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A roadmap to implement Metaverse in education field based on ADDIE model: A systematic review

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ABSTRACT

The Metaverse, hailed as the next-generation Internet, is a virtual realm where users can engage in real-time interaction with objects through their personalized avatars. In the education sector, it holds great potential to enhance accessibility, affordability, and skill development. However, to the best of our knowledge, there is no prior empirical study that provides a clear roadmap for Edu-Metaverse's implementation. To bridge this gap, this paper conducts a systematic bibliographic analysis of 168 empirical studies published between 2019 and 2025, following the PRISMA protocol. A bibliometric and thematic approach was employed to synthesize evidence and to construct a comprehensive research roadmap based on the ADDIE instructional design model. The findings underscore substantial potential for Edu-Metaverse enhanced learning and teaching while revealing critical gaps in methodological rigor and multimodal evaluation that must be addressed to advance evidence-based practice. Building on these findings, the study proposes an integrated framework that connects technological foundations, pedagogical design, and assessment practices to guide future Edu-Metaverse research and development.

1. Introduction

THE term Metaverse first appears in Snow Crash, a science fiction novel written by Stephenson in 1992, that is defined as an immersive three-dimension (3D) virtual world. In general, the word “meta” of Metaverse means virtuality and transcendence, and the word “verse” stands for the universe [1]. With the announcement that Facebook was renamed Meta made in 2021, the concept “Metaverse” suddenly attract widely attention [2]. The Metaverse, hailed as the next-generation Internet, is a virtual realm where users can engage in real-time interaction or objects through their personalized avatars [3].

From educational perspectives, the Metaverse provides virtual spaces with simulation and technologies that enable learners to experience more immersive and imaginative scenarios [4]. Despite online learning by video conference systems, for example, Zoom, Microsoft Teams, Tencent Meet, and Google Meet, playing a main role around the world, such technologies can only superficially change the ways of teaching and learning, in which it fails to satisfy some parts of the learning process, such as the laboratory part, visiting part and technical part [5]. Metaverse's application in the field of education (abbreviated as Edu-Metaverse) has been highlighted to pave the way for immersive and interactive e-learning by means of various cutting-edge technologies to inject dynamism into online education. Edu-Metaverse tends to be a new social communication platform with a higher degree of freedom, and to provide new experiences with high immersion and virtualization [6], of which the example is shown as Fig. 1.

1.1. Technologies behind Edu-Metaverse

The immersion and interaction experienced in Edu-Metaverse by participants are inseparable from integrated various emerging technologies such as Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), Extended Reality (XR) [7]. Specifically, VR generates a digital learning environment while AR develops digital content overlaid on a physical scenario. Previous studies revealed that AR technology enriched class activities and facilitated learning to be more interesting and playful that contributed to overcoming difficulties in learning and understanding easily complicated and abstract knowledge for students [8–10]. MR, which integrates elements of both VR and AR technology, provides an embodied and interactive experience within virtual learning environments [11]. Likewise, XR technology is the ultimate combination of VR, AR, and MR, which is named by commercial organizations

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Fig. 1. An example of learning scene in Edu-Metaverse.

and consultants [12,13]. Integrating with Internet of Things (IOT) technologies, XR can create a hyper-connected environment to provide deeper immersion [14]. In this sense, XR is pointed out as one of the best technologies to promote the teaching-learning process [15].

In addition, Artificial Intelligence (AI), high-speed communications, edge intelligence, deep learning and machine learning algorithms, digital twins, and Industry 4.0 are also essential technologies to assist in the Metaverse to follow the requirements defined by creators [3,16]. Moreover, decentralized technologies such as blockchains are required to guarantee personal property safety, avoiding modification in the Edu-Metaverse [17].

1.2. Related works

Despite most studies mentioning that Metaverse technology is still in its infancy, some researchers have given pilots or implementations in various sectors due to its unique and immersive experiences, supporting, especially pedagogical fields, which have been overviewed or summarized in several review studies or survey papers. Zhong et al. [18] investigated the application values and potentials of Edu-Metaverse and discussed opportunities and challenges applying Edu-Metaverse. Contreras et al. [3] explained the importance of Edu-Metaverse's application and revealed that VR, VR and brain-computer interfaces would be the next computing platforms in their own right. Divya Meena et al. [19] specified five components of Edu-Metaverse, consisting of avatars, digital content, collaboration tools, assessment tools, and security and privacy, and three platforms, including Minecraft, Sansar, and Engage, to develop Edu-Metaverse. The authors also classified the general purposes of the application of Edu-Metaverse. Soni et al. [20] compared the disparities of learning experience in traditional learning and Edu-Metaverse and discussed the implementation of Edu-Metaverse from the perspective of technology and the use of structure. Prior studies discussed the ways to support and foster immersive and interactive teaching or learning in Edu-Metaverse, of which Benedettdörr et al. [14] focused on the technologies, cultural and moral considerations, sustainable development, and applications, and Watanabe [21] highlighted avatar, knowledge, and education activities. Even though the aforementioned surveys elaborated on the characteristics and implications of Edu-Metaverse, they lacked comprehensive empirical evidence to support the investigation.

Recent reviews on Edu-Metaverse research have collectively examined its development trends, educational value, and implementation challenges [16,22–25]. Prior bibliometric and narrative syntheses consistently highlight the rapid growth of publications, dominant research themes, and the increasing involvement of emerging technologies such as AI, XR, blockchain, and digital twins [26–28]. Across these studies, scholars have explored typical application domains, learning strategies, and the benefits of immersive and interactive environments, as well as the constraints related to cost, usability, and ethical concerns. Existing evidence also indicates that the Edu-Metaverse holds strong potential for personalized and adaptive learning, while issues such as safety, legislation, user training, and system reliability remain central themes. Although previous reviews have offered important insights ranging from advantages and risks to platform characteristics, user experiences, and technology acceptance, they largely summarize general trends rather than synthesizing empirical research to articulate a systematic implementation process.

Wang et al. conceptualized the Edu-Metaverse as a multi-hub ecosystem comprising instructional design and performance-technology, knowledge, research-technology, and talent-training hubs [29]. Teichmann proposed an interdisciplinary and theory-grounded design process framework for immersive virtual learning environments to support diverse research interests and evaluation methods [30]. Their framework foregrounds system-level interactions among pedagogical design, infrastructure, and governance as essential to scaling metaverse-based education. However, they did not systematically focus on empirical implementations and map findings, including AI-driven measurement and concrete prototype practices onto an actionable ADDIE instructional design model to derive phase-specific evidence and gaps.

Therefore, to the best of our knowledge, no study has mapped out a life-cycle-based roadmap grounded in empirical findings. Addressing this gap, our work integrates evidence from empirical studies through the ADDIE model, offering a structured framework to explain how the Edu-Metaverse can be effectively designed, deployed, and evaluated in

Table 1
Comparative analysis of existing articles of review or survey.

Year	Refs.	Contribution
2022	[18]	Discussions on Edu-Metaverse in terms of application values, potentials, and challenges from three aspects: public opinion creation, technological concerns and safety ethics.
2022	[3]	Discussion on the importance of the application of Edu-Metaverse.
2022	[33]	Discussions on Edu-Metaverse in terms of potential, key elements in the hypothesis framework, and workflow of using Mozilla Hubs.
2022	[29]	Proposing a framework for the Edu-Metaverse Ecosystem, including instructional design and performance technology, knowledge, research technology, and talent and training hubs.
2023	[21]	Discussion on the architectural features of avatars and teaching /learning activities in Edu-Metaverse.
2023	[23]	Systematic review on Edu-Metaverse in terms of challenges, opportunities, and ethical considerations.
2023	[22]	Systematic review on Edu-Metaverse in terms of contributors, scientific cooperations, eight research themes and challenges.
2023	[16]	Systematic review on Edu-Metaverse applications in terms of potential benefits and drawbacks, platforms, opportunities, and challenges to empower the work environment.
2023	[19]	Discussions on key components, applications categories, challenges, platforms (Minecraft, Sansar, Engage), and open issues of Edu-Metaverse.
2023	[26]	An in-depth examination on advantages and challenges of Edu-Metaverse's implementation and discussions on its potential, limitations and critical factors contributing to successful education.
2023	[14]	Survey on potential applications of Edu-Metaverse in terms of pertinent technologies, cultural and ethical considerations, sustainability, future perspectives.
2023	[20]	Survey on the comparison between Edu-Metaverse and traditional learning, and limited discussions on the structure and technologies of the applications of Edu-Metaverse.
2023	[24]	Systematic review on the cost and benefits of Edu-Metaverse applications.
2024	[27]	Systematic review on Edu-Metaverse adoption in terms of framework, driving factors and future trends.
2024	[28]	Systematic review on 14 emerging technologies, benefits, and 6 types of learning in Edu-Metaverse applications.
2024	[25]	Survey on the evaluation of Edu-Metaverse with proposing an implementation scheme.
2025	[34]	Systematic review on trends, goals, and types of metaverse technologies and propose a framework that addresses the interconnected roles of learners, instructors, and institutions in Edu-Metaverse
2025	[30]	Proposing an interdisciplinary and theory-grounded design process framework for immersive virtual learning environments to support diverse research interests and evaluation methods.
Now	Ours	This systematic review proposes a comprehensive roadmap for empirically implementing Edu-Metaverse based on ADDIE model to offer a structured and end-to-end methodological foundation.

real educational contexts. Table 1 summarizes and compares the contributions of our paper with other pertinent scientific publications.

1.3. ADDIE model

The ADDIE model, consisting of five phases that analyze, design, develop, implement, and evaluate, is adopted in most empirical studies to instruct how to deploy and implement the Edu-Metaverse in educational and training activities. From the perspectives of educators, instructional designers and training developers, the ADDIE model clearly defines a linear process with a hierarchical structure that facilitates the implementation of an effective technical prototype [31]. Lampropoulos et al. [32] applied the ADDIE model into their experimental process, where at first the authors determined the learning requirements and then aimed to design an Edu-Metaverse-based gamification education. After developing the project via various tools, the application was implemented, and the participants were required to use and assess its functionality. Segura et al. [15] exploited ADDIE model to design and create MR content for the deaf students. In the analysis phase, the authors identified the learning objectives of the students by means of a survey. Based on the requirements, activities and assessments were designed to meet the learning needs in the second phase. Next, multimedia elements were created and validated and then programmed to Edu-Metaverse prototype in development and implementation phases, respectively. In the last stage, the authors evaluated the change of students' cognition and the usability of the scenes.

Despite existing studies proposing integrated frameworks that include technology adoption, learner engagement, or virtual environment design, they remain fragmented and lack a unified, process-oriented perspective for guiding empirical implementation. There is still no integrated roadmap that systematically connects these findings to guide the design, implementation, and evaluation of the Edu-Metaverse. The absence of such a roadmap hinders theoretical consolidation and practical progress, leading to duplicated efforts, inconsistent methodologies, and limited comparability across studies. Without a clear framework linking instructional design principles with technological implementation, educators and developers struggle to translate research insights into effective educational practice. Therefore, this paper attempts to systematically review experimental research and outlines a roadmap based on the ADDIE model to guide the implementation of Edu-Metaverse, which is shown as Fig. 2.

To this end, this study aims to achieve the following research objectives.

- To systematically review and analyze the current state of empirical research on the Edu-Metaverse from 2019 to 2025, identifying five key factors, encompassing (1) components and motivations, (2) strategies, (3) techniques, (4) participants, scenarios, and AI-powered services, and (5) data appraisal and assessment tools.
- To construct a comprehensive roadmap for implementing Metaverse technologies in educational contexts, guided by the ADDIE instructional design model to clarify practical strategies and technological frameworks for educators and developers.
- To synthesize and summarize existing data appraisal and assessment practices in Edu-Metaverse research, thereby proposing structured approaches for evaluating technology acceptance, learning outcomes, and system effectiveness.

Based on the theoretical gap and study motivation discussed above, the following Research Questions (RQ) are shown as follows.

RQ1: What is the current status of empirical research in the field of Edu-Metaverse?

RQ2: How to implement Metaverse technologies in the education sector?

RQ3: How to conduct and measure data appraisal in the Edu-Metaverse practice?

The contributions of this paper are (1) We provide a systematic overview of the current state of empirical research in the field of Edu-Metaverse based on bibliometric analysis spanning from 2019 to 2025. (2) We outline a roadmap based on the ADDIE model to reveal an evidence-based theoretical framework about how to implement Edu-Metaverse in practice. (3) This paper provides comprehensive instructions towards future research in the field of Edu-Metaverse and helps follow-up researchers to identify every phase in the life cycle of Edu-Metaverse empirically.

The rest of the paper is organized as follows. Section 2 details the methodology. Section 3 presents findings and discussions, and Section 4 provides conclusions, limitations, and future work.

2. Methods

Preferred Reporting Items for Systematic reviews and Meta-analyses (PRISMA) is used as a common method for systematic review research to report an evidence-based minimum set of items in various fields [35,36]. PRISMA has an explicit checklist and protocol to avoid arbitrary screening from impacting the rigor and transparency during the review research [16].

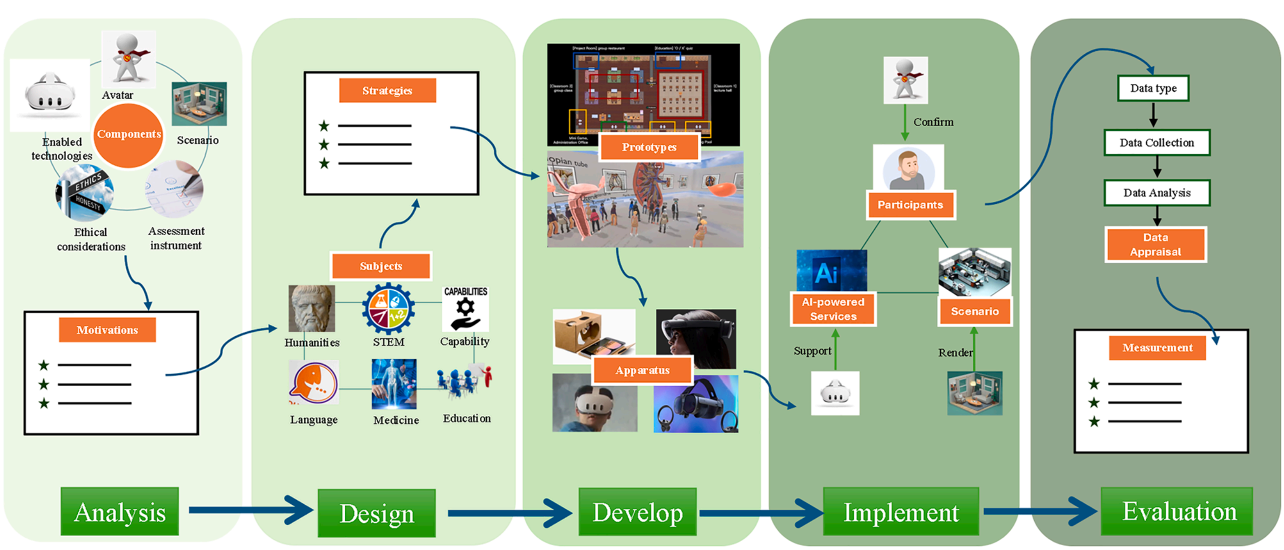

Fig. 2. A roadmap for Edu-Metaverse implementation based on the ADDIE model.

This study conducts a systematic review with descriptive and bibliometric analyses of 168 empirical studies on the Edu-Metaverse, following the PRISMA protocol. Unlike a meta-analysis, which statistically pools quantitative outcomes, our review focuses on identifying research patterns, thematic trends, and technological and pedagogical practices across the literature. To bridge the gap and answer the research question, this work adheres to PRISMA guidelines. First, the relevant articles were searched from typical databases. Then, the duplicate and ineligible papers according to pre-determined criteria were removed by automation tools. Next, screening and assessing the title, abstract, and the full text of each article manually were implemented. Finally, the remaining eligible articles were analyzed and discussed to answer the proposed research questions. The PRISMA flow diagram illustrates the procedures of data search and filtering, as depicted in Fig. 3, where N_{remove} and P refer to the exact counts and percentages of excluded papers at each stage, respectively.

2.1. Data search and selection

Many literature reviews showed that the number of Edu-Metaverse research papers has a sharp increase from 2019 due to Covid-19 pandemic [16,22]. Thus, this work focuses on the papers published from January 2019 to November 2025, following PRISMA 2020 guidelines [37]. The systematic search was conducted across six major databases: Web of Science, Scopus, IEEE Xplore, ProQuest, EBSCOhost, and Google Scholar.

Given that the Metaverse comprises all elements of AR and VR technologies [38], but AR or VR technologies cannot fully represent the Metaverse since there are certain differences between them [39]. Besides, traditional VR-based education does not match the key characteristic of Edu-Metaverse, as it fails to provide synchronous learning experiences based on a sense of presence and interaction. The term “VR” or “virtual reality”, independently shown in the title or keywords are not adopted in the searching process [40]. Hence, AR- or VR- related terms searching has to be carried out after searching the keyword “Metaverse”.

Initially, studies containing the words “Metaverse” and “Education” with the Boolean operator “AND” in the title, abstract, or keywords were searched from the databases, language (English or Chinese), and document types (academic articles or conference papers). 2474 articles were identified after search. Afterwards, the respective searches in the title and abstract were conducted based on the same search strategy. To ensure transparency and explicitation, the search strategy according to

Table 2
Database search methodology and parameters.

		First round	Second round
Keywords	Metaverse-related	“Metaverse”	“Metaverse” OR “VR” OR “AR” OR “XR” OR “virtual reality” OR “augmented reality” OR “mixed reality” OR “extended reality”
	Education-related	“education”	“education” OR “learning” OR “teaching” OR “training” OR “student” OR “teacher”
Boolean Operator		AND	AND

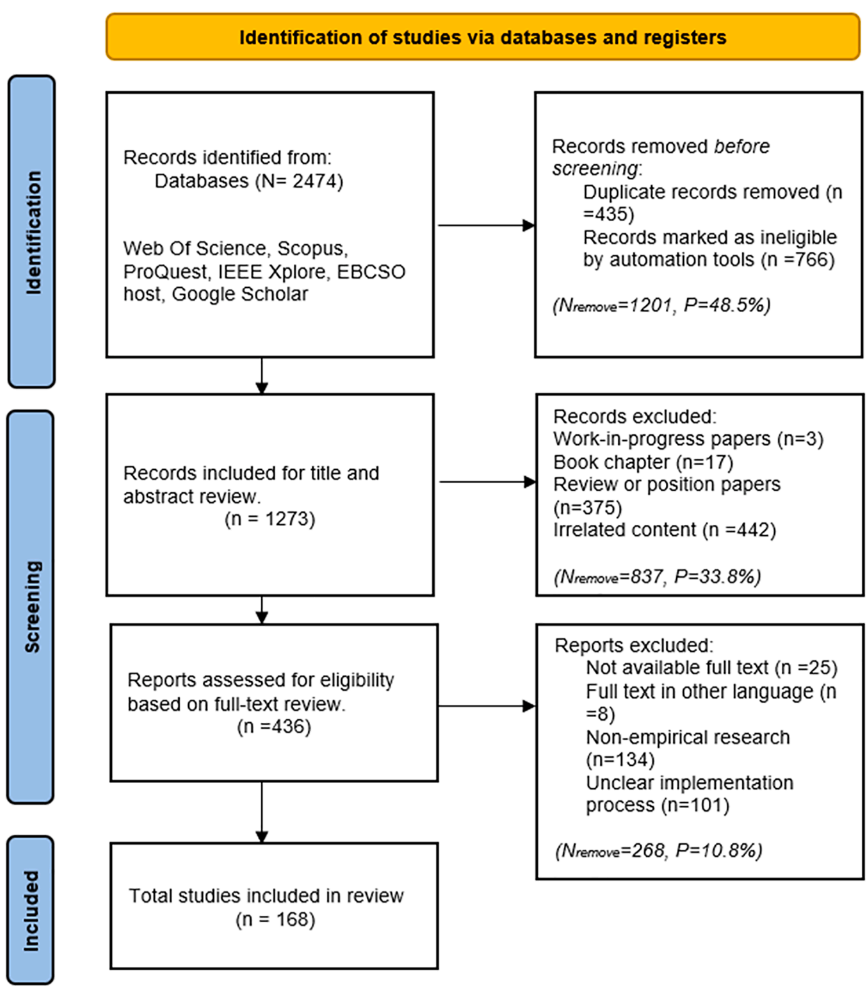

Fig. 3. PRISMA review process.

the defined inclusion criteria was detailed in Table 2. As a result, 766 papers were ineligible to be filtered out, and 435 duplicate papers were excluded; the remaining 1273 papers underwent title and abstract screening.

After title and abstract screening, the remaining 436 papers were conducted to full-text review. 25 documents that were not freely accessible or were retracted by the publishers for various reasons were excluded. 8 papers in other languages and 134 non-empirical research papers were discovered. Besides, it found that 101 papers were not explicit in the implemented process of Edu-Metaverse, of which most studies focused on exploring the attitude towards the usability or adoption of Edu-Metaverse via questionnaires or interviews without delineating how to implement Edu-Metaverse. Hence, they were not included in this review work. Ultimately, 168 papers were included for data analysis.

2.2. Eligible criteria

To explore the overall status of Edu-Metaverse's implementations or pilots, only empirical or experimental studies are considered in this review work, which means the articles must contain the phase of data collection by using evidence, observations or calibrated scientific tools. Additionally, some empirical articles that lack detailed application processes of Edu-Metaverse are not adopted. Table 3 shows the inclusion and exclusion criteria for this review. All the reviewed papers meet the inclusion criteria.

2.3. Overall research status (RQ1)

168 studies are empirical research with clear implementation processes and assessment results published from 2019 to 2025, and their language are English. The literature articles are mostly journal articles (n = 137), and conference articles (n = 31), of which the percentages are as shown in Fig. 4. In addition, in terms of the year of publication, the distribution of paper types and the count of papers as shown in Fig. 5. From Fig. 5, the number of empirical research published in 2023 increases significantly. ~~However, the supplementary update search could not retrieve certain publications from July to December 2024 due to temporary indexing gaps in several databases. Thus, the records in 2024 is incomplete. Nevertheless, the missing records in 2024 represent a narrow time window and are unlikely to change the overall themes or conclusions.~~ The number of papers published in 2023 and 2025 demonstrates that intensive implementation of Edu-Metaverse will be an inevitable trend.

Fig. 6 presents essential words and phrases that occurred in the abstracts of 168 studies. The results show the emphasis placed by scholars on empirical research of Edu-Metaverse. For instance, the words "student" and "teacher" identify the two key roles and research targets in the implemented processes of Edu-Metaverse. The words "virtual", "experience" and "immersive" suggest the features of Edu-Metaverse. The phases "virtual reality" and "augmented reality" show main technologies used in Edu-Metaverse. Moreover, the words "platform", "tool", "technology", "model", and "environment" present implemented elements to apply the Metaverse into educational sectors.

Table 3
Inclusion criteria and exclusion criteria for reviewing papers.

Inclusion Criteria	Exclusion Criteria
• The topic regarding Edu-Metaverse in the title, abstract, or keywords. • Publish year: main search (2019–2025). • Published academic articles, conference papers. • Studies published in English or Chinese	• Duplicate paper • Work-in-progress paper. • Not available in full text • Articles unrelated to Edu-Metaverse content • Non-empirical or non-experimental studies • Lack of an explicit implementation process of Edu-Metaverse

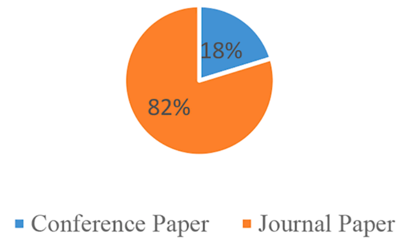

Fig. 4. Distribution of included article types.

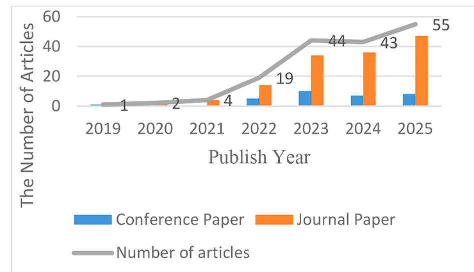

Fig. 5. Distribution of the number of included articles by the year of publication.

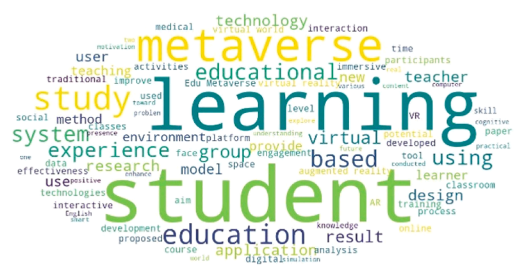

Fig. 6. Key emerging words in included articles.

3. Findings and discussions

To explore how to implement Edu-Metaverse in practice, this section articulates a road map comprehensively according to the five stages of the ADDIE model and elaborates related elements in each stage based on bibliometric analysis.

3.1. Analysis of Edu-Metaverse implementation

3.1.1. Components

To draw a roadmap to implement Edu-Metaverse, its components are the first to be considered, which ensures that learning and teaching activities are carried out with efficiency, equity and safety in virtual worlds [41,42].

(a) **Avatar** is a key element in Edu-Metaverse where learners simulate themselves into avatars to access the virtual world with a high degree of freedom to act following their own intention and interests. In addition, learners can customize their own persona data for avatars such as tall, beautiful, scary, different sex, different species, live-action, and cartoon.

(b) **Scenario** is populated with digital contents and educational resources to provide 3D visual experiences, which can be a game [31], story [43], exhibition [17], laboratory [44], or immersive scene [45].

(c) **Enabling Technologies** refer to manipulated toolkits behind Edu-Metaverse, comprising software, hardware and AI-driven algorithms facilitate the implementation of the prototypes.
(d) **Assessment instruments** play an integral role in the development of Edu-Metaverse, by which the educators can understand and monitor learners' learning behaviors in Edu-Metaverse resulting in constructive feedback to optimize experimental processes.
(e) **Ethical considerations** are inevitable in every empirical study of Edu-Metaverse. Generally, privacy issues such as data leak and ownership of copyright and security issues such as cybersecurity, health issues and online harassment are commonly considered. Specifically, mentioned health issues mainly concerns the headset devices causing discomfort, motion sickness, visual fatigue, or dizziness after sustained wearing in the Edu-Metaverse [46].

3.1.2. Motivations

Motivations of Edu-Metaverse implementation absolutely are the second to be considered in analysis phases. Based on a bibliographic analysis, three general intentions for constructing Edu-Metaverse empirical research are identified and discussed in the following aspects.

3.1.2.1. To enhance teaching and learning process. A significant amount of empirical literature has proven that applying Edu-Metaverse into the existing teaching and learning process has notable impacts on the learning performance in different countries, disciplines and educational levels, which educational resources are exploited and distributed in more reasonable way [47–49]. As a dynamic complement, Edu-Metaverse assists in integrating all available educational resources without time and space limitations to meet learning objectives which a traditional class cannot perform. For instance, users can create and share events that are hard to experience because of physical restrictions [50].

3.1.2.2. To foster collaborative and innovative learning. Due to the characteristic of traditional teaching that one-way mode of teaching and learn without interaction between educational materials and learners [51]. Previous empirical research on Edu-Metaverse intended to break traditional single-mode and attempted the combination of emerging technologies and upskilling education approaches such as Problem-based Learning (PBL), collaborative learning, simulation, and gamification education. PBL is student-centered education method focusing on fostering personal and professional capabilities [52]. Collaborative learning in Edu-Metaverse has two perspectives: one is between the machine and the learners, and another one is among the learners [53]. Specifically, collaborative learning between learners and intelligent systems functions as a form of partnership that leverages natural language processing, semantic analysis, and related technologies to enhance learners' engagement. Meanwhile, virtual environments also strengthen collaboration among learners, such as through peer-facilitated learning strategies implemented within Metaverse hands-on learning experiences [54].

3.1.2.3. To develop and evaluate the Edu-Metaverse prototype. Given the existing limitations in usability, applicability, and user experience, researchers have focused on developing Edu-Metaverse prototypes to bridge these gaps. These prototypes integrate interactive objects and multimedia resources tailored to different disciplinary contexts. Empirical studies proposing emerging Edu-Metaverse designs, or AI-supported prototypes built on existing platforms, generally aim to develop customized learning systems characterized by high immersion, low latency, and long-term sustainability [55].

3.1.3. Summary and discussion

Compared with traditional online teaching models, the Edu-Metaverse establishes an immersive, interactive learning environment and provides an open space for creative knowledge construction. As information technologies and intelligent devices continue to evolve, fragmented knowledge can be better integrated, and learning increasingly shifts from the passive accumulation of information to a more open and creative process. The Edu-Metaverse spans both physical and virtual worlds, encompassing real cities, social environments, and natural ecologies while simultaneously extending into virtual spaces. Under this convergence of real and virtual contexts, communication and interaction, both among learners and between learners and the virtual environment, intensify, enabling learners to assume meaningful roles in authentic learning scenarios [56].

From the reviewed literature, five essential components of Edu-Metaverse implementation are identified: avatars, scenarios, enabling technologies, assessment instruments, and ethical considerations**.** In addition, three primary motivations drive Edu-Metaverse adoption: enhancing the teaching and learning process, fostering collaborative and innovative learning, and developing and evaluating the Edu-Metaverse prototype**.** These elements collectively define the applicable contexts and form the foundation for the subsequent phases of the overall design roadmap.

In the analysis phase, review results indicate the implementation of Edu-Metaverse relies on five core components shaped by technological and pedagogical conditions. However, current studies lack frameworks for aligning these components with specific instructional goals. Besides, research seldom addresses long-term sustainability, scalability, and ethical risk management in real deployments.

3.2. Design of Edu-Metaverse implementation

3.2.1. Strategies to implement Edu-Metaverse

During design phase, deciding on and creating the instructional approach and activities are the backbone to implement Edu-Metaverse. Considering that different disciplines have different characteristics and attributes, the strategies to implement Edu-Metaverse in multidisciplinary fields are different. Purwanto et al. considered spatial thinking ability as a core cognitive competence that students must develop when learning geography, given that the discipline inherently integrates both physical and social dimensions of space. Based on this, they designed and implemented a metaverse-based learning medium to support the development of students' spatial thinking skills [57]. Metaverse-based art gallery has been shown to significantly enhance students' creativity and critical thinking in literature and visual arts [58]. Beyond the arts, such immersive environment can also support pharmacy and pharmaceutical science education by fostering a deeper understanding of patients' lived experiences with medication therapies, achieved through the humanized personification of medications [59]. In addition, previous studies have examined the use of Edu-Metaverse in vocational training [60] and skill development, for example, earthquake evacuation skill [61], medical emergency skill [62], hospitality aesthetic literacy [63]. Hence, based on bibliographic analysis, this section determines the strategies concerning about the subjects and domains such as STEM (acronym of Science, Technology, Engineering, and Mathematics), humanities (including art, geography), language, medicine, skill, and education.

To further inductively identify instructional strategies within Edu-Metaverse environments, a hierarchical thematic synthesis was presented in Table 4. The findings synthesize five overarching strategies**.** Given the pedagogical diversity across studies, these five strategies are further divided into ten specific codes. Primary subject areas indicate the disciplines in which the corresponding strategy most frequently appeared across the reviewed studies.

3.2.2. Summary and discussion

Drawing on the hierarchical thematic synthesis presented in Table 4, disciplines characterized by broad applicability and strong communicative demands, such as STEM and medicine fields, exhibit a higher

Table 4
Hierarchical thematic analysis of educational strategies in Edu-Metaverse.

Category	Strategies	Designed Focus	Primary Subject Areas	Refs.
Collaborative Knowledge Construction	Problem-oriented collaborative learning	Learner co-construct knowledge through self-exploration and peer interaction to solve problems in immersive environments	STEM, Medicine, Skill	[45,54, 67–78]
	Shared immersive learning spaces	Persistent multi-user virtual environments supporting social presence and collaborative meaning-making	Education	[79–83]
Immersive Experiential Learning	Art-based immersive creation	Learning through artistic exploration and creative production enabled by immersive media	Humanities	[17,51, 58, 84–86]
	Task-driven immersive experience	Authentic task execution and situated learning within simulated real-world scenarios	Language	[43, 87–92]
	Vocational and skill-oriented immersion	Skill acquisition and professional training through simulated practice environments	Medicine, Skill	[87, 93–103]
	Gamified immersive learning	Motivation and engagement enhancement via rule-based mechanics and immersive feedback	STEM, Skill	[8,13,32, 104, 105–111]
Assessment and Learning Analytics	Experience-based learning evaluation	Assessment embedded in immersive activities using learning performance, behavioral, or interaction data	Across various subjects	[10,44, 47,48, 112–131]
	System-level adoption and evaluation	Evaluation of technological acceptance, system usability, and large-scale adoption of Edu-Metaverse platforms	STEM, Medicine	[49,64, 132–143]
Instructional Design and System Integration	Technology-enabled instructional design	Integration of metaverse platforms with instructional strategies and AI support	STEM, Medicine	[41,50, 144–148]
Personalization and Inclusion	Disability-oriented personalized learning	Assistive immersive design supporting learners with disabilities	STEM, Skill	[15,149, 150]

concentration of Edu-Metaverse instructional strategies. These disciplines frequently incorporate collaborative knowledge construction, immersive experiential learning, and analytics-driven evaluation, which positions them as primary testing grounds for large-scale Edu-Metaverse implementation in higher education.

Across the reviewed literature, ten instructional strategies were identified through thematic coding, reflecting distinct pedagogical functions rather than isolated teaching techniques. The distribution of these strategies across disciplinary domains suggests that strategy selection in Edu-Metaverse design is highly dependent on disciplinary characteristics, including learning objectives, task structures, and interaction requirements. Importantly, the thematic synthesis also reveals notable asymmetries in application domains. For instance, personalization and inclusion-oriented strategies, such as Metaverse-supported personalized learning for disabled learners, remain underexplored in medicine, skills training, and humanities education, despite their potential relevance to diverse learner populations. Moreover, analytics-driven evaluation practices are frequently focused on short-term learning outcomes rather than longitudinal learning processes.

Beyond disciplinary differences, the reviewed studies indicate that Edu-Metaverse design strategies are further shaped by instructional materials, media formats, and learners' preferred learning styles [64]. Nevertheless, despite advances in the digitization of instructional content across higher education, Edu-Metaverse research and practice remain at an early developmental stage. Persistent challenges, including high equipment costs, teachers' readiness, and learners' operational skills, continue to constrain large-scale adoption. Furthermore, the lack of mature strategy selection frameworks limits the systematic alignment of pedagogical intentions with the technological affordances of Edu-Metaverse platforms.

Moreover, generative AI, particularly Large Language Models (LLMs), introduces new opportunities for designing innovative instructional strategies within Edu-Metaverse settings, offering adaptive, creative, and interactive support for learners [55,60,61,65].

3.3. Development of Edu-Metaverse

3.3.1. Edu-Metaverse prototypes

The implementation of Edu-Metaverse is inseparable from the support of hardware and software tools. Recent research and development efforts have shown the enormous potential and usability of various prototypes to put the Edu-Metaverse into practice. Table 5 summarizes technological prototypes proposed by previous empirical studies to access Edu-Metaverse in terms of immersion, hyper spatio-temporality, open, decentralization, interoperability, scalability, and compatible apparatus.

Based on the synthesis of recurrent themes identified in previous studies on metaverse-based learning environments [151,152]. Several technical characteristics emerge as foundational for designing Edu-Metaverse prototypes. First, **immersion** remains a core requirement. Prior research generally distinguishes three levels of immersive prototypes: non-immersive, semi-immersive, and fully immersive [153]. Non-immersive systems rely on 2D interfaces with limited interaction through conventional input devices (e.g., keyboard, mouse), whereas semi-immersive systems provide a panoramic or 360-degree

Table 5
Summary of existing Edu-Metaverse prototypes with different characteristics and compatible apparatus.

Category	Platforms/ Tools	Immersive	Hyper Spatiotemporal	Publicly Available	Decentralized	Interoperable	Scalable	Compatible Apparatus	Refs.
Virtual World/ Metaverse Platforms	Second Life	Partly	√	Partly	×	×	√	N/A	[70, 156]
	Altspace VR	√	×	×	×	×	√	Meta Quest 2	[153]
	Decentraland	√	√	√	√	×	√	N/A	[104]
	Spatial.io	Partly	√	√	√	×	√	N/A	[52,120, 122]
	Horizon workrooms	√	×	√	×	×	Partly	Meta Quest 2	[80]
								Meta Quest TV	[157]
	Gather.Town	×	×	Partly	×	×	√	N/A	[79, 141]
	ifland	Partly	√	√	×	×	×	N /A	[113]
	OpenSimulator	Partly	√	√	×	×	√	N/A	[136]
	Classlet	Partly	Partly	×	×	Partly	Partly	Meta Quest 3	[158]
Development Engines/ Specialized Tools	Unity	Partly	√	√	×	√	√	√	[81,139, 144]
	Studio GoMeta	Partly	√	√	×	×	√	N/A	[8]
	Eon-XR	√	√	√	×	√	√	√	[116]
	Frame.io	√	√	Partly	×	×	√	√	[105]
	A-Frame	√	√	√	×	×	√	Google cardboard	[17]
	PANO2VR	√	×	√	×	√	√	Google cardboard	[45]
	Vuforia Engine	√	√	√	×	√	√	Meta Quest 2	[15]

visualization via projected virtual scenes. Fully immersive systems offer real-time interaction with 3D virtual objects through head-mounted displays (HMDs). Because such immersive experiences rely heavily on hardware–software coordination, ensuring the compatibility of applications with HMD devices is a necessary technical consideration.

However, immersion is not determined solely by visual fidelity. Spatiotemporal responsiveness of a prototype is emphasized to support seamless transitions across locations, scenes, and temporal events, which substantially affects users' sense of presence in the Edu-Metaverse [151]. In this study, **hyper-spatiotemporality** refers to learners being able to fluidly navigate between virtual spaces (e.g., via controllers) and interact with dynamic, time-dependent events such as animations or simulations without noticeable delay.

Additionally, **scalability** is highlighted as a crucial characteristic in the literature [105]. Edu-Metaverse systems should be capable of accommodating a large number of concurrent users while maintaining smooth interaction. This includes support for complex and customizable instructional scenarios involving high-resolution assets or real-time simulations.

To maintain continual usability, it is important for platforms to be **publicly available** to deliver comfort user experience**,** which means accessible resources, flexible customization, and low barriers to entry. In parallel, adopting a **decentralized architecture**, where control and data are distributed across a network rather than concentrated in a single server, has been discussed as a means to reduce cybersecurity vulnerabilities and ethical risks in educational metaverse environments [151].

Finally, **interoperability** is essential for enabling learners or avatars to navigate across different systems, devices, and platforms without functional barriers. This involves integrating existing institutional systems or third-party technologies to ensure that content, identity, and interactions remain consistent across environments [19].

Taken together, these characteristics, including immersion, hyper-spatiotemporality, compatibility, scalability, openness, decentralization, and interoperability, are considered to reflect convergent patterns synthesized from current research on the design and implementation of Edu-Metaverse systems.

From Table 5, existing modern prototypes are introduced and discussed here with the support of pertinent empirical studies. Apart from the common techniques mentioned as follows, several prototypes were also used in research, such as a variant of PlaySAFe (a 3D game) [99], Metaverse-based educational platforms like GOXR [154], CoSpaces Edu [155], WBS LearnSpace 3D [114] and Moodle [73]. Unfortunately, Altspace was shut down by Microsoft in March 2023.

Second Life is a common platform to be used to simulate a 3D virtual learning scenario in Metaverse, where users called "avatar" can construct environment according to their own thoughts and interact with others online. Rudolphi-Solero et al. [156] deployed interuniversity competition online regarding radiology in second life and the result showed the way was feasible and acclaimed, from which the participants were beneficial.

EonXR platform provides MR visual processing technologies to help create interactive and immersive AR and VR lessons without any coding or advanced technological knowledge. Raja et al. [116] chosen EonXR as a VR delivery medium to give participants experiences in 360°'s VR content.

Unity is a professional real-time interactive 3D content development engine and operation platform with high compatibility. Lee et al. [144] proposed an immersive education system by means of Unity3D and a server built with Photon Unity Network 2 (PUN2) to implement aircraft maintenance simulation. Besides, based on the virtual environment supported by Unity3D, VR devices including Oculus Rift S, Quest2, and HTC Vive Pro Eye, were verified to work smoothly.

Studio GoMeta (earlier platform Metaverse Studio) is a free AR-generated platform without any programming required, in which can easily create interactive content. Based on Metaverse Studio, Estudante et al. [8] designed a new escape room scenario focusing on Solvay process of an educational AR game online and accessed by smartphone. Sofiadin [159] used Metaverse Studio platform to develop an XR app, in which it designed 360 virtual scenes including BMW drive in Mars and the Tesla factory tour. It is worth noting that the Metaverse Studio website has been shut down by GoMeta since 1st February of 2024.

OpenSimulator is a free and open-source multi-platform written in C# for developing VR based scenarios. It is also a multi-user 3D application server to support physical simulations and 3D content generation in real time. Díaz et al. [136] used OpenSimulator to develop a project named MVudec, where the avatars could walk, change appearance, fly, communicate with each other nearby via social chat and interact with certain metaverse objects.

Spatial.io is a free web-based development platform for 3D games and immersive environment interacted with users [127,160]. Unity-based toolkit powers the platform and amplifies creativity and interaction. In particular, professional design applications such as Adobe Illustrator and Blender can be compatible with spatial.io [122], which enables creators to customize the course materials for various pedagogical intentions. Once published, users can access it through web, mobile phone or VR everywhere. Across existing studies, Spatial.io has been widely used to build subject-specific immersive learning spaces. For example, Pigultong [79] embedded a URL linking to a Metaverse art gallery generated by spatial.io in a learning management system named Moodle, with which the participants interacted by basic computing devices instead of VR glasses. The other study used spatial.io to create avatars and develop a Metaverse environment to teach students how to operate automatic irrigation systems and design a meteorology station [161].

Gather, or called Gather.Town is a quick-start platform to generate a 2D interactive environment, on which developers can easily customize the scenarios and design team activities. In addition, users are allowed to customize the appearances, outfits, and accessories of avatars and communicate with each other in audio or video. However, the platform is not free to use. Lee et al. [162] applied Gather Town platform to design the Metaverse-based PBL (Problem-based Learning) curriculum to help students practice restaurant management operations. Gather supported [163] to conduct foreign language education to assist pre-service teachers in lesson planning. Considering the participants were elementary students, the author exploited Gather to create a simple narrative scenario to allow students to learn a second language for the purpose of easy manipulation [89].

Frame VR is a free web-based platform to produce 3D environments to let users explore and highlight 3D models and 360-degree photos with others in real-time, which is similar to spatial.io, but the rendering of avatars and objectives does not look as realistic as spatial.io [105]. Choose Frame as the platform to design immersive games for cybersecurity awareness cultivation.

Ifland has been one of the most attractive social Metaverse apps in Korea and has been launched in 49 countries throughout the world since 2022. Users can download ifland from Google Play or App Store. In the game, users are allowed to create their own space, customize their avatars, and interact with people from all over the world [113]. Conducted a comparison analysis among IFLAND, Gather, and Frame VR based on 57 students' experiences and opinions of each platform. The results showed that the degree of immersion in ifland's Metaverse class scored highest, the reasons of which are friendly avatar customization and personalized communication by emoji characters.

3.3.2. Edu-Metaverse headset apparatus

To amplify interactions and immersions, the authors employed VR headsets to connect Edu-Metaverse prototypes. Four prevalent HMDs and pertinent Software Development Kits (SDKs) are listed as follows, of which physical devices have been shown as Fig. 7.

(a) Google cardboard
(b) Microsoft HoloLens2
(c) Meta Quest glasses
(d) HTC Vive

Fig. 7. Four Edu-Metaverse headset apparatuses used in existing empirical studies.

3.3.2.1. Google cardboard. Google cardboard is a cardboard-based VR headset, which is prevalent due to its simple, affordable, and accessible characteristics. Users explore VR experiences via compatible smartphones held in front of the device after installing the Google Cardboard app from either Google Play or App Store. In [164] Participants wore a Google Cardboard headset to access and visit the construction and rehabilitation sites in the Metaverse environment generated by Pano2VR, which is a software that converts panoramic or 360 photos and videos into interactive scenarios. Ref. [17] utilized Google Cardboard to enable participants to enter in-person a virtual exhibition in the Metaverse designed by A-Frame, a web framework to build compatible 3D worlds.

3.3.2.2. Microsoft HoloLens2. Microsoft HoloLens2 is the second generation of mixed reality HMD (Head-Mounted Display), by which users can 'touch' virtual objects in a real environment without holding mobile devices. Besides, the built-in sensors help complete behavior analysis tasks including hand tracking, voice commands, and eye tracking. Spectator View enables other users to view their experiences within HoloLens by other devices. Ref. [145] created a Metaverse environment for aircraft maintenance via HoloLens 2, scanning the 3D model of the landing gear, and embedded a speech interaction module to control the system instead of clicking buttons or using hand gestures.

3.3.2.3. Meta Quest glasses (or called Oculus Quest). Meta Quest glasses are a series of mixed reality HMDs released by Meta, formerly known as Facebook, among which Meta Quest 2 has been the most popular external device since its launch due to its affordable price and outstanding performance. Segura et al. [165] carried out a gamification-based immersive education in programming logic for the students with hearing disabilities by using Oculus Quest 2 and Vuforia as a widely used cross-platform-based AR SDK. Nevertheless, the authors pointed out the communication barrier that the participants can hardly interact with each other in sign language since the Oculus Quest 2 glasses blocked their sight. **Horizon Workrooms** is a virtual software application employed on the Oculus headsets. Compared with Spatial.io, Mozilla Hubs and Arthur, Horizon Workrooms achieves superior performance in terms of avatar expressiveness, naturalness of interaction, eye contact, and overall immersion [166]. Hedrick et al. [80] used Horizon Workrooms to build and configure virtual classrooms and the participants were allowed to wear Oculus Quest 2 glasses to interact with each other in VR classrooms [153]. Selected Altspace Metaverse platform as the basis for the digital twin of cybersecurity lab due to its complete compatibility with Oculus Quest 2 headset and customization via Unity and other programming languages, while costly Engage XR platform was not taken into account. However, the freeware Altspace VR exposed to business limitations and lack of profitability has been shut down by Microsoft since March of 2023.

3.3.2.4. HTC VIVE. HTC VIVE, a popular VR gaming device, offers 360-degree precise tracking and feedback from sensory perception. The HDM enables users to move freely within a designated VR play area to explore endless virtual worlds, whether the users sit or stand. Ref. [167] used HTC Vive pro to collect gaze information and gesture information by LeapMotion of participants, and visualize the results, which improved interaction efficiency and user experience. Also, HTC Vive was applied to record participants' movements such as walking, jumping, squatting and reflected them into Edu-Metaverse [85].

3.3.3. Summary and discussion

The state-of-the-art prototypes and apparatus enable learners to realize human-computer interaction and seamless communication in Edu-Metaverse, which makes human beings get rid of the limitations and constraints of the body, stimulate the perception ability and cognitive experience in an all-around way, and finally move towards a more open and creative education mode. This not only breaks the inherent laws of human cognition, but also establishes a multi-dimensional space with the characteristics of virtual-real integration, embodied interaction, decentralization, creativity, sustainability, openness and so on.

However, while Edu-Metaverse prototypes continue to evolve rapidly, legal, security, and ethical frameworks remain underdeveloped. Emerging technologies raise concerns related to ethics, privacy, data security, and intellectual property rights. Prior research argued that Metaverse had intrusive, pervasive, and potentially addictive nature [168,169]. In this sense, excessive use of immersive tools and virtual environments may result in learners' overreliance on virtual worlds, reduced real-world engagement, diminished independent thinking, and weakened face-to-face communication skills. Besides, poorly developed immersive virtual scenario in usability may lead to dizziness, headaches, or fatigue and impact negatively on learning outcome [30]. Conversely, it is equally important to acknowledge that other studies have demonstrated the opposite effect: well-designed virtual social environments, such as VR-based social skills training [170], clinical communication simulations [94] or gamified experience-based learning [171] can effectively enhance learners' face-to-face communication abilities by replicating authentic social situations. Additionally, as data serves as the core resource in virtual environments, Edu-Metaverse relies heavily on collecting and reorganizing learner information to generate educational insights. This increases the risk of privacy leakage and data misuse when personal information is uploaded to the system [172]. Developing robust privacy protection mechanisms, such as privacy-preserving computation, digital encryption, and blockchain-based solutions, remains a critical challenge [151]. Furthermore, the physical side effects of immersive hardware cannot be ignored. Prolonged use of head-mounted displays (HMDs) may lead to discomfort, motion sickness, eye strain, or dizziness, posing additional constraints on the sustainable development of Edu-Metaverse applications [167].

3.4. Implementation of Edu-Metaverse

3.4.1. Participant and scenario

In Edu-Metaverse, avatars, as a crucial component, digitally represent participants encompassing students, learners and educators and project social and learning behaviors, which means the participant in the real world is a physical form of avatar in virtual world. Hence, the participant plays an integral role in the implementation phase of Edu-Metaverse. Likewise, scenario is the fundamental component that guarantees participants' immersive experience and innovative learning in Edu-Metaverse to provide well-organized stories and learner-centered events [42].

Given that students are targeted as participant in most empirical papers, the educational level, sample size, sample methods, subjects, Software Development Kits (SDKs) and apparatus, scenario types and description based on a student-centered view are presented in Table 6 by means of coding analysis. Additionally, several empirical studies focus on non-students as participants in implementing Edu-Metaverse for different pedagogical purposes. Hence, the same elements targeting non-students, except for educational level and subjects, are listed in Table 7 for comparison.

3.4.2. AI-powered services

Analyzing complex multimodal data comprising visual, tactile, taste, smell, and auditory information is the core idea of enhancing the interoperability, simulation, evaluation effect and user experience during teaching-learning processes [23]. Considering the limitations existing in the implementation process of Edu-Metaverse, AI-based algorithms are utilized for breaking down the barriers and providing learners with highly personalized offerings, which are depicted in Table 8. The limitations that AI can address are discussed as follows.

3.4.2.1. Lack of manipulation proficiency. Various cutting-edge technologies engines the application of Edu-Metaverse, which means the requirements towards users in proficiency of manipulation are inevitable. If participants are more familiar with the functions of Edu-Metaverse, they will concentrate more on the learning activities [89]. Lee et al. [129] pointed out that the learners were required to have high level of control skills and operational skills, otherwise they could not fully engage in Edu-Metaverse and complete the learning tasks. To address the issue, the authors proposed a Convolutional Neural Networks (CNNs)-based ensemble model including an object-tracking module and a multiple-instance module to detect learners' learning behaviors classified into participation and non-participation to determine whether learners should be allowed to proceed to the next phase in Edu-Metaverse, of which the results showed the participants with limited manipulation skills could navigate the learning in Edu-Metaverse and the system encouraged learners' concentration and immersion.

3.4.2.2. Limitation in simulation. Even though Metaverse provides efficient, fair, and safe environments to simulate dangerous and inaccessible scenarios for pedagogical purposes, the mental state and behaviors of participants in reality are hardly reflected in the virtual world. With the benefits from AI algorithms, the Metaverse can link virtual space and human society in physical space, which simulates the real world more closely. Since some disasters, such as earthquakes, floods, and fires, are difficult to reproduce, Gu et al. [173] designed a virtual scenario and artificial society based on the social force model to simulate crowd evacuation in an emergency, and they employed Rainbow DQN, an enhanced Deep Reinforcement Learning (DRL) algorithm, to train a dynamic evacuation guidance system based on the experience obtained

Table 6
Coding analysis of empirical Edu-Metaverse study samples focusing on students and scenarios.

	Refs.	size	Sample methods	Subjects	Application	Prototype/ Apparatus	Scenario Description
Primary	[89]	72	NA	Language	Narration	Gather. Town	A story of Rose theft in a town, where learners were asked to solve problems and fulfill the missions.
	[9]	75	Simple random sampling	Biology	Storyboard	Metaverse Studio	A storyboard including human digestive system materials to show in images and students were asked to answer the questions.
Secondary	[67]	30	NA	Agriculture	Exhibition	Spatial.io	Using photos and videos to show how to control electronics or agricultural applications and key elements for sowing crops of onion and tomato.
	[127]	46	Cluster sampling	Skill Training	Exhibition	Spatial.io	Based on constructionist and imagineering learning theories, self-directed learning in both virtual and physical world were encouraged.
	[64]	85	NA	Geography	Virtual Trip	GeoVirtex/HMD	A virtual trip in five Ijen Geopark Geosites.
	[43]	48	NA	Language	Storyboard	Metaverse Studio	A storyboard including 47 scenes to help students train writing skills.
	[121]	76	NA	Language	Game	Metaverse Studio	A game based on scavenger hunt elements to introduce the United Nation's Global Goals.
	[68]	102	NA	Geography	Virtual Trip	HMD (Samsung Gear VR)	A virtual field trip in Greenland based on a documentary to experience the consequence of climate change.
Higher	[85]	96	NA	Art	Immersion	HMD (HTC Vive)	Recreating a 3D art environment using several iconic works of Van Gogh.
	[17]	60	NA	Skill Training	Exhibition	A-Frame/HMD (Google Cardboard)	A virtual exhibition created by learners with their artworks to share.
	[90]	60	NA	Language	Immersion	HMD	A virtual real-life context where learners collaborated with each other to complete the tasks.
	[31]	20	Random sampling	History	Game	Unity/ HMD (HTC Vive)	A game called 'Penjelajah' where the player explored to look for pre-historic objects.
	[53]	95	NA	Education	Immersion	Cospaces Edu/HMD	To create a virtual 3D animal zoo by learners to explore human-machine collaboration and complete tasks.
	[141]	47	NA	Anatomy	Exhibition	Spatio.io	3D models to be presented for human anatomy education.
	[178]	14	Random sampling	Nurse	Simulation	VR Chat	Simulating mock trial regarding the case between nurse's malpractice and patient safety incidents.
	[32]	117	NA	Computer Science	Game	Unity	A game where students answered questions and quizzes, explored areas, interacted with virtual objects and characters, viewed short educational videos, and solved puzzles.
	[45]	110	NA	Architecture	Immersion	PANO2VR/ HMD (Google Cardboard)	A virtual environment where learners could digitally visit construction and rehabilitation sites.
	[156]	300	NA	Radiology	Game	Second Life	A game called "League of Rays" includes various scenes created by photos and videos, where each team scored according to the results of weekly tasks' completion.
	[44]	79	NA	Biology	Virtual Lab	HMD (Lenovo Mirage Solo standalone)	A biology lab with necessary equipment where students could manipulate to complete assignment and interacted with oral and written instructions.
	[179]	50	NA	Economics	Game	Classlet	A game called "The Great Depression" mirrors realistic financial dynamics settings of Wall Street of the 1930s

Table 7
Coding analysis of empirical Edu-Metaverse study samples focusing on non-students and scenarios.

Refs.	Target	Sample Size	Sample Method	Scenario Type	Platform/Apparatus	Scenario Description
[157]	High school teachers	120	NA	Workshop	HMD (Meta Oculus Quest2)	Respectively experiencing distance learning in Horizon Workrooms, virtual tour by Meta Quest TV, and situated language learning in Immerse app.
[99]	Employee	10	NA	Game	HMD (Meta Oculus Quest2)	A serious game included quizzes, challenges, and a series of virtual playground for the training where participants earned credits and accumulated.
[84]	Teachers and students	16	NA	Immersion	Unity/ HMD (Meta Oculus Quest2)	A virtual soundstage where the teacher worked with the student in one-on-one manner for lighting lesson.
[70]	Teachers and students	30	NA	Exhibition	Metaverse Studio	A happy farm included agriculture courses with 3D animation for high-quality egg production.
[60]	Apprenticeship	9	NA	Workshop	GoPro Max2 and WebStorm	An interactive 360-degree learning environment to train participants how to use 3D printer.

from the interaction between escape situations and decision-making actions in Edu-Metaverse. It is worth noting that the authors tested the system in two different virtual scenarios to improve the stability of the neural networks, which enabled the algorithm to learn more and become more suitable for the real world.

3.4.2.3. Challenge in effective measurement. In a virtual Edu-Metaverse environment, learners are allowed to interact with vision, hearing, and communication with others, during which a vast amount of learning behavior data is produced. These data are notably important for researchers to understand users' perceptions and optimize teaching and learning processes in virtual environments. However, the progress and performance of students are complex to be measured in interdisciplinary learning environments [67]. Traditional methods, such as simple linear data analysis, cannot represent and precisely interpret the relationship between learning behavior data, while underlying information can be dug out by AI-based assessment. The support of AI algorithms facilitates not only collecting multifaceted data during the experiment such as

Table 8
Summary of AI-supported services in Edu-Metaverse empirical research.

Refs.	Model	Algorithm	Modality	Device	Training Objective	Research Limitations/ Future Works
[129]	Object-tracking learning and multiple-instance learning	CNNs	Trajectory	Video cameras	To judge learning activities and improve performance	Lack of generalization, and a vast amount of training data with significant diversity, and reliability in continuous experimental environment.
[51]	VR visualization model	DNNs	Image	CAD	To improve the quality of 3D images	NA
[90]	AI evaluation system	NA	Textual	NA	To assess grammar, syntax, and vocabulary of reading and interpretation exercises in real time	NA
[177]	Evacuation guidance system	DRL	Image	Video cameras, smoke detectors	Teaching building evacuation guidance by using dynamic navigation signs	Applying the proposed system in other scenarios with more complex building layouts.
[125]	Validation prediction model	ML	Scale value	NA	To predict elements of the given theoretical model's underlying relationship	The analyzed essential factors in the proposed conceptual model were limited and the measurement was simple.
[167]	Immersive interactive management model	ML	Gesture and gaze	LeapMotion and HMD	To improve human-machine interaction and work efficiency	Lack of the large-scale experiment verification.
[88]	Emotion recognition model	CNN-RNN fusion model	EEG	VR glasses OpenBCI EEG Electrode Cap Kit	To measure students' sense of interactivity, immersion, and cognition	The scenario in Edu-Metaverse needs to be optimized and the sample size was small due to the inaccessibility.
[174]	Perception evaluation model	ANN	Textual	NA	To evaluate participants' perception for using the Metaverse	The conceptual study model was insufficient, and more variables needed to be measured. The findings were only applicable in pedagogical field.
[145]	Speech interaction model	CNN	Vocal	Microsoft HoloLens 2	To support seamless workflow by using speech commands	Enlarging the diversity of referencing speech commands and application functions to deal with complex interactions.

electroencephalogram (EEG) [88], voice [145], and action [129], but also analyzing and evaluating participants' behaviors in Edu-Metaverse from diverse perspectives to visualize the results [90], such as the level of engagement, the degree of interactions with instructors, and mood swings [125]. Applied Machine Learning (ML) to anticipate potential relationships among the given indicators in the validation process. To explore the predictors regarding to students' acceptance of Edu-Metaverse, Almarzouqi et al. [174] Applied several methods to analyze data collected via questionnaires and compared their performances. The results indicated that the deep Artificial Neural Network (ANN) algorithm had a higher predictive outcome than the Machine Learning (ML) algorithms and Structural Equation Modelling (SEM) in assessing the association among various variables. Additionally, considering the people with autism and limb dysfunction who cannot express themselves by gesture or body movement spontaneously, Guo et al. [88] selected EEG data as learning behavior data to analyze learners' sentiment based on a proposed CNN-RNN fusion network-based emotion recognition model so as to perform personalized teaching by judging their emotional state for English education in Metaverse.

3.4.2.4. Unsmooth user experience. User experience is a key indicator to investigate the adoption of Edu-Metaverse prototypes. In fully immersive Edu-Metaverse environments, users need to interact by the handle, which will cost time remembering the instructions [167]. Siyaev et al. [145] mentioned that the users had to pronounce a precise speech command predefined to make the system respond. As a result, the users needed to learn all commands to interact with the voice before using the smart glasses, which was inconvenient. Therefore, authors trained a speech interaction model to support voice instructions and prevent inconvenience that only click, or hand gestures control the equipment under busy hands. To elevate the ease of user interaction, Wei [167] collected and processed gesture and gaze information by means of visualization algorithms so that an integrated interactive panel containing analyzed data can be visualized to interact with the virtual environment in HMD instead of manual manipulation.

3.4.3. Summary and discussion

This section clarifies how key Edu-Metaverse components, such as avatars, scenarios, and enabling technologies, participate in the implementation phase, offering researchers evidence-based perspectives for operationalizing Edu-Metaverse in educational settings. Notably, several studies emphasize that the spatial and embodied properties of the Metaverse can mitigate "free riding" in collaborative tasks; learners can only hear or communicate with peers when they are physically proximate in the virtual environment, thereby encouraging active participation [17].

In addition, numerous studies employed quasi-experimental designs by assigning learners to control and experimental groups to compare learning outcomes, rather than using randomized sampling procedures [17,43,68,85,90,121]. These quasi-experiments provide preliminary evidence for the effectiveness of Metaverse-based interventions, but A lack of randomized controlled trials could lead to restrict the strength of causal claims regarding Metaverse effectiveness [95].

On the other hand, AI-driven algorithms inject new vitality into the implementation of Edu-Metaverse, as evidenced by their applications in manipulation, simulation, measurement, and user experience optimization [175]. Future integration of AI is expected to play a crucial role in supporting personalized feedback, learning diagnostics, and performance prediction, thereby advancing adaptive and data-driven educational practices within the Metaverse [66,176]. Furthermore, research into ethical safeguards, bias mitigation, and long-term reliability of AI-driven adaptation within the Metaverse represents a critical future direction for bridging existing gaps in this domain.

3.5. Evaluation of Edu-Metaverse implementation (RQ3)

Evaluation is the final phase in the ADDIE model, based on which the feedback enables appropriate adjustments to improve implementation processes and elevate research outcomes. In the evaluation phase, existing empirical literature in terms of data collection instruments, data type, methodology and measurement are illustrated via thematic coding analysis in Fig. 8.

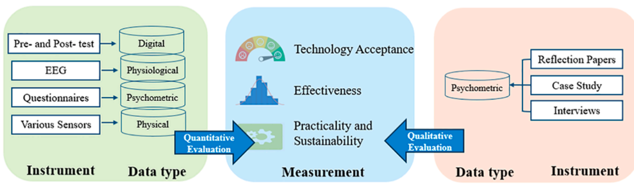

Fig. 8. The summary framework of data appraisal and measurement in the evaluation phase.

3.5.1. *Data acquisition and data appraisal*

In terms of the disparity in data collection instruments, evaluation data is classified into four categories: digital, physiological, psychometric, and physical types [36]. Digital data refers to the digits with specific information collected from test or external sensors, such as cameras, smoke detectors [177]. In contrast, physical data obtained by various sensors equipped by VR headset, such as gesture and gaze [95], is analyzed to interpret learners' learning process. Physiological type refers to the data objectively reflected human internal physiological characteristics including EEG [85]. Psychometric data is relatively widespread to be utilized for the reflection of learners' mental state, which is typically acquired from self-report questionnaires or interviews.

To give an overview of how previous studies construct the evaluation process, several aspects consisting of data collection instruments, analysis techniques, measurement, and outcome on effectiveness according to quantitative (Table 9), qualitative (Table 10), and mixed methods (Table 11) are detailed, respectively. Specifically, positive (P) or moderate (M) represent the outcome of measurement.

3.5.2. *Measurements*

According to the differences of the assessment intentions in empirical Edu-Metaverse research, three categories encompassing technology acceptance, effectiveness, usability and sustainability are summarized as follows. Respective measurement criteria and methods are also presented in this section.

3.5.2.1. Acceptance of Edu-Metaverse technology (AET) measurement. Most measurements of AET rely on learners' subjective perceptions, typically focusing on dimensions such as perceived ease of use, learnability, usefulness, immersion, interest, intention, and satisfaction. Representative studies using these constructs show that AET assessments generally emphasize how learners experience and evaluate the usability and engagement of Edu-Metaverse prototypes, rather than objective behavioral or physiological indicators [32,141,180,181]. Positive emotions can elicit better learning outcomes and enhanced learning motivation, and engagement [32], which plays an integral role in understanding the impact of the prototypes. To do this, self-reported questionnaires with 5-point Likert type scale are prevalent to be applied to collect data and analyzed by SPSS statistics such as *t*-test and the Partial Least Squares Structural Equation Modeling (PLS-SEM) to investigate the relationship between variables. Segura et al. [15] evaluated perceived criteria regarding immersion, learning motivation, satisfaction, and excitement to construct the usability tests of a MR software prototype through survey. Jovanović et al. [182] estimated user experience of VoRtex that an open-source, accessible VR software prototype, in terms of interest, satisfaction and perceived ease of use via questionnaires and advantages and disadvantages by interviews. Particularly, a usability scale questionnaire regarding participants' competence, immersion, flow, tension, challenge, negative and positive aspects was designed to assess the usability of Edu-Metaverse prototypes [32,135]. Natale et al. [180] tracked students' attitudes before and after learning in Edu-Metaverse to measure their continuance intentions, persevering in using Edu-Metaverse to learn in the future.

In addition to structured questionnaire items, many studies incorporate open-ended responses to capture learners' experiences from qualitative perspectives. These qualitative data are typically analyzed through thematic or sentiment-based approaches to complement subjective ratings. Representative work has used thematic coding to classify learners' comments (e.g., positive, negative, suggestions, teamwork) and compare patterns across cohorts [72], while others have employed open-ended reflections to evaluate satisfaction, instructional value, or domain-specific perceptions such as nursing problem-solving [167,178]. Text-oriented methods, including sentiment analysis and reflective journaling, further illustrate how qualitative evidence can enrich the understanding of user experience in Edu-Metaverse environments [17]. Beyond self-reported data, some studies integrate objective indicators to assess cognitive or affective states. For instance, EEG-based measures collected through wearable devices have been applied to monitor learners' attention levels in real time, and combined with questionnaire-based scales of control, enjoyment, mental load, and mental effort to evaluate flow experience and cognitive load within immersive learning environments [85]. Collectively, these mixed-method approaches show an expanding trend toward multi-source assessment that triangulates subjective perceptions, qualitative reflections, and physiological signals to provide a more comprehensive evaluation of Edu-Metaverse learning processes.

Table 9
Quantitative sample.

Refs.	Data Type	Data Collection instrument	Analysis Techniques	Measurement Indicators	Effect
[68]	Psychometric/ Digital	Questionnaires and pro-and post- tests	Sensitivity power analysis	Perception, learning outcome	P
[104]	Psychometric/ Digital	Pre- and post-exercise surveys, completion time	NA	Ease of use, immersion, user experience	P
[17]	Psychometric	Questionnaires, and reflection papers	*t*-test, and sentiment analysis by Orange3.0	Creativity and satisfaction	P
[15]	Psychometric/ Digital	Pre- and post-tests with control group, and open-ended questionnaires	*t*-test and eta-squared statistical tests	Usability, effectiveness	P
[127]	Psychometric/ Digital	Questionnaires, pre-and post- tests	Mean, standard deviation, and *t*-test	Validity and Learning outcomes	P
[32]	Psychometric	Questionnaires	System usability scale	Learnability, usability and attitude	P
[157]	Psychometric	Questionnaires	Reliability test using Cronbach's Alpha coefficient	Technology acceptance	P
[177]	Physical/ Digital	Video cameras, smoke detectors, and evacuation time	Deep reinforcement learning	Effectiveness	P
[64]	Psychometric/ Digital	Pre- and post- tests and questionnaires	N-Gain score test, expert validator	Practicality and effectiveness	P and M
[167]	Psychometric	Questionnaires	5-point Likert scale	Learning outcomes	P
[141]	Psychometric	Questionnaires	PLS-SEM by SmartPLS	Technology acceptance	P
[85]	Physiological	EEG brain wave detection equipment, NeuroSky headset, pre-and post- test, and Questionnaires with control group	one-way ANOVA, Paired-sample *t*-test, and eSense algorithm	Attitude, learning outcome, cognitive load and flow state, attention level	P

Table 10
Qualitative sample.

Refs.	Data Type	Data Collection instrument	Analysis Techniques	Measurements	Effect
[53]	Psychometric	Case study	NA	Validity and Engagement	P
[99]	Psychometric	Semi-structured interviews	Thematic analysis	User experience	M
[178]	Psychometric	Questionnaires, and Reflective journal	SPSS statistics and thematic analysis	Immersion and usability	P
[60]	Psychometric	Observation, Semi-structured interview, Concept Map	Video analysis, Think-aloud method	Usability	P
[101]	Psychometric	Reflection papers and semi-structured post-interviews	Inductive analysis and open coding	Perception	P

Table 11
Mixed method sample.

Refs.	Data Type	Data Collection instrument	Analysis Techniques	Measurements	Effect
[182]	Psychometric	Questionnaires and interviews	Mannien's matrix	Usability and user experience	P
[90]	Psychometric/ Digital	Pre- and post- tests, Questionnaires and Interviews	Post-test by Multivariate Analysis of Covariance	Effectiveness, Satisfaction, Attitude	P
[31]	Psychometric/ Digital	Pre- and post- tests, and Questionnaires	Expert judgement, White and black box test	Validity and Effectiveness	P
[84]	Psychometric	Questionnaires and interviews	NA	User experience	M
[67]	Psychometric	Questionnaires and observation	NA	Attitude and Learning outcomes	P
[89]	Psychometric/ Digital	Pre- and post- tests, Questionnaires, Interviews and journals	*t*-test, thematic coding analysis	Perception	P
[156]	Psychometric/ Digital	Questionnaires, pre- and post- test	Mann-Whitney *U* test, *t*-test, and thematic analysis	Technology acceptance, learning outcome	P
[135]	Psychometric	Questionnaires and interviews	System usability scale	Usability and satisfaction	P
[122]	Psychometric/ Digital	Post-tests with control group, and semi-structured interviews	SPSS statistics and thematic coding analysis	Effectiveness	P

3.5.2.2. Learning effectiveness measurement. Learning effectiveness measurement objectively assesses learners' cognitive changes concerning academic performance, skills, and knowledge acquisition before and after learning in Edu-Metaverse, which mostly aims to quantitively investigate whether the participants acquire relevant concepts and knowledge during the teaching-learning process to meet pedagogical standards. The measurement of effectiveness is a straightforward way to confirm the impact of Edu-Metaverse. To this end, pre- and post- tests focusing on test and control groups are prevalent to be adopted to measure the learning outcomes. The knowledge test scores of two-group samples were compared with each other and measured in language learning [90], immersive learning [68], gamification learning [127, 156] to verify that the implementation of Edu-Metaverse has significantly improved students' learning outcomes. To explore the change of learner's knowledge, authors typically repeated the test process with the same questions [17,68]. Sapliyan [127] designed pre-test-post-test for one-group students to compare the learning achievement scores before and after utilizing the proposed learning system based on Edu-Metaverse. Besides, Hwang [17] Conducted creativity measurements by means of questionnaires from three aspects that were creative problem solving, creative cognition and creative curiosity based on 6 Likert scale and analyzed by a response sample *t*-test. Gu et al. [177] measured the effectiveness of the proposed method in counting the evacuation time by processing physical data collected by various sensors with deep reinforcement learning algorithms.

Furthermore, in order to examine whether to foster effective collaboration and useful problem-solving during the teaching-learning process of Edu-Metaverse, formative assessment was applied since traditional summative assessment is insufficient to measure the learning experience. In [178], Participants were asked to complete a questionnaire and a reflective journal after a mock trial on medical malpractice in Edu-Metaverse, of which the reflective journal was used to explore students' learning experiences measured by thematic analysis method consisting of six stages: familiarization, coding, generation themes, reviewing themes, defining, and naming themes.

3.5.2.3. Practicality and sustainability measurement. The measurements of practicality and sustainability are considered from three main perspectives that are function, performance and reproducibility to explore whether Edu-Metaverse' s prototypes match the overall functional requirements in terms of ease of access, validity of operation, and response speed [127]. Jovanović et al. [182] compared the Edu-Metaverse prototypes' features regarding scenario design, scalability, security, content generation and interoperability based on Mannien's matrix and evaluated emerging technologies by means of weight as parameters. Putra et al. [64] respectively organized a small-scale trial based on questionnaires and a large-scale trial based on pre-and post-test to assess the practicality and effectiveness of GeoVirtex, a proposed VR-based Edu-Metaverse prototype. In addition, they verified the validity and suitability of the system in the experiment by the expert validators.

On the other hand, the reproducibility embodies in iterative development of scenarios in Edu-Metaverse for sustainable updating. Al-Karaki et al. [104] followed the approach namely 'build it, break it, fix it, use it' to develop a secure code-based messaging system in Edu-Metaverse for cybersecurity education and training. Authors tested the system from several aspects, such as web-based, access, functionality, and message storage, before implementation. Billert et al. [60] organized three iterations to discover and optimize flaws of proposed 360-degree learning environment, for example, they improved the loading time in the last iteration.

3.5.3. Summary and discussion

This section overviews the data appraisal methods and measurement approaches used in existing Edu-Metaverse empirical studies. Across the reviewed literature, a consensus emerges that positive emotional experiences and well-designed Edu-Metaverse prototypes contribute to improved academic outcomes. It is important to note that the boundaries between different measurement criteria are not always distinct, as researchers often employ overlapping indicators to evaluate multiple dimensions. For example, exploring the degree of satisfaction and immersion of participants can measure not only AET but also practicality [64].

Most evaluation approaches focus on small-scale experimental settings, with limited consideration given to broader and routine educational practice. On the other hand, a major limitation in current empirical research is the heavy reliance on subjective self-reported questionnaires to infer learners' psychological states [36]. Although such psychometric instruments are widely used, they may not accurately capture real-time cognitive or emotional processes. In contrast, objective data reflecting learners' behavioral and physiological states, such as gesture, gaze, or facial cues remain underutilized. For instance, while gesture and gaze data were collected in [167], they were not further analyzed to assess behavioral or cognitive engagement. Moreover, interpreting emotional states solely based on physical indicators is inherently constrained; individuals may intentionally suppress or alter their emotional expressions through training or social norms [88].

These limitations highlight the need for multimodal data approaches that integrate behavioral, physiological, and self-reported data to achieve a more holistic understanding of learners' cognitive and affective experiences. Leveraging AI-supported analytics to process such multimodal data presents a promising direction for enhancing the evaluation phase of Edu-Metaverse research.

4. Conclusion

Drawing on a systematic review of empirical Edu-Metaverse studies published between 2019 and 2025, this study synthesizes current implementation practices and consolidates evidence on how Edu-Metaverse has been designed, deployed, and evaluated in educational contexts. Following PRISMA guidelines, the review work moves beyond general claims about the transformative potential of the Metaverse and instead provides an evidence-based account of its practical enactment across diverse educational settings.

By organizing the reviewed empirical findings within the ADDIE framework, this study identifies five interrelated phases that are analysis, design, development, implementation, and evaluation, which collectively constitute a structured roadmap for Edu-Metaverse implementation. Each phase is grounded in recurring patterns observed in the literature, with corresponding component analysis, instructional strategies, technical considerations, and evaluation practices synthesized and discussed. This alignment demonstrates how established instructional design principles are being adapted to immersive and virtual learning environments, rather than applied in isolation.

Importantly, the thematic analysis exposes structural imbalances and research gaps within the existing empirical literature. While general disciplines such as STEM and medicine dominate current applications, domains including skills training, and the humanities remain underexplored, particularly with respect to personalized and inclusive learning designs. Moreover, evaluation practices are frequently limited to short-term learning outcomes, with comparatively less attention paid to longitudinal learning processes, instructional design scalability, and institutional integration. These patterns suggest that the current evidence base, although expanding, remains uneven in both disciplinary coverage and methodological depth.

Overall, this study contributes conceptual clarity and methodological guidance to the Edu-Metaverse research landscape by grounding its conclusions in a structured thematic synthesis. The proposed ADDIE-based roadmap serves not merely as a descriptive summary of prior work but as an evidence-informed framework to support future empirical research, design-based experimentation, and strategic decision-making. By articulating the instructional components, processes, and evaluative mechanisms underlying effective Edu-Metaverse implementation, this study provides a foundation for advancing the sustainable and pedagogically aligned integration of metaverse technologies in education.

4.1. Practical implication

The findings of this study provide actionable insights for educators, researchers, and policymakers seeking to advance the effective integration of the Edu-Metaverse. For educators, the synthesized roadmap based on the ADDIE model can serve as practical guidance for designing immersive, learner-centered experiences that align with specific disciplinary needs and pedagogical goals. For researchers, the bibliometric mapping inspires to identify research gaps and underexplored areas, such as the potential of AI-powered services and cross-disciplinary collaboration that warrant systematic investigation in future empirical studies. For policymakers and institutional leaders, the results highlight the urgent need to develop ethical, infrastructural, and pedagogical standards that ensure equitable access, interoperability, and responsible adoption of Metaverse technologies in education. Collectively, these implications aim to bridge research and practice, supporting evidence-based decision-making in the evolving landscape of AI- and Metaverse-enhanced education.

4.2. Limitations and future directions

The inclusion of this review work focuses on empirical research regarding Edu-Metaverse; thus, the studies including pertinent terms such as "VR", "AR" or "XR" independently without the term "Metaverse" in the title, abstract or keywords are not considered, which could exclude related and potential papers. Additionally, it could be limited to consider only the impact of different disciplines on the development of strategies from a practical perspective, since the selection of strategies to implement Edu-Metaverse can be dominated by the educational material, media, and learners' learning styles.

~~A methodological limitation concerns the temporal coverage of the updated search. While the supplementary 2025 search was conducted using the same procedures and criteria as the main search, database indexing restrictions prevented full retrieval of publications from July to December 2024. This gap represents a narrow window and is unlikely to impact the thematic structure or conclusions of this review, as the main search had already comprehensively captured literature up to July 2024 and the 2025 update ensured recency. Future reviews may re-examine this period once database indexing becomes fully accessible.~~

A methodological limitation concerns that the title and abstract screening was conducted by a single reviewer. Although predefined inclusion and exclusion criteria were applied consistently in accordance with PRISMA guidelines, the absence of a second independent reviewer may have introduced selection bias. Specifically, certain empirical studies, particularly those situated at the intersection of disciplines or employing less explicit metaverse terminology, may have been unintentionally excluded. This limitation may have influenced the observed distribution of instructional strategies and disciplinary domains identified in the thematic synthesis. Furthermore, confirmation bias could have played a role, where the reviewer might have unconsciously favored studies that aligned more closely with the initial theoretical framework (e.g., the ADDIE model) while overlooking studies with novel or unconventional methodologies. Future systematic reviews are therefore encouraged to adopt multi-reviewer screening procedures and report inter-rater reliability to enhance the robustness and reproducibility of study selection.

This paper sheds light on the way to apply Edu-Metaverse into practice to explore its charm and vitality through the technology of immersion and interaction. Meanwhile, it sets the agenda for further research into the feasibility of strategies to implement Edu-Metaverse in several subjects. Specifically, future studies are encouraged to develop and evaluate inclusive designs that enhance accessibility for special-needs learners, including those with physical disabilities or limited access to traditional educational resources, particularly in medical education, skill training, and the humanities. In addition, AI-powered services hold great potential for assessment and adaptive learning, enabling intelligent analytics to support personalized feedback, learning diagnostics, and performance prediction. The integration of AI in simulation, measurement, and user experience analysis also presents a promising direction for empirical and design-based research. Furthermore, exploring ethical and governance issues, such as data privacy, digital identity, and equity in virtual learning spaces is essential for establishing a more ethical, inclusive, and sustainable Edu-Metaverse ecosystem.

CRediT authorship contribution statement

Yu Shi: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Wei Wei Goh:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Investigation, Formal analysis, Data curation. **N.Z. Jhanjhi:** Writing – review & editing, Visualization, Validation, Supervision, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

Authors declare no conflict of interest.

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