Metaverse in Education: Contributors, Cooperations, and Research Themes

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***Abstract*—Research on Educational Metaverse (Edu-Metaverse) has developed into an active research field. Based on 310 academic papers published from 2004 to 2022, this study identifies contributors, scientific cooperations, and research themes using bibliometrics, social network analysis, topic modeling, and keyword analysis. Results suggest that Edu-Metaverse has been gaining increasing attention in academia since 2019. Countries/affiliations located in the same regions are close partners in scientific cooperation. By jointly interpreting topic modeling and keyword analysis results, this study reveals eight main themes in the field of Edu-Metaverse: 1) Metaverse-based physical education; 2) Metaverse-supported simulations for collaborative problem-based learning (PBL) in health/medical education; 3) 3-D virtual learning environment-supported art appreciation and creation in art education; 4) Metaverse-enabled laboratories for STEM education; 5) language and 21st century skill development through Metaverse-supported immersive language learning; 6) Metaverse for developing autism children' social communication abilities; 7) virtual world Metaverse-supported gameful experience-based education; and 8) quantitative research on Edu-Metaverse focusing on learners' experience. We also identified challenges and directions needing further attention: 1) data security and privacy protection; 2) balance between the real world and virtual world identities; 3) preparing instructors for Edu-Metaverse; and 4) assessment of higher-order thinking competencies in Edu-Metaverse-based PBL. This work helps facilitate researchers' and practitioners' understanding of Edu-Metaverse research and raises their awareness of research frontiers and future directions.**

***Index Terms*—Bibliometrics, Educational Metaverse (Edu-Metaverse), social network visualization, structural topic modeling.**

I. Introduction

METAVERSE, as a continuity of the real world in a virtual world for multisensory interaction and immersion, is considered a trend in future education. The research field of Educational Metaverse (Edu-Metaverse) is increasingly active. This study utilizes bibliometrics-based topic modeling and social network visualization methods based on up-to-date literature to gain a comprehensive review of Edu-Metaverse research from the perspectives of contributors, cooperations, and research themes.

Manuscript received 15 December 2022; revised 8 April 2023; accepted 9 May 2023. Date of publication 19 May 2023; date of current version 14 December 2023. This work was supported by the Special Grant for Strategic Development of Virtual Teaching and Learning, University Grant Committee, Hong Kong. *(Corresponding author: Di Zou.)*

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Digital Object Identifier 10.1109/TLT.2023.3277952

A. Metaverse and its Application in Education

Coined in 1992 in a science-fiction novel *Snow Crash* describing a digital world inhabited by avatars of real people, the Metaverse is a compound term combining "meta," meaning transcendence, and "verse" in the cosmic stem of "universe" [1]. As a 3-D virtual environment, Metaverse is regarded as a catch-all concept for diverse immersive technologies such as extended reality (XR) utilized to access it.

Metaverse has three unique features: "shared," "persistent," and "decentralized" [2]. Regarding the "shared" feature, instead of interacting with a system alone, the Metaverse allows barrier-free connections among users to interact, irrespective of global location, using a new identity in diverse social activities (e.g., discussion, collaborating on projects, playing games, and solving problems) that mimic real-life scenarios for value creation via multiuser virtual reality systems. Regarding the "persistent" feature, a Metaverse system, with a lifelogging ability to fully record and digitize its users' details of life in it, provides a continual world that allows users to "live" to work, learn, interact, create, and entertain. Regarding the "decentralized" feature, the Metaverse guarantees the safety of users' property/treasures and logs using such decentralized technologies as blockchains.

Attracted by the Metaverse's abilities to provide immersion, collaboration, and interaction opportunities that support the development of social experiences by allowing "parallel world[s]" to emerge [3], educators and scholars started to seek possibilities of its integration into instructional practices.

Edu-Metaverse allows students to feel the presence of learning and have more experiential learning opportunities for experiencing, exploring, learning, and practicing in complex, diverse, and authentic tasks/contexts that they cannot experience in the real world. They are also allowed to work, interact, and collaborate with people they hardly meet in the real world. In Edu-Metaverse, barriers in terms of time, space, cost, dangers, or real materials can be addressed.

A typical scenario for Edu-Metaverse's application is to allow students to virtually attend lectures to interact/communicate with instructors and classmates through avatars. Examples include Guo and Gao's [4] experiential, situational English-teaching Metaverse for immersive and interactive teaching and learning via digital identities and Lee et al.'s [5] VR-based Edu-Metaverse system for students' remote, real-time interaction with instructors and peers.

Owing to the advancement of wearable devices, high-speed computers/networks, and sensing technologies, Edu-Metaverse is becoming increasingly prevalent. Consequently, research on Edu-Metaverse has become an active topic.

B. Literature Review and Research Gaps

The remarkable opportunities of Edu-Metaverse are intensively discussed among scholars and instructors. Hwang and Chien [6] discussed potential applications and research issues concerning Edu-Metaverse and artificial intelligence (AI)'s roles in Edu-Metaverse. A survey conducted by Iwanaga et al. [7] identified a limited use of Metaverse among nonclinical anatomy instructors compared to its use in the clinical realm. Zhang et al. [8] identified the Metaverse's significance in blended learning, virtual experiment learning, language learning, and inclusive education. They pointed out challenges relating to technologies and equipment, privacy and data security, ethics and morality, addiction, and identity and social interaction. They also propose potential research issues on the topic of Edu-Metaverse, for example, methodological/pedagogical model design, stakeholders' perception of Edu-Metaverse, instructors' professional development, Edu-Metaverse's cognitive and noncognitive effects on students' performance, and assessment of learning in Edu-Metaverse. The above-mentioned studies provide a rough overview of Edu-Metaverse; however, without a systematic synthesis, they fail to enable an inclusive understanding of the state-of-the-art of Edu-Metaverse.

Several literature reviews on Edu-Metaverse and relevant topics, such as VR in education, are available. Based on a content and bibliometric analysis of 81 papers in Web of Science (WoS) and Scopus, Tlili et al. [9] suggested that the use of Metaverse expands educational opportunities for exploring environments/materials traditionally inaccessible because of space, time, and cost obstacles. Tlili et al. also indicated that the field of Edu-Metaverse is in its infancy, with research gaps in lifelogging applications, particularly relating to mobile learning, hybrid learning, and microlearning. Sarıtaş and Topraklıkoğlu [10] systematically analyzed 22 Edu-Metaverse studies in Scopus, WoS, ERIC, and ProQuest databases in terms of annual production, contributing countries, study types, and research contexts. They revealed a change of understanding of the Edu-Metaverse concept from the perspective of 3-D software to digital reality. They also indicated the prevalence of descriptive/design-based research, Second Life platforms, and Edu-Metaverse in higher education and a lack of statistical/methodological evidence. Yu and Xu [11] and Yu [12] systematically analyzed empirical studies to understand VR's effect on educational outcomes. Results showed that VR positively influenced learning outcomes, improved outcomes across the world except for Europe, and facilitated outcomes at different educational levels except for primary schools. Meanwhile, VR negatively affected anxiety, cognition, creativeness, gender differences, learner attitudes, satisfaction, and engagement.

Although previous reviews promote the understanding of Edu-Metaverse's basic status, there are research gaps. First, previous studies mostly used limited sources (e.g., WoS and Scopus) for data search. To assure review comprehensiveness and timeliness, more databases, such as IEEE Xplore, ScienceDirect, EBSCO, and especially Google Scholar, needed to be considered. Additionally, previous reviews rely much on expertise knowledge. Methodologies (e.g., bibliometric indicators, social network visualization, keyword analysis, and topic modeling) that involve the use of computer software, programs, or computational tools and are suitable for Big Data analytics are expected to automatically generate comprehensive and objective understanding of the state-of-the-art of Edu-Metaverse research.

C. Research Aims and Questions

Considering the continuing popularity of Edu-Metaverse, a review giving an inclusive understanding of its research landscape using analytical approaches capable of Big Data analysis is timely. To that end, this work provides a bibliometric overview of Edu-Metaverse to understand its contributors, scientific cooperations, and thematic structure in response to the following three research questions (RQ):

RQ1: What were the most productive sources/countries/regions/affiliations?
RQ2: What were the scientific collaborations among countries/regions/affiliations?
RQ3: What were the prevalent and emerging research topics?
RQ4: What were the subject areas and Edu-Metaverse's effects on students' learning in first-quartile (Q1) journal articles according to journal impact factor (JIF) since 2010?

The motivations for answering the RQs are illustrated as follows. First, answers to RQ1 help researchers identify sources dealing with Edu-Metaverse with an international scope, recognize suitable channels to make contributions, and be aware of essential contributors to learn from [13]. Second, research collaboration, by sharing competencies and data, can improve labor efficiency and research quality and support scientific production and knowledge creation [14]. As such, government agencies have positioned scientific collaboration at the core of innovation policy to "facilitate the creation, diffusion, and utilization of scientific knowledge and, ultimately, to boost technology development" (p. 1295) [15]. By answering RQ2, this study helps intuitively understand the social structure and leading Edu-Metaverse researchers, recognize potential academic collaborators, and supports government agencies in research policy-making to promote the production of knowledge concerning Edu-Metaverse [16]. Third, answers to RQ3 help understand the historical and present-day research progress, technological applications, and drivers of future efforts to promote Edu-Metaverse. This keeps Edu-Metaverse researchers and practitioners informed of essential issues that need attention when taking scientific or technological actions [13]. Fourth, it is important to understand how digital technologies support instruction and learning in specific subject areas [17]. Thus, answers to RQ4 concerning the disciplinary differences in the

Edu-Metaverse effect help understand Edu-Metaverse's effective integration into instructional practices for achieving specific learning outcomes.

To answer the four RQs, this study jointly applies bibliometric indicators, social network visualization, topic modeling, and phrase frequency analysis to quantitatively probe 310 Edu-Metaverse academic papers. Details about these data analysis methodologies are presented in Section II.

II. Dataset and Methods

A. Derivation and Formation of Search Terms

This study considered "Metaverse" to cover Metaverse-relevant papers. Initially, we identified "Metaverse" as a highly important and relevant term, inspired by previous reviews [9], [18], [10] that used "Metaverse" as the exact term for searching papers related to the Metaverse. Based on this term, we further extended the search list by adding relevant terms such as "augmented reality," "virtual reality," and "mixed reality." Subsequently, we conducted searches by combining education-related terms developed by referring to previous reviews [19], [10] focusing on the Metaverse's application in education and the exact "Metaverse" term or the extended "Metaverse" search term list. The use of the extended list generated a dataset with over 20 thousand records in the WoS. A random examination showed that the dataset was problematic as it contained excessive noise. Plus, it would be very demanding and time-consuming to handle the huge and noisy dataset. On the contrary, an examination of the dataset retrieved using the exact "Metaverse" term showed that most of the included records were highly relevant. Thus, we finalized to use the precise search term "Metaverse" to improve analysis efficiency and result reliability and reduce costs of time and effort.

B. Data Search and Selection

For data collection, we used ProQuest, EBSCO, ERIC, ScienceDirect, ACM, IEEE Xplore, Scopus, and WoS databases. Take the WoS as an example, the search query is as follows:

(TS = (Metaverse) AND TS = ("education" OR "college∗" OR "undergrad∗" OR "graduate∗" OR "postgrad∗" OR "K-12" OR "kindergarten∗" OR "corporate training∗" OR "professional training∗" OR "primary school∗" OR "middle school∗" OR "high school∗" OR "elementary school∗" OR "teaching" OR "learning"))

There are 600 papers collected from the above-mentioned databases. Of them, 187 duplicated papers were excluded, with the remaining 413 undergoing full-text screening. The screening results in 209 papers were excluded and 204 remained. Of the excluded papers, 202 were about Metaverse in general or other fields than education, 3 were not Metaverse-focused, and 4 were review or position papers. We additionally identified 106 papers from Google Scholars using the same search and screening strategy. As a result, 310 papers were included for data analysis. All of them 1) focused on Edu-Metaverse, 2) were journal articles, conference papers, or book chapters, and 3) were written in English.

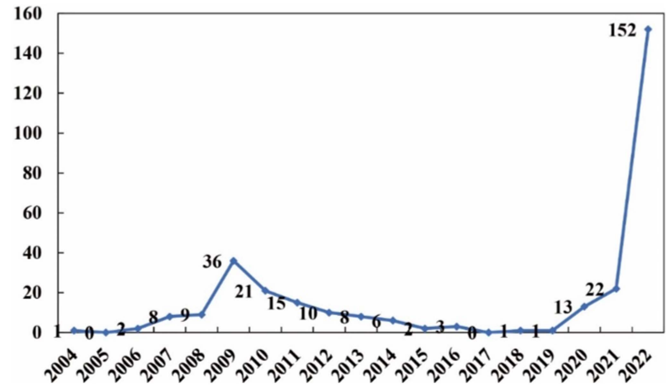

Fig. 1. Number of papers by year.

In total, 310 papers were categorized based on the published year to understand the development of Edu-Metaverse research, as depicted in Fig. 1. The earliest paper was "Exploring the instruction of fluid dynamics concepts in an immersive virtual environment: A case study of pedagogical strategies" [20], which explored a professor's pedagogical approach for instructing fluid dynamics concepts within Metaverse. However, in [9] and [18], the earliest papers regarding Metaverse's educational use were published in 2007 and 2005, respectively. This difference may be because of the wider coverage of data sources (ProQuest, EBSCO, ERIC, ScienceDirect, ACM, IEEE Xplore, Scopus, and WoS) in this study compared to the research of Tlili et al., who used WoS and Scopus, and Narin, who used WoS. For the years between 2004 and 2009, similar to Tlili et al. and Narin, we found a slow increase in Edu-Metaverse papers. The number reached a peak with 36 academic papers in 2009. The first wave of Edu-Metaverse research (approximately between 2007 and 2013) can be linked to the advancement of computers and Web 2.0 and earlier examples of virtual technologies, such as Second Life. After 2009, consistent with Tlili et al., we found a decrease in the number of Edu-Metaverse research papers until 2019 and a sharp increase from then onward. Especially in the post-COVID-19 period, the number reached a spike, with 152 academic papers in 2022. The second wave (approximately since 2021) can result from increased investments in Metaverse technologies (e.g., Facebook). The results suggested that driven by the prevalence of virtual technologies, Edu-Metaverse has aroused researchers' interest and engagement in this research field.

C. Data Analysis

In response to the RQs, 310 papers were examined to understand contributors, cooperations, research themes, subject areas, and Edu-Metaverse's effects using bibliometrics, social network visualization, phrase frequency analysis, topic modeling, and coding analysis of Q1 journal articles since 2010.

Regarding RQ1, we adopted Svensson's paper count (also called the number of papers) approach [21] to measure the productivity of publication sources, countries/regions, and affiliations. The number of papers for each publication source, country/region, and affiliation was calculated by totaling the number of contributed papers. Because the paper count approach assesses the academic levels of publication sources, countries/regions, and affiliations from a quantitative perspective, it allows the identification of top contributors in publishing Edu-Metaverse research.

Regarding RQ2, we visualized the scientific cooperations among affiliations/countries/regions based on social network analysis (SNA) [22]. SNA focuses on quantifying units' (e.g., such as individuals, organizations, or countries) relationships and the structures created through their interaction using graphical networks with nodes representing units and lines representing their quantifiable interactions [23]. As SNA displays data in a more accessible and visible manner to audiences without technical backgrounds, it has been a compelling tool for providing quantitative information regarding scientific collaborations among scholars, affiliations, or countries [24].

The present study followed [25] to define scientific collaboration that occurs when two authors affiliated with different countries/regions/affiliations copublish a paper. The affiliated country/region/affiliation of an author was determined based on the author's address information appearing in each of the analyzed papers. Thus, the cases in which some researchers change their affiliations do not affect our analysis. The following example illustrates how collaborations are determined. Suppose a paper has five authors, A1, A2, A3, A4, and A5, with affiliations I1, I2, I2, I3, and I4 that belong to countries C1, C2, C2, C2, and C3, respectively. Regarding countries/regions, there are collaborations between 1) C1 and C2, 2) C1 and C3, and 3) C2 and C3. Regarding affiliations, there are collaborations between 1) I1 and I2, 2) I1 and I3, 3) I1 and I4, 4) I2 and I3, 5) I2 and I4, and 6) I3 and I4.

Regarding RQ3, topic modeling and phrase frequency approaches were utilized to perform a computer-assisted content analysis of the Edu-Metaverse papers to identify frequently occurring themes and future directions [26], [27]. Computer-assisted content analysis is the use of computer-designed software, programs, or computational tools for automatic, quantitative analysis of texts [28]. Exampled ways of manipulating texts using computer tools include ordered word frequency lists and text content category classification using word frequency analysis and topic modeling approaches [29].

Topic models assume that documents consist of an arrangement of words that are grouped into topics based on their relationships. Each topic is a mixture of words, within which the most possible and recurrent ones present the aboutness of this topic. For example, if one of the topics in a paper is game-based learning (GBL), then it can be assumed that words such as "game," "gameful," and "gamification" are more frequent, compared to other non-GBL papers. With a collection of documents, topic models regard them to have similar topics with varied distributions. For instance, document A can be 10% and 90% related to topics Y and Z, respectively, and document B can be 40% and 60% related to topics Y and Z. As an unsupervised approach, topic models can be automated and require no human effort in creating coding sheets, thus presenting a less time- and effort-consuming approach for large-scale textual data analysis [30]. As such, topic modeling is a good fit and has been popularly adopted to uncover meaningful topics buried within big-volume academic documents [13].

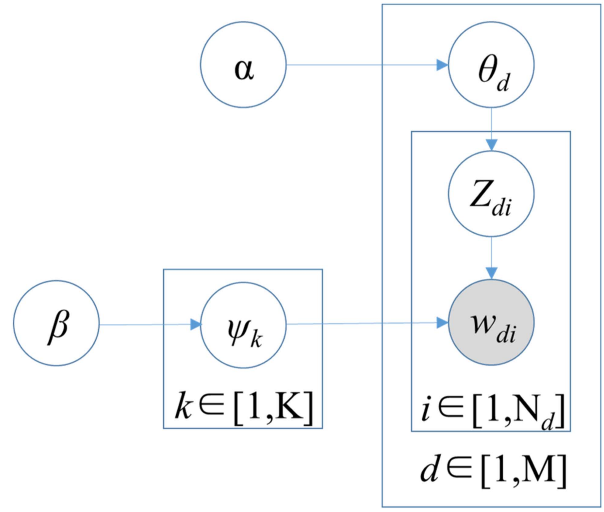

Fig. 2. Graphical representation of a typical topic model.

Fig. 2 shows a typical topic model's graphical representation [31]. A topic modeling procedure involves three stages. First, determine the word distribution of each topic k using $\psi_k \sim$ Dirichlet$_V(\beta)$. Second, determine topic distribution for each document d using $\theta_d \sim$ Dirichlet$_K(\alpha)$. Third, regarding each word w_{di} in each document d, choose a topic $Z_{di} \sim$ Multinomial $_K(\theta_d)$ and a word $w_{di} \sim$ Multinomial $_V(\psi_{Zdi})$. The inference of topic models based on a variational expectation–maximization algorithm [32] results in a series of topics underlying the thematic structure of a set of documents.

This study utilized structural topic modeling as it allows the integration of document metadata into modeling. We first used term frequency-inverse document frequencies with a threshold of 0.03 for term filtering, then followed [13] to identify 13 topics from the Edu-Metaverse dataset. Each topic's prevalence was decided using $P_k = (\sum_d \theta_{d,k}/D)$, with P_k being kth topic's prevalence and $\theta_{d,k}$ $(d = 1,\ldots,203, k = 1,\ldots,10)$ the possibility of document d's association with the kth topic.

This study also adopted phrase frequency analysis, expecting to provide a joint and comprehensive understanding of important issues addressed in Edu-Metaverse research. Phrase frequency analysis is a straightforward method to lift the recurrent phrases from and provide a compact representation of large-scale text documents [33].

Regarding RQ4, we analyzed the top ten Edu-Metaverse empirical studies published in Q1 journals according to JIF. JIF quartile estimates a journal's scientific value based on a large-source database and is extensively utilized to evaluate the quality, importance, and visibility of academic journals. For the ten Edu-Metaverse studies, we coded them from the following aspects: participants, sample size, subjects, and Edu-Metaverse's effects, to understand how Edu-Metaverse helps achieve specific learning outcomes in specific subject areas.

TABLE I
TOP PUBLICATION SOURCES RANKED BY THE NUMBER OF PAPERS

Publication sources	Number of papers
British Journal of Educational Technology	19
Metaverse	10
Computers & Education	4
IEEE Access	4
Journal of Digital Contents Society	4
IEEE Global Engineering Education Conference	3
International Conference of the Immersive Learning Research Network	3
Interactive Learning Environments	3
Journal of Educational Computing Research	3
Journal of Information Systems Education	3
Procedia Computer Science	3
Sustainability	3

TABLE II
TOP COUNTRIES/REGIONS RANKED BY THE NUMBER OF PAPERS

Country/Region	Number of papers	Country/Region	Number of papers
USA	62	India	7
South Korea	52	Indonesia	7
China	29	Taiwan	7
UK	28	Colombia	6
Japan	20	U Arab Emirates	6
Spain	13	Canada	5
Brazil	10	Hong Kong	5
Turkey	10	Singapore	5

III. RESULTS

A. Publication Sources, Countries/Regions, and Affiliations (RQ1)

Among the 310 papers, 194 and 83 were published in academic journals and conference proceedings, respectively. The top 12 sources in publishing Edu-Metaverse papers are presented in Table I, with the British Journal of Educational Technology having the most papers (19) and Metaverse being the second with 10 papers. These 12 sources together contributed to 20% (62 papers) of the total corpus. Among the 62 papers, about half (i.e., 29 out of 62) were published in journals that are among the top 25% (i.e., Q1) of the JIF distribution.

There are 64 countries/regions and 370 affiliations that have contributed to the 310 papers. Among the top 17 productive countries/regions (see Table II) that contributed to 280 papers, 10 are in Asia. These 10 Asian countries/regions contributed to more than 146 out of 280 papers. The USA contributed to most papers (i.e., 62), followed by South Korea (i.e., 52).

Among the top 21 productive affiliations (see Table III) that contributed to 100 papers, 5 are in Japan and 5 in South Korea. These 10 affiliations contributed to 48 papers. The results again suggest the notable contribution of Asian affiliations in publishing Edu-Metaverse research. The Nagaoka University of Technology contributed to the most papers (i.e., 14), followed by the National Institute of Technology (i.e., 12) and Clarkson University (i.e., 10).

TABLE III
TOP AFFILIATIONS RANKED BY THE NUMBER OF PAPERS

Affiliations	Number of papers
Nagaoka University of Technology	14
National Institute of Technology	12
Clarkson University	10
Arizona State University	6
Gifu National College of Technology	6
Chonnam National University	4
Fukui National College of Technology	4
Korea University of Technology and Education	4
Niigata University	4
Bar-Ilan University	3
King Mongkut's University of Technology North Bangkok	3
Kyushu University	3
Nanyang Technological University	3
Soongsil University	3
Sungkyunkwan University	3
Temple University	3
Federal University of Rio Grande do Sul	3
University of British Columbia	3
University of Leicester	3
University of Salford	3
YONSEI University	3

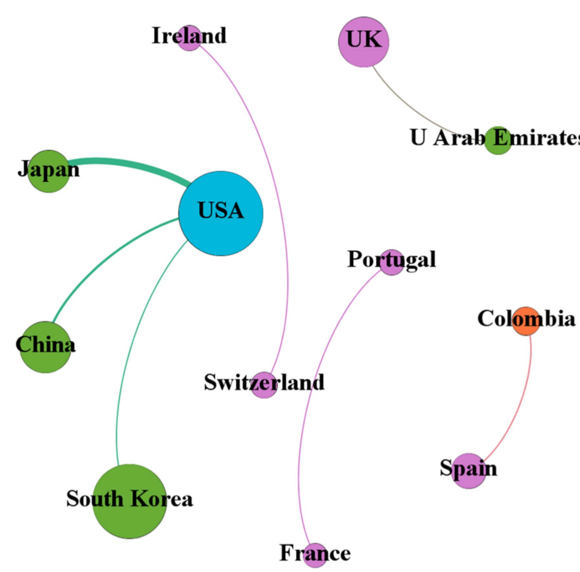

Fig. 3. Cooperations among countries/regions.

B. Scientific Cooperation (RQ2)

The cooperation among countries/regions with a minimal cooperative frequency as 2 is shown in Fig. 3. In the cooperative networks, affiliations/countries/regions are represented as nodes with the node sizes suggesting productivity and node colors suggesting geographical locations. For example, the USA was represented by the largest node, indicating it has published the most papers. The nodes in blue and green colors suggest that their represented countries/regions are in North America and Asia, respectively. Lines in the networks indicate cooperation, with their width suggesting cooperative frequencies. For example, the USA is linked with Japan, China, and South Korea, suggesting

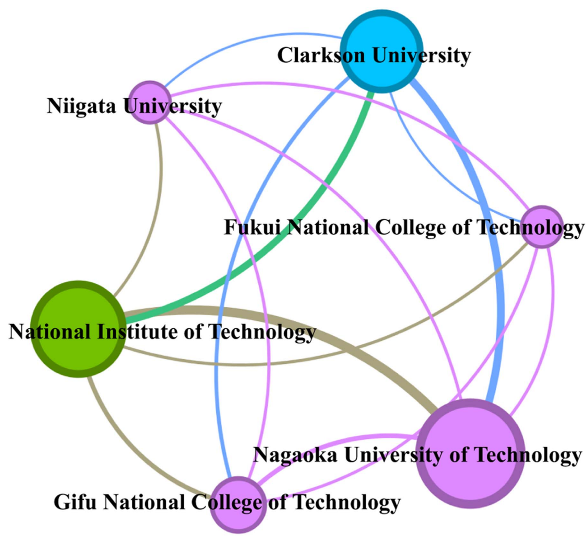

Fig. 4. Cooperations among affiliations with $3 \leq$ cooperation time ≤ 12.

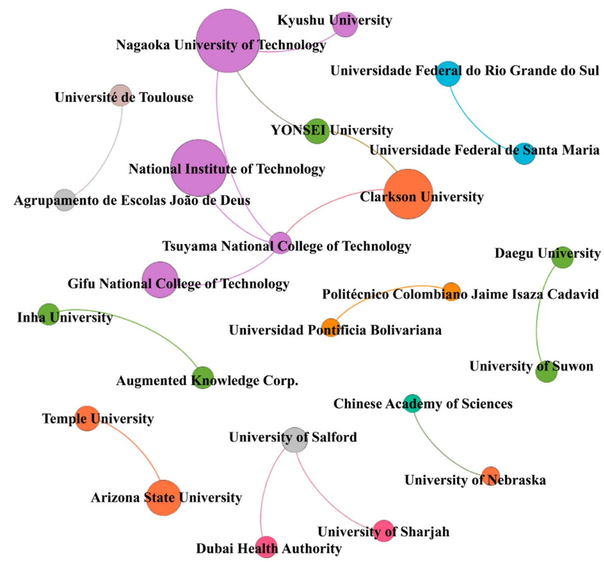

Fig. 5. Cooperations among affiliations with cooperation time = 2.

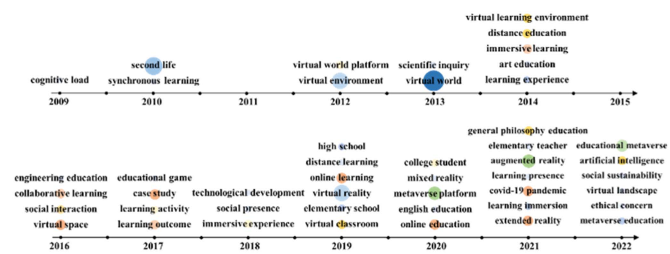

Fig. 6. Top frequent phrases.

Fig. 7. Key emerging phrases in 2022.

the USA has collaborated with Japan, China, and South Korea in publishing Edu-Metaverse papers. Especially the USA and Japan cooperated in publishing 11 papers. The USA and China cooperated in publishing four papers. These three countries are also ranked top regarding productivity (see Table II). The results also showed that countries located in the same regions are more engaged in collaboration, as evidenced by, for example, 1) Ireland and Switzerland and 2) Portugal and France.

The cooperations among affiliations with a cooperative frequency of more than 2 are presented in Fig. 4. The nodes representing the Nagaoka University of Technology, Gifu National College of Technology, Fukui National College of Technology, and Niigata University are colored in pink to suggest that they are from Japan. The nodes representing the National Institute of Technology and Clarkson University are colored in green and blue, suggesting that they are from India and the USA, respectively. Three wide lines suggest close cooperative relationships among 1) Nagaoka University of Technology and National Institute of Technology (cooperating in 12 papers), 2) Nagaoka University of Technology and Clarkson University (in 10 papers, and 3) National Institute of Technology and Clarkson University (in 9 papers). These three affiliations are also ranked top regarding productivity (see Table III). The cooperations among affiliations with a minimal cooperative frequency of 2 are presented in Fig. 5, which shows that the cooperations among affiliations from the same countries/regions are intense, especially those from Japan.

C. Frequent and Emerging Phrases (RQ3)

Fig. 6 gives the frequently-used phrases, integrating with a timeline averaged by the publication years of the papers, including each phrase. Fig. 7 presents emergent phrases in 2022. The results show important research issues concerned by Edu-Metaverse scholars. For example, the phrases "digital medium art" and "art education" suggest the Metaverse's use in art education. Phrases, such as "engineering education," "scientific inquiry," "science teaching," "engineering competency development," and "artificial intelligence education" suggest Metaverse's use in STEM education. Phrases, such as "physical education," "football teaching," and "sport science" suggest Metaverse's use in physical education. Phrases, such as "patient care," "medical education," and "autism spectrum disorders" suggest Metaverse's use in health/medical education and special education. Phrases such, as "english education," "korean

TABLE IV
RESEARCH TOPICS AND THEIR PROPORTIONS

Labels of topics	Topic proportions
communication in metaverses	13.05%
second life	12.30%
problem-solving and gamification in metaverses	9.58%
architecture design of metaverse systems	9.51%
course content development with metaverses	8.60%
presence and interest development for metaverses	7.08%
3D virtual reality in metaverses	7.06%
teacher training in metaverses	7.06%
collaboration in virtual environments and metaverses	6.70%
design and culture in metaverses	5.90%
adoption of metaverses in higher education	5.78%
metaverses for GBL	4.82%
ethical issues in metaverses	2.56%

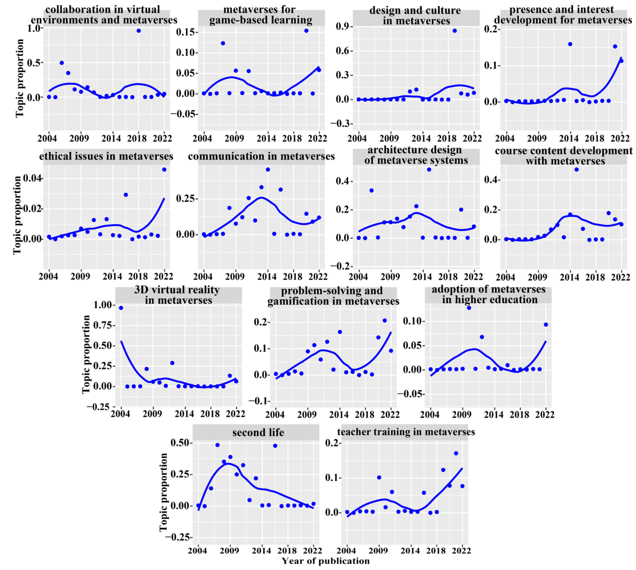

Fig. 8. Proportions of research topics by year.

language," "multicultural education," and "global citizenship education" suggest Metaverse's use for language and multicultural education. Phrases, such as "digital game," "Metaverse game," "gameful experience," and "educational game" suggest Metaverse-supported GBL. Phrases, such as "learning satisfaction," "learning motivation," "cognitive increment," "immersive experience," "learning experience," "learning presence," and "social presence" suggest an increased interest in understanding learners' experience in Metaverse-supported learning environments. Phrases, such as "statistical analysis," "quantitative research," and "mixed-method approach" suggest diverse research and analysis methodologies used in Edu-Metaverse research.

D. Research Topics and Their Developments (RQ3)

Table IV gives topic modeling results with 13 topics. The most prevalent topics are *communication in Metaverses*, *second life*, *problem-solving and gamification in Metaverses*, and *architecture design of Metaverse systems*. A further interpretation of papers focusing on each of the identified topics strengthens our understanding of the main research focus. For example, most papers related to the topic of *communication in Metaverses* focused on social communication ability development.

Fig. 8 visualizes the proportions of research topics by year, with the x- and y-axis suggesting the year of publication and the annual proportion of each topic, respectively. The results showed that some topics became more popular with time going on, for example, *Metaverses for GBL*, *presence and interest development for Metaverses*, *ethical issues in Metaverses*, *problem-solving and gamification in Metaverses*, *adoption of Metaverses in higher education*, and *teacher training in Metaverses*. The year-by-year analysis provides detailed insights into how each topic developed. For example, there has been an increased interest in the learners' *presence and interest development for Metaverses* among scholars since 2017. Also, there has been a sharp increase in research interest in *problem-solving and gamification in Metaverses* and *Metaverses for GBL* since 2015.

E. Coding Analysis of Edu-Metaverse Experimental Studies (RQ4)

The results of the participants, sample size, subjects, and Edu-Metaverse's effects in the ten Edu-Metaverse empirical studies are presented in Table V.

In [34], 102 middle school students were assigned to head-mounted display (HMD) and 2-D video groups to participate in a 6-lesson inquiry-based climate change intervention. A structural equation modeling analysis suggested that the HMD group showed significantly higher levels of presence, enjoyment, interest, and retention compared to the video group.

By analyzing students' emotional electroencephalograms using convolutional and recurrent neural networks, Guo and Gao [4] suggested that Metaverse-empowered experiential situational English instruction promoted students' sense of interactivity, immersion, and cognition.

By using a workshop-based mixed-method with nine precision mechanics as participants, Billert et al. [35] showed interactive, Metaverse-empowered 360° learning environments' positive effect on learning outcomes and motivation.

Heo and Kim [36] proposed a projection-based augmented reality (AR) affordance system that allowed learners to observe demonstrations in real-time and climb as instructed even when instructors are absent. A comparison with the conventional instruction approach showed the effectiveness of AR in promoting sports climbing motor performance.

Garrido-Iñigo and Rodríguez-Moreno [37] adopted an OpenSim platform to teach French to 108 undergraduate students. Assessment results of reading comprehension, listening comprehension, and written expression showed the Metaverse design's positive effect on language acquisition.

By evaluating the attitudes and experiences of 16 nursing undergraduate students who were exposed to 6 simulated clinical scenarios within Second Life, Rogers [38] showed Second Life's effectiveness in developing cognitive understandings of

TABLE V
CODING ANALYSIS OF EDU-METAVERSE EXPERIMENTAL STUDIES

Studies	Publication sources	Participants	Sample size	Subjects	Edu-Metaverse's effects
Makransky and Mayer [34]	Educational Psychology Review	Elementary school students	102	Climate change	Improve presence, enjoyment, interest, and retention
Guo and Gao [4]	Frontiers in Psychology	No specify	No specify	English	Improve sense of interactivity, immersion, and cognition
Billert et al. [35]	IEEE Transactions on Learning Technologies	Precision mechanics age range of 25-40 years	9	Work-process-integrated learning	Improve learning outcomes, motivation, ease of use, and sense of presence
Heo and Kim [36]	Human-Centric Computing and Information Sciences	No specify	40	Sport climbing	Improve motor performance
Garrido-Iñigo and Rodríguez-Moreno [37]	Interactive Learning Environments	Undergraduate students	108	Foreign language	Improve language acquisition
Rogers [38]	British Journal of Educational Technology	Undergraduate students	16	Nursing	Improve problem-solving, technical, and interpersonal skills
Charles et al. [39]	British Journal of Educational Technology	Undergraduate students	No specify	Computing	Improve engagement, identity, social dimension, and performance
Ketelhut et al. [40]	British Journal of Educational Technology	Middle-school students	2000	Science	Improve understanding of scientific inquiry
Erlandson et al. [41]	Educational Technology Research and Development	Undergraduate students	78	Science	Reduce cognitive load
Passig and Eden [42]	Journal of Educational Computing Research	Pre- and elementary school students	134	Language	Improve cognitive abilities

team-orientated procedural and problem-based decision-making skills.

Based on an evaluation of undergraduate learners' experience with a game-based feedback (GBF) system that offers reward-based feedback for participation in a computing course within multiuser virtual environments (MUVEs), Charles et al. [39] showed that the GBF could harness unique aspects of virtual worlds to improve learners' engagement, identity, social dimension, and performance.

By evaluating 2000 middle-school students' experience with MUVEs as pedagogical vehicles in standards-based science curricula, Ketelhut et al. [40] suggested that inquiry- and standards-based content integrated into virtual environments helped low-performing students master complex inquiry skills.

In [41], a control-treatment experiment with 78 undergraduate education majors participating in science inquiry curricula within MUVEs showed that the use of voice-based communication could reduce cognitive load.

By examining the expression of time and cause-connectives among participants, Passig and Eden [42] showed 3-D virtual representations' effectiveness in facilitating both hearing children and children with hearing impairment to express stories while producing connectives indicating relations of time and cause and effect.

IV. DISCUSSION

A. Answers to RQs

This topic modeling-empowered bibliometric study explores contributors, cooperations, and research themes in the field of Edu-Metaverse. From Fig. 1, there are two waves of Edu-Metaverse research: during 2007–2013 and from 2021 onward, owing to advanced computer and Web 2.0 technologies and increased investments in virtual and Metaverse technologies. Since 2019, Edu-Metaverse has attracted growing attention from educational researchers.

In response to RQ1, at present, Edu-Metaverse studies are distributed in a wide range of sources. However, as reflected in Table I, among 62 papers published in the top 12 sources, about half were published in two journals: Metaverse and British Journal of Educational Technology, whereas the rest sources contributed to less than five papers each. We thus call for special issues or sessions regarding Edu-Metaverse launched by international educational technology journals and conferences to encourage more research output in this field. According to the country/region analysis (see Table II), the large increase in the number of Edu-Metaverse papers is attributable to important contributions made by the USA and Asian countries/regions (e.g., South Korea). Analysis of affiliations further suggests the numerous contributions from Asia, with several affiliations (e.g., Nagaoka University of Technology and National Institute of Technology) playing important roles in publishing Edu-Metaverse papers, as shown in Table III.

In response to RQ2, according to Figs. 3–5, countries/regions that showed a greater number of international collaborations developed rapidly, as reflected by the USA, Japan, Clarkson University, National Institute of Technology, and Nagaoka University of Technology, all of which are ranked top regarding productivity in Tables II and III. This demonstrates the importance of international collaborations in the research field of Edu-Metaverse. Figs. 3–5 also suggested that countries/regions/affiliations in the same regions are more engaged in collaborating on Edu-Metaverse research. This can be a result of the naturally easy and convenient research communication and resource sharing owing to geographical advantage. However, Guerrero Bote et al. [43] suggested addressing negative neighborhood effects by collaborating with countries/regions farther away to increase gains in impact. We thus call for more cross-regional cooperations to better embrace challenges as Edu-Metaverse advances.

In response to RQ3 relating to research themes, this study developed eight themes based on a joint interpretation of the results of phrase frequency (see Figs. 6 and 7) and topic modeling (see Table IV and Fig. 8) analysis as well as by examining papers focusing on the identified topics and phrases. More details about the formation of each theme are illustrated below.

In response to RQ4, the coding analysis of the ten Edu-Metaverse empirical journal articles since 2010 showed Edu-Metaverse's prevalence in various subject areas, especially in language and science education. Undergraduate students are participants in most studies. Common learning outcomes reported include motivation, sense of presence, engagement, immersion, interest, and performance.

The following sections introduced the eight main themes that represent the current and emerging research issues in the field of Edu-Metaverse. Thereafter, challenges and future directions for applying and researching Edu-Metaverse are discussed.

B. Metaverse-Based Physical Education

Evidenced by the emerging phrases such as "physical education," "football teaching," and "sport science," as indicated in Fig. 7, this study formed the first theme as "Metaverse-based physical education."

The application of Metaverse in motor learning and physical education is promoted to tackle challenges of training disruptions caused by force majeure such as COVID-19. The demand for combining (shifting) online and (to) offline is challenging for motor learning where learners need to repeat monotonous and tedious movements for skill acquisition [36]. With Metaverse, a learner can carry out real-world tasks in twinned virtual spaces under instructors' real-time guidance to master techniques, tactics, and knowledge. Affordances of a Metaverse in physical education included [44], [45]: 1) stimulating immersion/interest, 2) supporting flipped learning, and 3) providing routes/feedback in real time. These affordances can be explained by demonstrating exampled physical learning activities.

First, AR space makes emotional satisfaction derived from interest and pleasure by inducing learners to imitate/learn easily through virtual characters. The virtual character presents a specific situation associated with a sports activity to a real-world learner. The learner is synchronized with the movement of the character to act/move in real-world scenarios in a state close to unconscious processing, which, according to Allen et al. [46], has a positive impact on motion performance to ensure accuracy. Take rock-climbing training as an example, a projection-based AR maximizes a learner's multisensory immersion by projecting virtual characters directly on real rock walls. The sensory immersion makes the learner feel the character's movements as real and motivates her/him to actively participate by touching/grabbing the holds on augmented rock walls [36].

Second, the Metaverse provides opportunities for learners to self-watch instructor-prepared 360° panoramic VR videos concerning a particular sports training before class, and thereafter, attend classes with what they do not understand to communicate and discuss with instructors and peers. Take football training by Li et al. [45] as an example, instructors develop 360° panoramic football instructional videos integrating with relevant knowledge and football testing and upload them to the Edu-Metaverse platform for learners to learn and practice to master football movements independently in their spare time. To promote preclass learning effectiveness and improve learners' quality of experience, VR videos' quality, which relies highly on intelligent and effective distribution and caching, has been a wide concern by scholars. For example, Li et al. explored the K-means model's potential for VR football instruction video delivery in mobile Internet environments to achieve independent football teaching and receiving. Taleb et al. [47] utilized "network functions virtualization and multi-access edge computing technologies for the provision of video content delivery network functionality as a service over a multi-domain cloud" (p. 2010).

Last, the Metaverse improves understanding and application capabilities through complex posture/movement visualization in 3-D spaces and overlays them on real scenarios to assist learners in deciding and controlling their behaviors [36]. For instance, Sano et al. [48] augmented soccer learners' positions to help them develop decision-making competencies. A visualization instrument is developed by Kelly and O'Connor [49] to augment information about tennis techniques, timing, and body postures to facilitate learners' learning. According to Heo and Kim [36], visual animation information that is learned by observing virtual characters' demonstrations in real-time when moving/acting has a positive effect on motor performance, even without instructors' guidance. In mimicking the character's animation provided by AR affordance to climbing walls, learners could focus on controlling their bodies to learn unfamiliar movements in real time. In [50], a self-correction projection tool was utilized to project climbing videos and routes as shadow-shape images onto artificial climbing structures to allow learners to check and adjust their movements in real time when climbing. In adjusting motivations, the Metaverse also allows recording and analyzing a learner's moves/actions to automatically generate concrete and clear clues/routes suitable for her/his motor abilities and learning styles in real time. This feature is especially useful for beginners in their learning of motions without the presence of instructors after determining their preferred routes/moves. Compared to video playback or coaching feedback, augmented feedback induces faster and more efficient motor learning [51]. Particularly, in the case of group sports learning, Metaverse's use can reduce the time needed for a team to adjust positioning and master new tactics.

C. Metaverse-Supported Simulations for Collaborative Problem-Based Learning (PBL) in Health/Medical Education

There is an increased interest in health/medical education supported by Edu-Metaverse, evidenced by the emerging health/medical education-related phrases such as "patient care" and "medical education," as indicated in Fig. 7. An examination of the papers containing these phrases showed that Metaverse was mainly adopted to support problem-based clinical simulations, especially in collaborative learning settings. We thus formed the second theme as "Metaverse-supported simulations for collaborative problem-based learning (PBL) in health/medical education."

In health/medical education, clinical simulations expand learners' clinical experiences by providing valuable practice-based learning opportunities for problem-based decision-making in safe and nonthreatening environments based on real-life scenarios. During simulated PBL, learners learn professional concepts from direct experience, observation, and reflection, the process of which, known as experiential learning, allows learners to make illuminating discoveries and develop higher-level cognitive understandings.

Given problem-based simulations' affordances for increasing self-confidence, improving clinical judgment, and developing problem-solving abilities, they are increasingly integrated into health/medical classrooms for various purposes. Examples include teaching facts, principles, and concepts, evaluating learners' progress/competencies with specific skills, operating medical apparatus/equipment, and developing problem-solving and diagnostic reasoning abilities [38].

Researchers and instructors have exploited technologies' role in promoting effective simulations, especially when in-person learning is unavailable [7]. Various computer-based clinical simulation (CBCS) tools have been tested and are now popular in instructional practice due to their advantages in low-cost, allowing flexible learning, learner-centeredness, and promoting active learning. However, there are challenges relating to CBCSs and their effects on learners' learning, for example, the lack of collaboration and team-guided practices, which are essential for promoting clinical reasoning and encouraging learning. According to Petty [52], learners retain 10% (30%) of what they read (view); however, they retain 50% (90%) from interactive learning (of what they act on). This conforms to the constructivist theory suggesting knowledge construction and more effective learning from active engagement in collaborative problem-solving [53]. Therefore, simulations require team-based social structures to allow learners to co-construct knowledge collaboratively [38].

Information and communication technologies (ICTs), such as emails and instant online communication apps, are popular in supporting virtual teams' communication, coordination, and control [54]. Compared to these ICT tools, Metaverses can more effectively transmit nonverbal cues such as facial expressions/gazes via digital presence, which allows turn-taking in socioemotional environments to achieve effective collaboration and knowledge sharing. In such nonthreatening simulated environments, with user-represented avatars, people communicate with voices and texts, interact with objects, and produce, observe, post, and receive information, to apply experiential knowledge, values, and skills. This is especially important in clinical simulations since an effective educational simulation ought to offer experiences in and appreciation for PBL in social richness environments. As such, the Metaverse is increasingly used in clinical simulations. For example, Rogers [38] optimized clinical simulations in Second Life to promote teamwork/collaborative PBL among nursing learners in isolated locations. The simulation covered diverse "problem-based scenarios [incorporating] concepts of technical skills, patient interaction, teamwork, and situational awareness" (p. 608). Qualitative feedback from learners suggested Metaverse-supported simulations' effectiveness in creating artificial social structures to allow learners' active mental model co-construction of technical/interpersonal competencies through collaboration and interaction in problem-based scenarios.

D. 3-D Virtual Learning Environment (VLE)-Supported Art Appreciation/Creation in Art Education

Third, art education is a popular issue among Edu-Metaverse scholars, evidenced by the high frequency of "art education" and emerging phrases, such as "digital medium art," as indicated in Figs. 6 and 7. Furthermore, most of the studies focusing on the identified topic of *3-D virtual reality in Metaverses* presented in Table IV were related to art education, so we formed the theme "3-D VLEs-supported art appreciation/creation in art education."

Alongside the pervasion of digital visual culture in the young generation's lives, educators have been exploiting computer-mediated learning environments for delivering or enriching art instruction by engaging/motivating young learners to apply their preferred and familiar digital technologies as effective learning media. 3-D VLEs, with immersive and interactive features, have received attention for their potential to promote art appreciation and creation in art learning. For one thing, within the 3-D visually enriched learning environment, art instructors can deploy well-designed instructional activities to transform learners into active participants to initiate navigation, interaction, and knowledge construction. An example of this is Art Café [55], which, with art galleries for featured exhibitions, allowed learners worldwide to select preferred virtual identities/appearances, interact in real-time, ask instructors/peers questions about work intentions, and receive instant instructor/peer support/feedback. Such interactive experiences stimulate active learners by engaging them in meaningful conversations about art/visual culture and preserving a sense of ownership of their art conversations.

For another thing, 3-D VLEs bring exceptional opportunities for learners to blend physical surroundings with digital creativity to convey ideas/observations and share feelings/thoughts. This is a result of the prevalence of computer-enriched computational arts and the advances in AI that allows computers' active participation in art creation with creators, thus bringing exciting opportunities for human–AI collaboration in artistic creation at scale [56]. For instance, an AI-empowered instrument developed based on a StyleGAN model creates new anime characters based on intuitive adjustment of parameters relating to mouth, eyes, and hair. In the Metaverse, content creation is a critical ecosystem factor to its sustainability. By allowing virtual–physical co-existence due to the high-level scene understanding feature, Edu-Metaverse provides massive opportunities for art learners to discover new ways of creating artworks with computer-empowered settings and seamlessly mixing virtual arts and physical surroundings/objects to convey ideas, messages, and creativity. By allowing multiuser socialization and cocreation, art learners (creators) in the Metaverse can socialize with each other virtually and achieve their common goals of creating new artistic content.

E. Metaverse-Enabled Laboratories for STEM Education

We formed the fourth theme, "Metaverse-enabled laboratories for STEM education," to discuss a wide interest in STEM education among Edu-Metaverse scholars, evidenced by the high frequencies of STEM-related phrases, such as "engineering education," "scientific inquiry," "science teaching," "engineering competency development," and "artificial intelligence education," as indicated in Figs. 6 and 7.

Alongside the increasingly complicated world are growing expectations/demands for equipping individuals with contextualized knowledge/skills covered by STEM using transdisciplinary education approaches to resolve real-life problems. In traditional STEM instructional classrooms, there are problems of time constraints, integration, and large-scale learners, which can be overcome by Metaverse. Metaverse provides enormous near-real experience opportunities for STEM education to "increase the means to present applications more appropriately (p. 3)" [57] by coordinating engineering, science, and mathematics with a transdisciplinary theme.

In modern engineering education, to encourage leading innovation, solving engineering problems, and converting research findings into value-added products/services, learners' engineering competency and design capability are critical. The former emphasizes applying technical knowledge to real-world engineering practices; the latter stresses planning and devising problem-solving procedures/approaches. To achieve this, laboratory practices and hands-on or case-based learning in highly interactive class sessions are popular engineering instructional strategies [58]. However, a physical laboratory that requires a substantial amount of space and complex, specialized hardware/infrastructure [59], is costly to build and maintain. Moreover, challenges in managing infrastructure and organizing physical laboratories become more obvious when there are learners in volumes, thus making the infrastructure unscalable. To address the limitations of physical laboratories, educators have leveraged advanced ICTs to create technology-enabled laboratories, such as virtual, remote, take-home laboratories, and non-face-to-face (NFF) education through teleconferencing platforms. However, in NFF education, there are difficulties in recognizing nonverbal communication and giving/receiving feedback. Metaverse-empowered NFF education is presented to resolve this limitation and promote engineering learning outcomes through immersion. For example, a remote laboratory in OpenSim supported students' engineering learning by allowing them to interact in the virtual world with replicas of faculty instruments; their actions were then performed in physical laboratories with results being visualized remotely [60]. In [59], a "RelmagIne Lab" leveraged digital twins and XR technologies for streamlining the operations of hands-on, virtual, and remote engineering laboratories, where high-level interaction, immersion, and collaboration are encouraged to boost learners' engagement.

Traditional mathematics instruction modes, where instructors explain subject matter on blackboards and learners listen to understand the delivered content, often lead to a feeling of boredom and reduced learning interest. Realizing this, Educators have exploited ICT-supported mathematics learning media to increase learners' interest and willingness to learn and help them understand and master mathematics knowledge. The use of ICTs in mathematics allows experimental learning to visualize a problem situation and test hypotheses and conjectures, which is more effective than when using only pencils and paper. Literature has evidenced that ICT-empowered mathematics instruction not only consolidates classroom learning but only increases learners' interest in and desire for learning, thus increasing permanence and outcomes. Among the diverse ICTs, Metaverse-empowered instruction adds value in cultivating learners' visual understanding and perception of mathematics concepts by visualizing abstract concepts to look actual and blend into the real world. This conforms to Saundarajan et al.'s [61] discoveries that using AR helped grasp the association between information and the comprehension of things displayed with real-time visual assistance. The enhanced visual understanding, in turn, promotes learners' development of spatial visualization capabilities/skills [62]. Because of these benefits, Edu-Metaverse platforms developed based on VR/AR are increasingly utilized in mathematics instruction. In [63], with the capabilities of embodying abstract concepts, making the lesson fun, and facilitating learning, a mobile AR-empowered mathematics instructional tool was reported to improve primary school learners' success in creating symmetry and understanding symmetry concepts.

The visual and experimental experiences provided by Metaverse are especially important in science education because "the intuitiveness of presenting scientific phenomena and the operability of experimental instruments require learners to directly observe, contact and operate in teaching activities to obtain cognitive results (p. 132)" [64]. In real-world science classrooms, restricted by environments and resources, a lot of practical activities are not easy to implement; thus, instructors mostly explain scientific knowledge/scenes verbally or guide learners to spot scientific phenomena through personal demonstrations. Such instructional approaches provide limited care and guidance for individuals and are unfavorable for developing learners' competencies to understand, explore complicated scientific knowledge, and practice intuitively, particularly for those with weak abstraction abilities. Science instruction models that involve experimental operations and observations in the Metaverse overcome the constraints of environmental/resource factors and have attached great importance to real immersive experiences. In their learning in the Metaverse, learners' subjectivity and self-learning abilities are awakened through experiencing situated scientific inquiry learning involving such process skills as questioning, hypothesizing, and testing. By converging theoretical explanations and concrete practices [5], the Metaverse helps learners develop personal understandings in favor of mastering scientific knowledge/skills. Specifically, in the Metaverse, diverse learning resources are visually presented to learners through AR. Instructors set up virtual tasks and explain operation steps through mixed reality (MR). Learners perform practical operations as virtual avatars independently or collaboratively under instructors' remote personalized guidance to resolve scientific problems, raise questions, develop reasonable conjectures and assumptions based on practical evidence, and confirm/change perspectives to attain scientific knowledge and master scientific skills in depth. In a multiuser virtual world created by Ketelhut et al. [40] to assist instructors in an infusing inquiry into standards-based science curriculums, learners interacted with "avatars" of peers, digital artifacts, and computer "agents" representing mentors/colleagues in a virtual community at the time of first bacteria being discovered to conduct scientific inquiry. In a virtual immersive education system developed by Lee et al. [5] using VR and Metaverse, learners effectively immersed themselves in aircraft maintenance simulations that are high-cost and high-risk in the real world by interacting with virtual objects and repeating practicing complex and difficult training in a safe and low-cost manner.

F. Language and 21st-Century Skill Development Through Metaverse-Supported Immersive Language Learning

There is an increased interest in immersive language education supported by Metaverse evidenced by the emerging phrases such as "english education" and "korean language" presented in Fig. 7. By examining the papers that contain these phrases, most relevant studies adopted Metaverse for promoting the development of language skills and 21st-century competencies such as cultural awareness, evidenced by emerging phrases such as "multicultural education" and "global citizenship education" presented in Fig. 7. We thus formed the fifth theme as "language and 21st-century skill development through Metaverse-supported immersive language learning."

3-D VR tools featuring multiple communication channels and high visual appeals address the limited exposure learners experienced in oral-visual interaction owing to physical distance by extending communicative/interactive opportunities beyond lecture experiences to foster "spontaneous communication and interaction (p. 554)" [65]. This is especially essential in language learning since learners need direct and frequent social interaction to practice the target language in authentic, situated exchanges [16]. Specifically, the Metaverse removes the limitations of decontextualized foreign language classrooms to offer learners immersive learning experiences by merging the boundaries between the real and virtual worlds. Language instructors are allowed to check on learners' knowledge and analyze their language use from syntagmatic, paradigmatic viewpoints based on their performance and behavior data during virtual learning [37].

Advances in AI, especially natural language processing, speech recognition, and social communication technologies, make it affordable to use Metaverse to support social, authentic, and immersive language learning to cultivate spontaneous productive skills, improve second language fluency, and develop communicative competencies [66]. Consequently, educators and researchers working on computer-aided language education are increasingly exploiting pedagogical values of a Metaverse in language learning, with positive outcomes being reported, for example, increased motivation, engagement, and attention in learning increased language proficiency and vocabulary acquisition, cultural learning, and decreased foreign language anxiety.

In addition to language skills, the Metaverse also provides exciting opportunities for cultivating 21st-century competencies, for example, teamwork, autonomy, and cultural awareness. For instance, the use of a spherical video-based VR system for English-speaking training with peer assessment approaches significantly promotes learners' critical thinking. A collaborative VR learning system described in [67], by allowing learners to access places/situations inaccessible in conventional classrooms to communicate in target languages for problem-solving, contributes to learners' language gains and increases critical thinking. The interactive aviation English tasks in VR were reported by Park [68] to facilitate learners' adoption of diverse cognitive and metacognitive strategies strategy types, thus improving their test performance.

G. Metaverse for Developing Autistic Children's Social Communication Abilities

As indicated in Fig. 8, there is an increased interest in supporting students with "autism spectrum disorders" using Metaverse among Edu-Metaverse researchers. An examination of papers containing terms such as "autism" and studies focusing on the topic of *communication in Metaverses* (see Table IV) showed the prevalence of Metaverse's use for supporting autistic children's development of social communication abilities. We thus formed the sixth theme as "Metaverse for developing autistic children's social communication abilities."

The socialization capability of Metaverse is especially essential for children and adults with autism spectrum disorders (ASDs) to develop their social communication abilities. ASD is a complicated developmental condition involving persistent difficulties in "social communication and interactions across multiple settings (p. 51)" [69], with restricted/repetitive behaviors. These difficulties complicate relationship development/maintenance for autistic children and adults, thus placing them at high risk for anxiety/depression. To improve autistic children's cognitive development/behaviors, continuing training is inevitable; however, traditional offline training suffers from the limitation of fixed training locations due to the shortage of special education instructors, making the training difficult to continue.

The democratization of VR technologies, plus the growing demand for shifting conventional therapeutic settings to internet-driven therapy, has stimulated educators to exploit technology-empowered interventions to enhance social outcomes for autistic individuals for their mental and behavioral health [70]. By continuously providing realistic, immersive instruction, Metaverse-based training systems show exciting opportunities for improving social competence/skills for autistic individuals, and meanwhile, guaranteeing care continuousness, low cost, high accessibility, and easy dissemination. By allowing to participate in various types of collaborative activities via the internet, VR Metaverse games contribute to fostering a sense of belonging and developing friendships, which helps in autistic children/adolescents' social/emotional development.

Rather than regarding ASDs as something that needs to be mediated/accommodated, the Metaverse strengthens healthy communication/social connections and alleviates social isolation by allowing autistic individuals' possessed skills and insights to be accessed and shared. Metaverse has thus been considered valuable by autistic children's parents and educators for providing practice opportunities with reduced social pressure and constraining viewing areas and auditory input to make them concentrate on relevant stimuli. Affordances of Metaverse for autistic children have also been evidenced in the literature, for example, improving social skills, social engagement, and social knowledge, and meanwhile reducing ASD symptoms.

H. Virtual World Metaverse-Supported Gameful Experience-Based Education

There is an increased interest in "virtual world Metaverse-supported gameful experience-based education," evidenced by the increasing tendencies of *problem-solving and gamification in Metaverses* and *Metaverses for GBL* since 2015 (see Fig. 8) and emerging phrases such as "digital game," "Metaverse game," "gameful experience," and "educational game" (see Fig. 7).

Metaverse's main users are Generation Z, or digital natives, who are highly familiar with ICTs and digital media and are capable of multimedia use. As such, compared to previous generations, Generation Z learners generally prefer integrating technologies into learning processes. In this sense, online education involving Web 2.0 and social media tools, such as computers, mobiles, and the internet, if conducted and designed properly, is an efficient way for them to attain skills/knowledge. According to Guraya's meta-analysis [71], about 70%–80% of surveyed learners utilized social media daily, and nearly 20% used them for study purposes. However, learners are likely to feel isolated/lonely in current online learning and disconnected from instructors and peers, resulting in their reluctance to interact and resistance to learning. These problems have become more serious with the spread of the COVID-19 pandemic.

According to Castro and Tumibay [72], online learning environments ought to promote learners' accessibility and flexibility and prolong learning convenience to support their sustainable education. Gamification, referring to applying game mechanics elements (e.g., point badges and leaderboards) and rules in nongame settings [73], has been popular in assisting Generation Z learners in receiving sustainable online education by improving their learning immersion. Educators have thus focused on exploiting knowledge/skills delivery approaches based on gameful experiences to induce learners' motivation, participation, interaction, and continuity. Such gameful experiences are favored by Generation Z learners since they grew up at a time when personal computers and mobile devices integrated with game features were evolving.

Online games have many similar characteristics to the Metaverse, for example, virtual identity, high-level social interaction, creation freedom, and immersive experiences, making GBL an ideal application for Edu-Metaverse. Thus, as virtual technologies advance, educators have been interested in exploiting the Metaverse's potential for flexibly creating riskless and low-cost educational contexts for GBL. Edu-Metaverse-supported gameful learning is a new way of learning that, empowered by such technologies as VR, AR, MR, Al, and brain–computer interfaces, utilizes immersive games integrating with knowledge and entertainment for achieving learning enjoyment.

According to Park and Kim [74], five types of worlds can encourage learners' motivation through gameful experiences in the Metaverse, including survival, maze, multichoice, racing/jumping, and escape room worlds. A survival world requires users to compete with others for knowledge till the last survivor wins. A maze world requires users to transmit knowledge in the process of choosing maze walls or forked roads. A multichoice world requires users to find the most correct answers among options, for example, OX quizzes and solving puzzles. A racing/jumping world requires users to move avatars to reach the final point. An escape room world requires users to use knowledge and hidden hints to resolve problems for escaping space. For example, in a digital mobile VR game developed by Estudante and Dietrich [75] based on an open Metaverse application, learners followed in physicists' footsteps to resolve puzzles relating to such concepts as the periodic table and chemical equilibrium reactions to master chemical knowledge.

Edu-Metaverse-supported gameful learning also allows Generation Z learners to exercise a greater level of control within the Metaverse to create new worlds by expanding knowledge frames based on exchanged information. For example, in [76], a Metaverse game for educational simulations supports the programmability of learners' generated content to empower them to create 3-D reconstructions of excavation sites and create exhibitions within the virtual excavation.

I. Quantitative Research on Edu-Metaverse Focusing on Learners' Experience

According to Figs. 6 and 8, there has been an increased interest in the *presence and interest development for Metaverses* among scholars since 2017. In addition to "learning presence" and "social presence," learners' satisfaction, engagement, and acceptance are also widely concerned by Edu-Metaverse scholars, evidenced by frequent and emerging phrases, such as "learning satisfaction," "learning motivation," "learning management," "cognitive increment" "immersive experience," and "learning experience," as presented in Figs. 6 and 7. An examination of the papers containing these phrases showed the increased application of research and analysis methodologies, such as "statistical analysis," "quantitative research," and "mixed-method approach" (see Fig. 7).

Due to the high cost of establishing experimental setups with sensors and classroom configuration [9], the case study has long been a preferred research approach in Edu-Metaverse studies. However, thanks to technological advances in compatible glasses with affordable prices in recent years, quantitative and mixed-method research on Edu-Metaverse is increasingly implementable. Among these studies, a large portion focuses on examining learners' acceptance/perception of learning in Metaverse-empowered virtual environments in comparison to using traditional technology-assisted learning approaches. To achieve this, the technology acceptance model (TAM), based on reasoned action theory, is widely accepted to be effective in exploiting the causal relationships of beliefs, attitudes, and behaviors to how learners accept/utilize Edu-Metaverse. For example, by evaluating learners' perception of the Metaverse's application for medical education using TAM approaches, Almarzouqi et al. [77] identified that learners' innovativeness, which was affected by perceived ease of use and perceived usefulness, closely influenced their intentions to use Metaverse.

Besides the factors involved in the TAM, many personal factors, for example, learners' learning-related emotions (e.g., cognitive load) and self-efficacy, also affect their acceptance/perception of such new technology as Edu-Metaverse, particularly in case of a pandemic crisis and emergency. Cognitive load refers to cognitive efforts needed for processing/understanding the information given by instructors [78]. Higher cognitive loads are reported to result in lower acceptance levels of remote learning components like Edu-Metaverse. To reduce cognitive load, more specifically, communication cognitive load and content cognitive load in Edu-Metaverse to improve learners' acceptance, Erlandson et al. [41] suggested using voice-chat (VoIP) communication approaches rather than text-chat communication approaches. Regarding communication cognitive load reduction, learners using VoIP approaches were more at ease, owing to the more humanized nature of voice-chat compared to text-chat technologies, thus attaining higher-level satisfaction and acceptance. The reduced content cognitive load for learners utilizing voice-chat approaches is attributed to the reduced visual attention required for voice-based communication, thus allowing more streamlined cognitive processing of in-world curriculum information.

As a basic concept in social cognitive/learning theory, self-efficiency focuses on people's faith in completing a task without complications. Learners with higher-level of self-efficacy show more optimism about using new technologies such as Metaverse and can accept them more easily. A more specific concept associated with Edu-Metaverse is social self-efficacy, which is about learners' perceived competencies in their social skills. According to cognitive-social learning, training of social skills involves processes of knowing, modeling, role-playing, and reinforcing [79]. Edu-Metaverse provides learners with ample opportunities to exercise their social competencies safely by participating in virtual, collective problem-solving and mutual support. An improved sense of social presence in Edu-Metaverse also facilitates learners' supportive interaction and their co-learning of positive social competencies. As such, Edu-Metaverse is believed to promote learners' social skill development while enhancing their self-confidence in real-world communication and relational maintenance. Oh et al.'s [80] exploratory study of young Koreans based on structural equation modeling suggested that the number of supportive interactions had a positive effect on learners' perceived social self-efficacy in Edu-Metaverse. They also found that social self-efficacy mediated the relationship between the number of supportive interactions and learners' sense of loneliness.

J. Challenges and Future Directions for Applying and Researching Edu-Metaverse

This section discusses challenges related to Edu-Metaverse and potential solutions and future directions for applying and researching Edu-Metaverse. In addition to challenges relating to technical difficulties such as network traffic, interactive/interface design, and costly infrastructures, other barriers include data security and privacy protection, the balance between real-world and virtual world identities, preparing instructors for Edu-Metaverse, and assessment of higher-order thinking competencies.

1) Data Security and Privacy Protection: In the Metaverse, learners' data, for example, interaction traces, emotions, and gestures, can be easily collected by analytical toolkits and sensors [1]. However, such data may involve personal information, which can be discovered to reveal learners' true identities and some of their sensitive data, thus posing threats to data security and privacy. To resolve this problem and ensure safe learning/instruction experiences in the Metaverse, Falchuk et al. [81] suggest social cloning by creating various clones of each learner to hoodwink attackers intended to track learners. Another solution is to utilize blockchain technologies and nonfungible tokens to make attackers' behaviors or actions in the Metaverse traceable [82].

However, within the Metaverse, attackers can easily target third-party applications by making use of inadequate security mechanisms, thus leading to the compromise of personal information. This is more common in public blockchains, where transactions can be hidden, but the electronic addresses of assets, tokens, and wallets are visible and can be linked purposefully or accidentally to specific users, thus posing a threat to the privacy of ongoing or past transactions. Thus, researchers and instructors ought to exploit ways to persuade Edu-Metaverse applications that something about a particular user is real without disclosing his or her information. This can be achieved by using cryptographic techniques such as zero-knowledge proof on blockchains to provide individuals with easy access to the Edu-Metaverse and meanwhile protecting their privacy and preserving ownership over their possessions.

2) Balancing Real-World and Virtual World Identities: The high-level immersion and the presence akin to the reality brought by the sensor/virtual technologies, together with a wide range of scenarios that are available in the Metaverse but are unavailable in the physical world, make learners easily become addicted to the bizarre Metaverse worlds. According to Xi et al. [83], the blended boundary between real and virtual worlds is likely to make learners feel puzzled by their "real-me identity" and "virtual-me identity." When learners, especially those with low-level of self-discipline/control, rely heavily on avatars' social connections in virtual worlds especially when gameful experiences are integrated, they may have risks of addiction and emotional/social barriers [8], resulting in poor mental health, chronic fatigue, and difficulties in establishing social relationship/connections in real worlds. To avoid over-reliance on virtual technologies and prevent false spiritual satisfaction from them, instructors and researchers can explore effective ways to curate content, limit exposure, and monitor responses and reactions. Attention should be paid to effectively guiding learners in balancing their time in and out of the Metaverse, discerning real and virtual identities, and paying attention to real-world interaction.

3) Preparing Instructors for Edu-Metaverse: As the key agents and gatekeepers in determining what enters classrooms, instructors take an important role in successful education and education reform. Hence, instructors' readiness is a prerequisite to retaining Metaverse-empowered sustainable education to ensure equal opportunities for learners. However, instructors undergoing inadequate training may encounter overwhelming technological challenges. For example, according to Erturk and Reynolds [84], limited by instructor competencies and pedagogical structure, digital resources deployed in the current Edu-Metaverse are most not well-designed. In Edu-Metaverse-empowered learning environments, instructors are expected to propose new thoughts on innovating digital teaching resource/content design based on Metaverse features under the guidance of pedagogical theories associated with ubiquitous/virtual learning, for example, embodied cognition, situated cognition, flow theory, and cognitive load theory [8]. To achieve this, instructors ought to have digital citizenship and 21st-century competencies entailing the 4Cs principles: critical thinking, communication, collaboration, and creativity.

Attention should also be attached to developing instructors' meta-modality application competencies to equip them with transformative powers of adaptivity and personalization through ubiquitous/virtual learning systems. By doing so, instructors would be capable of fully utilizing Metaverse's affordances to practice sustainability in classes by authorizing learners to construct knowledge, skills, and values for long-term outcomes. Metaverse itself provides exciting opportunities for teacher education to prepare instructors to teach with Metaverse. For example, Lee and Hwang [85] reported that the transformative experiences of preservice instructors in designing instructional VR content relating to K-12 English contribute to capacitating preservice instructors' technological readiness, 4Cs in digital citizenship, and perceived pedagogical benefits.

4) Assessment of Higher-Order Thinking Competencies: With the involvement of various types of PBL scenarios, Edu-Metaverse is widely considered effective for developing higher-order thinking competencies, for example, problem-solving and critical thinking. However, these competencies are difficult to evaluate based on tests. The perception, connection, computing, and disposal of intelligent technologies within Edu-Metaverse provide exciting opportunities to evaluate how learners behave and progress in PBL. For example, learners' multimodal data (e.g., audio, video, and text) created during PBL within Edu-Metaverse can be analyzed via integrated technologies such as automatic speech recognition and face and action recognition technologies to understand their development of higher-order thinking competencies scientifically and efficiently. The analysis results can be visualized via visual presentation technologies to craft digital profiles of learners. We thus call for instructors and researchers to exploit the potential of the integrated intelligent technologies into the Edu-Metaverse platforms for providing learners with constant feedback and needed support, as well as ways to identify learning difficulties and progress made toward their learning goals.

K. Contribution of This Study Compared to Previous Reviews

Compared to previous reviews on VR/AR/Metaverse in education, this study's contribution lies mainly in providing results that are not restricted to predefined codes but are more specific and fine-granted and can represent the latest trends in Edu-Metaverse research.

First, compared to previous studies using systematic and meta-analysis methodologies, the results and insights obtained are not restricted to predefined codes or categories. This is because we utilized the STM-based bibliometric methodologies capable of analyzing large-scale literature data, which is different from systematic analysis or meta-analysis approaches (e.g., a systematic review on Metaverse' effects on learning) that analyze predefined codes or categories of a limited number of papers. The latter obtains results commonly restricted to individual predefined codes. For example, Ng's [86] systematic analysis of 19 papers focused on identifying five main types of Metaverse technologies adopted in education. However, in this study, what Edu-Metaverse research-related issues to be identified are not restricted to, for example, subjects that Edu-Metaverse has been mostly applied or Edu-Metaverse's effects. As long as the issues are widely concerned by Edu-Metaverse researchers, they would be identified in this study, for example, context-related issues (e.g., collaborative learning and PBL), research method-related issues (e.g., quantitative and experimental), subject-related issues (e.g., art, STEM, and language), device/technology-related issues (e.g., second life and games), and outcome-related issues (e.g., social communication and learning interest).

Second, compared to previous studies that used systematic analysis and meta-analysis approaches, this study can provide insights into specific and fine-granted research themes due to a joint interpretation and refinement of results of topic modeling and phrase analysis along with a careful examination of papers focusing on the identified topics and phrases. For example, one of the research themes highlighted in this study is "Metaverse-supported simulations for collaborative PBL in health/medical education," which considers the Metaverse's effects in supporting health/medical students' PBL in clinical simulations where collaborative learning approaches are adopted. This theme is more specific, fine-granted, and implementable compared to the general issues stated in previous reviews. For example, Sarıtaş and Topraklıkoğlu [10] discovered that most Edu-Metaverse studies were related to higher education. However, as no additional information is provided, we do not know whether Metaverse is more effective for supporting secondary students in specific or general learning contexts compared to undergraduate students.

The above limitation is also common in previous bibliometric reviews on VR/AR/Metaverse-supported education. For example, Tlili et al. highlighted Metaverse's significance in promoting communication and social interaction, whereas we more specifically identified Edu-Metaverse's use for communication and interaction promotion in different contexts such as collaborative learning and PBL and for autistic children. Rojas-Sánchez et al.'s review [87], by analyzing Keywords Plus of 273 papers on VR-supported education, identified the most frequently used words including "e-learning," "environments," "augmented reality," "technology," "simulation," and "learning systems." However, no further analysis was conducted to form more fine-granted topics. They also conducted a factor analysis and identified two general clusters of words related to VR display devices and VR applied to education, respectively. They also conducted keyword co-occurrence analysis and discovered general themes such as "education technology for simulation environments with augmented reality" and "VR for e-learning systems." Similarly, Avila-Garzon et al.'s [88] analysis of keywords of 3475 papers related to AR in education identified general trending topics such as "increasing interest in exploring the effect of AR in higher education courses" and "the use of AR in learning environments populated by students with special educational needs." However, Avila-Garzon et al.'s and Rojas-Sánchez et al.'s reviews did not provide additional information about, for example, specified educational contexts to form more fine-granted themes such as supporting autistic children for social skill development.

Additionally, compared to previous reviews, this study provides more insights into the latest trends in Edu-Metaverse research. For example, Tlili et al. [9] and Sarıtaş and Topraklıkoğlu [10] suggested the dominance of descriptive studies while the lack of quantitative/experimental studies. However, this study identified an emerging trend and growing interest in statistical and quantitative research on Edu-Metaverse especially focusing on learners' experience. One reason for this is the wider coverage of relevant and up-to-date papers in this study compared to previous reviews. Another explanation lies in the lack of analysis of topics' developmental trends and emerging issues in previous reviews compared to this study. Thus, we can identify the latest trends in Edu-Metaverse research that are seldom mentioned in previous reviews, for example, Metaverse's use in art education and Metaverse for supporting 21st-century skill development.

L. Limitations and Future Work

This study has limitations. First, we did not include papers written in a language other than English. Future research may consider including results from other languages to compare international research efforts. Second, in data retrieval, although we only considered the exact term "Metaverse" combined with education-related terms to construct the Edu-Metaverse data corpus, the results obtained suggest that the data corpus is acceptable since major issues in the field of Edu-Metaverse are covered. The search strategy of using exact search terms has been widely adopted in review studies. For example, Xie et al.'s [89] review on personalized/adaptive learning adopted the search terms "personalized learning" and "adaptive learning." Nevertheless, we might omit some studies; thus, we could not claim to have examined every issue of relevance in the Edu-Metaverse. This is a common limitation in literature reviews, as it is always impossible to reach 100% coverage in literature reviews [12]. Future work can consider using additional search terms to generate more comprehensive results. However, this would require effective tools being proposed to facilitate data screening given a large dataset retrieved.

Additionally, this study utilizes the STM-based bibliometric analysis methodology that focuses on analyzing large-scale literature data using unsupervised modeling algorithms. As it is unsupervised, what research issues to be identified are not predictable. The identified issues are not restricted to subject areas or Edu-Metaverse's effects. This is different from systematic reviews that focus on analyzing predefined codes or categories given a limited number of papers. Future, work can consider exploiting the advantages of machine learning and systematic analysis methodologies to automatically analyze sizable Edu-Metaverse papers to gain an in-depth understanding of fine-granted aspects (e.g., subjects that Edu-Metaverse has been mostly applied and its effects on students' learning of these subjects).

V. Conclusion

This work is the first and timely to trace modern developments Edu-Metaverse research, a field receiving increasing attention, using topic modeling, computer-aided content analysis, and social network visualization. Results showed that Metaverse has been increasingly popular in various areas (e.g., physical education, health/medical education, STEM education, art education, language education, and special education) to promote collaborative learning, gameful experiences, PBL, social learning, and simulated learning. An increase in quantitative and mix-method approaches in Edu-Metaverse research demonstrates a shift of academic focus from understanding Metaverse's educational potentials to understanding Edu-Metaverse's application values and its effects on learners' performance and perception/acceptance. In addition to promoting learner interest, engagement, immersion, and motivation, Edu-Metaverse has been increasingly reported to facilitate the development of learners' language, social, communicative, and 21st-century competencies, for example, higher-order thinking, collaboration, and problem-solving. We additionally reveal Edu-Metaverse's challenges in data security and privacy protection, putting learners at risk of addiction and emotional/social barriers, bringing about overwhelming technological difficulties to instructors, and assessing learners' higher-order thinking competencies. We thus highlight the need to trace attackers' behaviors via cryptocurrency and blockchain technologies, raise learners' awareness of differences between real-world and virtual-world identities, capacitate preservice instructors' technological readiness via professional training, and leverage the Metaverse's technological affordances to trace and analyze learners' behaviors and processes. The findings and implications obtained are expected to strengthen scholars' and educators' understandings of Edu-Metaverse applications and guide future research on advancing Edu-Metaverse-empowered learning and instruction.

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