions.

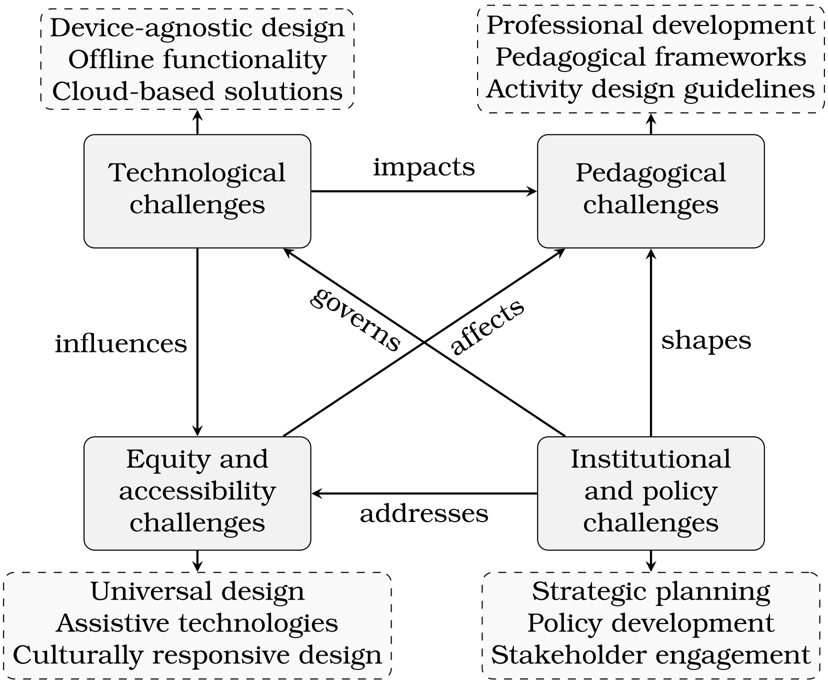

Figure 5: Interrelationships between mobile learning challenges and solutions.

8. Emerging trends and future directions

Analysis of recent literature reveals several emerging trends and promising directions for future research and practice in mobile learning. This section examines key trends and proposes a research agenda for advancing the field.

8.1. Emerging trends in mobile learning research

Several bibliometric analyses and systematic reviews have identified emerging trends in mobile learning research. Ekin and Algabsi [17] conducted a bibliometric analysis of 7829 publications on mobile learning between 1984 and 2021, finding that computer science was the most common research area, with “mobile learning”, “e-learning”, and “higher education” as the most frequently used keywords.

Kaisara and Bwalya [29] analyzed mobile learning in higher education literature published between 2002 and 2022, observing consistent growth in scholarship, with the USA and China as the most productive countries. They noted increasing contributions from universities in the Middle East and identified key topics, including context, augmented reality, COVID-19, continuance intention, and knowledge.

Lazaro and Duart [35] reviewed mobile learning applications for online higher education, finding that mobile learning has empowered interaction in content creation, communication, and collaboration between learners and instructors, significantly impacting learning effectiveness. Their review highlighted that while mobile learning is well-established in higher education, it remains attractive for educators due to its pedagogical potential.

Key emerging trends identified in recent literature include:

1. *AI-enhanced personalization* – the integration of artificial intelligence to create more personalized and adaptive mobile learning experiences, as described by Baba et al. [9].
2. Increasing use of augmented and virtual reality to create *immersive and context-rich mobile learning experiences*, as highlighted by Yen et al. [62].
3. Development of *seamless learning ecosystems* that integrate mobile learning with other educational technologies and approaches, facilitating transitions between formal and informal learning contexts.
4. Growing emphasis on *learning analytics and data-driven approaches* to mobile learning design and evaluation, as proposed by Fulantelli, Taibi and Arrigo [18].
5. Increasing focus on *social and collaborative dimensions of mobile learning*, using social networks and collaborative tools to enhance learning experiences.

8.2. Gaps in mobile learning research

Despite significant advancements in mobile learning research, several gaps and limitations remain. Moya and Camacho [40] conducted a systematic review of mobile learning studies between 2009 and 2018, identifying a lack of current research in the field of strategies and frameworks for mobile learning.

Naveed et al. [42] reviewed mobile learning in higher education, highlighting gaps in theoretical frameworks, methodological approaches, and contextual applications. They noted that while quantitative research designs dominated (90% of studies), qualitative (3%) and mixed methods (7%) approaches were underrepresented.

Parsons et al. [43] observed that while many mobile learning frameworks reference pedagogy, there is limited analysis of how mobile learning pedagogy might be defined as distinct from other learning contexts. They concluded that further research is needed on the special affordances addressed by mobile learning theory.

Based on our analysis, we identify the following key gaps in mobile learning research:

1. *Limited longitudinal research* examining the sustained impact of mobile learning over extended periods.
2. *Insufficient attention to developing comprehensive theoretical frameworks* specific to mobile learning that account for its unique characteristics and affordances.
3. *Limited research on mobile learning in diverse geographical, cultural, and socioeconomic contexts*, particularly in low-resource settings.
4. *Inadequate exploration of policy and governance issues* related to mobile learning implementation at institutional and system levels.
5. *Limited consideration of ethical implications* of mobile learning, including privacy, surveillance, and digital wellbeing concerns.

8.3. Future research agenda

Building on our analysis of current trends and identified gaps, we propose a research agenda for advancing mobile learning research and practice:

1. *Develop more robust and comprehensive theoretical frameworks* specific to mobile learning that accounts for its unique characteristics, affordances, and challenges.
2. *Conduct longitudinal studies examining the sustained impact* of mobile learning on learning outcomes, skill development, and educational trajectories.
3. *Investigate novel pedagogical approaches and strategies* designed explicitly for mobile learning contexts, with attention to different subject domains and educational levels.
4. *Explore the integration of artificial intelligence* in mobile learning, including ethical considerations, design principles, and impact on learning experiences and outcomes.

5. *Investigate approaches to designing inclusive mobile learning environments* that address the needs of diverse learners, including those with disabilities, from different cultural backgrounds, or in low-resource settings.
6. *Examine how mobile learning can support seamless learning across different contexts*, including formal and informal, physical and virtual, and individual and collaborative learning settings.
7. *Investigate policy frameworks, implementation strategies, and governance models* that support sustainable and effective mobile learning initiatives at institutional and system levels.

This research agenda provides a roadmap for advancing the field of mobile learning, addressing current gaps, and leveraging emerging technologies and approaches to enhance learning experiences and outcomes.

9. Conclusion

This systematic review has examined the evolution of mobile learning environments from 2014 to 2023, highlighting significant developments in conceptualizations, theoretical frameworks, empirical evidence, technological integration, design principles, implementation strategies, challenges, and future directions. The review builds on our earlier work on the taxonomy of learning environments, providing an updated and expanded understanding of mobile learning in contemporary educational contexts.

Our analysis reveals a shift in mobile learning definitions from technology-centred to pedagogy-centred and context-aware conceptualizations, reflecting a deeper understanding of how mobile technologies mediate learning experiences across contexts. Theoretical frameworks for mobile learning have become more diverse and sophisticated, drawing on established learning theories such as social constructivism, connectivism, and situated learning while also developing specialized frameworks that address the unique characteristics of mobile learning.

Meta-analytic evidence consistently demonstrates the positive effects of mobile learning on various learning outcomes across different educational levels and subject domains. Pedagogical approaches such as project-based learning, collaborative learning, and situated learning have been found to significantly enhance the effectiveness of mobile learning, highlighting the importance of pedagogical design in leveraging the affordances of mobile technologies.

The integration of emerging technologies such as artificial intelligence, extended reality, and learning analytics is transforming mobile learning environments, creating new opportunities for personalization, immersion, and data-driven design. These technologies offer promising avenues for enhancing mobile learning experiences but also raise important questions about ethics, equity, and implementation.

Despite the significant potential of mobile learning, various challenges persist in its implementation, including technological barriers, pedagogical integration issues, equity and accessibility concerns, and institutional and policy challenges. Addressing these challenges requires comprehensive strategies that consider the complex interrelationships between technology, pedagogy, learner characteristics, and institutional contexts.

Mobile learning research and practice will likely continue to evolve in response to technological advancements, pedagogical innovations, and changing educational needs. The proposed research agenda identifies key areas for future investigation, including theoretical advancement, longitudinal impact studies, pedagogical innovation, AI integration, inclusive design, cross-context learning, and policy and implementation.

In conclusion, mobile learning has evolved from a peripheral technology-focused approach to a central and sophisticated educational paradigm with the potential to transform learning experiences across contexts. Realizing this potential requires continued research, thoughtful design, and strategic implementation that leverages the unique affordances of mobile technologies while addressing persistent challenges. As we advance into an increasingly mobile and connected world, the development of effective, inclusive, and pedagogically sound mobile learning environments remains a critical endeavour for educational research and practice.

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