JTPED
Journal of Technological Pedagogy and Educational Development
Vol. 2, No. 3, 2025, pp. 104-118
https://ejournal.jtped.org/ojs/index.php/jtped


# Understanding Education 4.0 through a Systematic Review of Pedagogical Innovations, Technology Integration, and Systemic Challenges

Rugaya Tuanaya [a,1,*], Razan Madyasta Athayanandi Wibowo [b,2], Firdaus Amruzain Satiranandi Wibowo [c,3], Gulzhaina K. Kassymova [d,4]

[a] Educational Research and Evaluation, Graduate School, Universitas Negeri Yogyakarta, Indonesia
[b] Institute and Clinic for Occupational, Social and Environmental Medicine, LMU Hospital Munich, Germany
[c] Department of Mathematics Education, Faculty of Mathematics and Natural Sciences, Universitas Negeri Yogyakarta, Indonesia
[d] Satbayev University, Shevchenko str, Almaty 050010, Kazakhstan
[1] rinanaya74@yahoo.com; [2] razan.wibowo@med.uni-muenchen.de; [3] firdausamruzain.2021@student.uny.ac.id;
[4] g.kassymova@satbayev.university
* Corresponding Author

ARTICLE INFO

**Article history**
Received August 09, 2025
Revised November 05, 2025
Accepted November 09, 2025

**Keywords**
Education 4.0;
Digital Pedagogy;
Technology Integration;
Systemic Transformation;
Thematic Synthesis

ABSTRACT

This study presents a systematic review of Education 4.0, emphasizing the interplay between technology integration, pedagogical innovation, and systemic transformation. Following PRISMA guidelines, literature searches in Scopus and Web of Science identified 26 peer-reviewed articles focusing on technology-based pedagogy and competency-based learning. Thematic coding classified findings into three areas: dominant technologies and pedagogies, systemic contributions, and conceptual challenges. Results show that artificial intelligence (AI), learning management systems (LMS), hybrid learning, and immersive technologies (AR/VR) are the most common tools, supporting personalized and project-based learning. However, there remains a gap between technology adoption and transformative pedagogy, with most contributions being localized and exploratory. Recurring themes include digital identity, teacher readiness, resistance to change, and digital divides, particularly in developing contexts. Few studies adopt longitudinal approaches or address policy-pedagogy-technology alignment comprehensively. This review proposes a conceptual model linking technology, pedagogy, human capacity, and policy to form an adaptive and inclusive Education 4.0 ecosystem. Implications highlight the need for stronger theoretical foundations, participatory technology design, long-term institutional strategies, and evidence-based policymaking to ensure sustainable educational transformation. The synthesis offers a conceptual and practical guide for advancing Education 4.0 in diverse contexts



## 1. Introduction

The development of digital technology has transformed nearly every aspect of human life, including the education sector. In the era of the Fourth Industrial Revolution, the integration of technologies such as artificial intelligence, big data, the Internet of Things (IoT), and virtual reality has led to the emergence of a new paradigm known as Education 4.0 [1], [2], [3]. This concept

https://doi.org/10.59247/jtped.v2i3.25

demands that the education system be more adaptive, flexible, and centered on personalized, collaborative, and competency-based learning. The implementation of Education 4.0 is becoming increasingly relevant in preparing future generations to compete in a complex and dynamic workplace [1], [4], [5], [6]. This emphasizes the importance of innovation in pedagogical strategies, the development of 21st-century skills, and the strengthening of digital literacy. Therefore, a deep understanding of the dynamics and practices of Education 4.0 is an urgent need for educators, researchers, and policymakers worldwide. The concept of Education 4.0 first emerged as an extension of the Industry 4.0 model, which emphasizes automation, connectivity, and digitalization across industry sectors [1], [7], [8]. In the context of education, Education 4.0 encourages the integration of cutting-edge technologies to create learning that is responsive to individual needs, competency-based, and relevant to 21st-century challenges. Some key approaches developing within this framework include adaptive learning, the use of artificial intelligence, project-based learning, and cross-border online collaboration.

Various global initiatives have demonstrated efforts to adopt Education 4.0 principles in both formal and non-formal education systems [1], [2], [4], [8]. Previous research has underscored the importance of technology as a lever for change in curriculum, pedagogy, and assessment [3], [9], [10], [11], [12], [13], [14]. However, the implementation of Education 4.0 has not always been uniform across countries, given disparities in infrastructure, educator readiness, and education policies. These differences raise important questions about how Education 4.0 practices and approaches are developed, adapted, and evaluated across local and global contexts. Although the concept of Education 4.0 has been widely discussed and promoted globally, significant gaps remain in understanding how this concept translates into concrete educational practices [2], [8], [15], [16]. Many studies focus on technological or policy aspects, but there are still limited studies that comprehensively map pedagogical approaches, implementation strategies, and educational institutions' responses to these changes [2], [17], [18]. The lack of a comprehensive synthesis of the direction, trends, and diversity of Education 4.0 approaches makes it difficult for educators and policymakers to make evidence-based decisions [19], [20]. To date, there has been no literature synthesis that comprehensively maps the relationship between pedagogical approaches, technology integration, and education system transformation within the Education 4.0 framework [4], [21]. The absence of an integrated conceptual framework and systematic thematic mapping makes it difficult to formulate policies, design learning interventions, and develop sustainable research directions.

As attention to the concept of Education 4.0 grows, various studies have begun to explore the dynamics of educational transformation in the digital age. However, most available research tends to be limited to sectoral approaches, such as focusing on the implementation of specific technologies, local-scale case studies, or partial curriculum innovations [19], [20]. These studies are generally conducted separately, and few attempt to comprehensively link aspects of technology, pedagogy, and learning context within a unified conceptual framework. This leads to a lack of comprehensive understanding of how the key components of Education 4.0 interact and contribute to systemic educational transformation. Furthermore, there is limited research examining the development of the Education 4.0 discourse longitudinally and systematically [2], [8]. Information on publication trends, shifting thematic focuses, and the variety of approaches used remains limited and poorly documented. Consequently, researchers and practitioners struggle to gain a comprehensive picture of the direction of research developments, including the empirical and theoretical contributions produced. Yet, such understanding is crucial for building a solid scientific foundation and guiding education policy toward a more adaptive and evidence-based approach.

Amidst the accelerated adoption of digital technology in the education system, a number of studies have shown that the use of tools such as Learning Management Systems (LMS), artificial intelligence, and virtual reality-based technologies has not been fully accompanied by a transformation in teaching approaches [3], [21], [22], [23]. Technology integration often still focuses on operational or administrative aspects, without fundamentally changing the learning paradigm [3], [10], [24]. Meanwhile, innovative learning approaches such as flipped classrooms, project-based

learning, and AI-powered microlearning are beginning to show potential in improving student engagement and learning outcomes [25], [26]. However, these findings remain scattered across individual reports and articles without a synthesis that could illustrate emerging patterns or the effectiveness of approaches used in different contexts. Furthermore, the existing review structure does not clearly classify study characteristics based on their epistemological orientation [27], [28]. Not all literature explicitly distinguishes between descriptive, conceptual, and evaluative research. This makes it difficult for readers to understand the extent to which a study contributes to the development of theory or practice in the field. Furthermore, pedagogical approaches that place students at the center of learning, although increasingly mentioned, have not been widely discussed in an integrative manner in relation to digital platforms, instructional strategies, and expected learning outcomes within the Education 4.0 framework.

Initial searches of scientific publications recorded in international databases such as Scopus and Web of Science show that the volume of articles on Education 4.0 has increased significantly since 2020 (Fig. 1). However, the content discussed in these publications still exhibits a high degree of fragmentation [29]. Topics such as online learning, the use of AI, strengthening 21st-century skills, and developing competency-based curricula are often discussed separately and have not yet been directed towards developing indicators of success or best practices that can be widely adopted [29]. This misalignment indicates that despite the growth of the Education 4.0 discourse, there is no strong consensus in the literature regarding the dominant approach or contextual and sustainable implementation strategies at various levels of education.

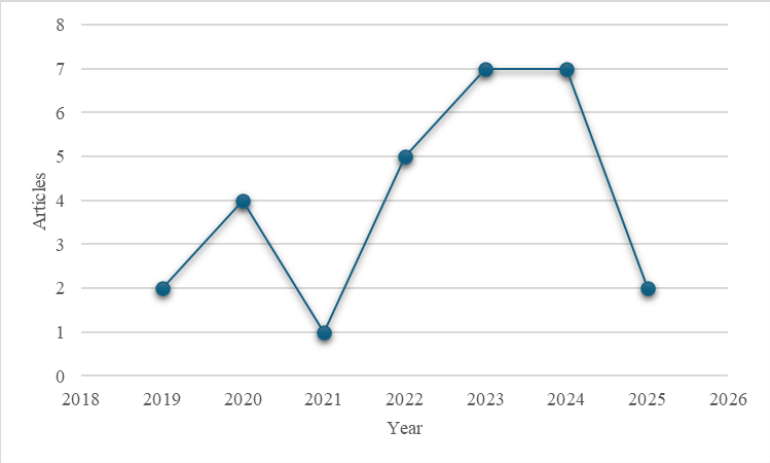


**Fig. 1.** Annual scientific production

In Indonesia, the transformation of education towards the Education 4.0 era has begun to be driven through strategic policies such as "Independent Learning," the integration of digital platforms such as Rumah Belajar and the national Learning Management System, and strengthening technological literacy at all levels of education [3], [23], [30]. However, significant challenges remain, particularly in terms of the digital divide between regions, teachers' readiness to adopt new pedagogically based technologies, and limited data-based evaluation of the effectiveness of digital learning strategies [23], [31], [32]. Amidst this complexity, a literature review that can systematically map approaches to technology, pedagogy, and competency-based learning is highly relevant, not only as a conceptual reference, but also as a basis for policy-making and the development of more adaptive and contextual learning practices according to Indonesia's needs. To address the need for a more comprehensive understanding of the dynamics of Education 4.0, this study was conducted using a Systematic Literature Review (SLR) approach. This study aims to systematically identify, evaluate, and synthesize scientific literature that discusses the integration of technology, pedagogical approaches, and competency-based learning within the Education 4.0 framework [33], [34], [35]. The main focus of this study includes mapping publication trends, classifying learning approaches, and exploring the dominant issues and contributions that have emerged over the past decade. By adopting

a structured SLR methodology, this article aims to present a comprehensive, evidence-based knowledge map that can serve as a foundation for policy development, teaching practices, and future research directions in technology-based educational transformation.

To address these issues, the SLR approach was chosen as a methodological strategy to identify, classify, and synthesize various approaches and contributions in Education 4.0 studies. Thus, this study is designed to answer three main questions: (1) what the dominant technological and pedagogical approaches in Education 4.0 studies are; (2) how do these studies contribute to the transformation of the education system; and (3) what are the conceptual challenges and research directions that are still open in the Education 4.0 literature. The contribution of this study is to provide a structured thematic synthesis of current pedagogical and technological approaches in Education 4.0, offering a conceptual foundation for future research and informing more adaptive educational policies.

## 2. Method

This study is a systematic literature review conducted in a transparent and documented manner. The review procedure follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines as outlined by [36]. The data synthesis process was carried out thematically and categorically to identify the technological focus, pedagogical approach, and conceptual contribution in the Education 4.0 study [37].

### 2.1. Literature Search and Selection

The literature search for this study was conducted systematically across two major databases: Scopus and Web of Science (WoS). The search string used combined three main components: the Education 4.0 concept, pedagogical approaches, and technology integration. The search string included a combination of the following terms:

> ("Education 4.0" OR "Fourth Industrial Revolution" OR "digital education" AND "pedagogy" OR "teaching model" OR "learning approach" OR "student-centered learning" OR "competency-based education" AND "technology integration" OR "AI in education" OR "smart learning" OR "digital pedagogy").

The inclusion criteria used included: (1) peer-reviewed scientific articles published in journals or conference proceedings; (2) written in English; (3) explicitly addressing the Education 4.0 theme with a focus on technological, pedagogical, or competency-based learning approaches; and (4) available in open access, either in full or in part. Studies with qualitative, quantitative, or mixed approaches were all considered. The initial search yielded 56 articles, which were then filtered through a process of deduplication and selection based on title and abstract. After a full reading and application of exclusion criteria to irrelevant articles, 26 articles were deemed suitable for further analysis. The entire article search and selection process is summarized in detail in Fig. 2.

### 2.2. Coding and Synthesis Process

Twenty-six articles that passed the selection stage were then analyzed through a thematic coding process based on an extraction table. Each article was manually coded to identify and record the following information: article title, author(s) and year, publication source, country/context of study, methodological approach, research objectives, technological or pedagogical focus, key findings, and contribution to Education 4.0. The coding process was conducted iteratively by the first author, then validated by two independent reviewers to ensure consistency and reliability of the themes. This process resulted in thematic categories that could systematically answer the research questions. Three main categories developed in the synthesis process include: (1) the type of technology or pedagogical approach used; (2) the form of contribution to the transformation of the education system; and (3) variations in the geographical context and methodological approach of the reviewed studies.

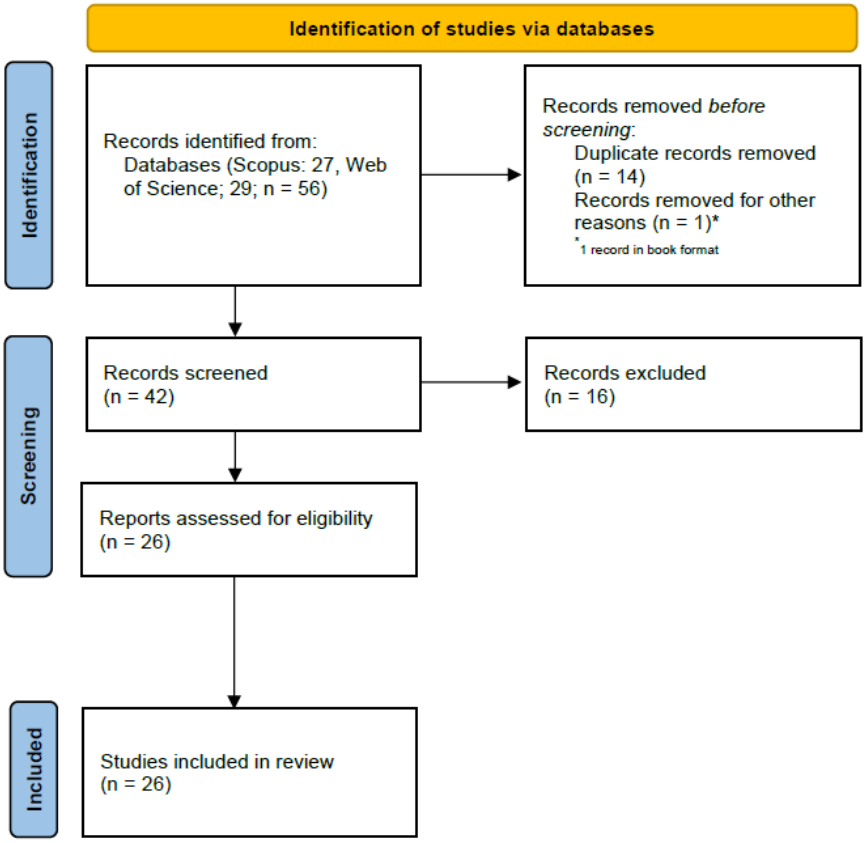


**Fig. 2.** PRISMA flow chart

### 2.3. Data Analysis

The analysis was conducted thematically and categorically. The primary focus was to identify trends in technology use and pedagogical approaches (RQ1), variations in contributions based on country context and methodological approach (RQ2), and patterns of findings and key challenges from the reviewed studies (RQ3). The findings were classified into a synthesis table and analyzed narratively to identify patterns that could answer the research questions. The analysis process was conducted using Microsoft Excel software.

## 3. Results and Discussion

### 3.1. General Characteristics of the Reviewed Studies

This study reviews 26 scientific articles highlighting educational phenomena and approaches in the Education 4.0 era. Initial analysis found that the general characteristics of these studies demonstrate tendencies that reflect global socio-technological dynamics, particularly in the post-pandemic context.

#### 3.1.1. Publication Year Distribution

As shown in Fig. 1, there was a significant increase in the number of publications in 2022 and 2023. This surge is likely a response to the sudden transformation of the global education system due to the COVID-19 pandemic [38], [39], [40]. In this case, Education 4.0 is positioned not only as a framework for the future, but as an emergency solution that will then become part of the new normal [41]. This marks a paradigm shift from conventional education to a more digitally integrated learning model. However, these findings also indicate that the Education 4.0 discourse has only received significant systematic attention in the past three years, leaving ample potential for further exploration.

### 3.1.2. Country and Study Context

The country distribution shows that most studies come from developing and transitional countries, such as Nigeria, India, and Indonesia, as well as several European countries such as Romania and Ireland (Fig. 3). This fact is interesting because it shows that challenges and innovations in digital education are not limited to developed countries. Developing countries even serve as natural laboratories for observing the complexities of implementing Education 4.0, particularly in terms of infrastructure limitations, human resource readiness, and policy adaptation [42]. However, the predominance of studies in micro-contexts (institutional or regional) (see Fig. 4) without cross-national connections indicates that Education 4.0 studies remain fragmented. The lack of international comparative and integrative approaches represents a significant gap that future studies need to address.

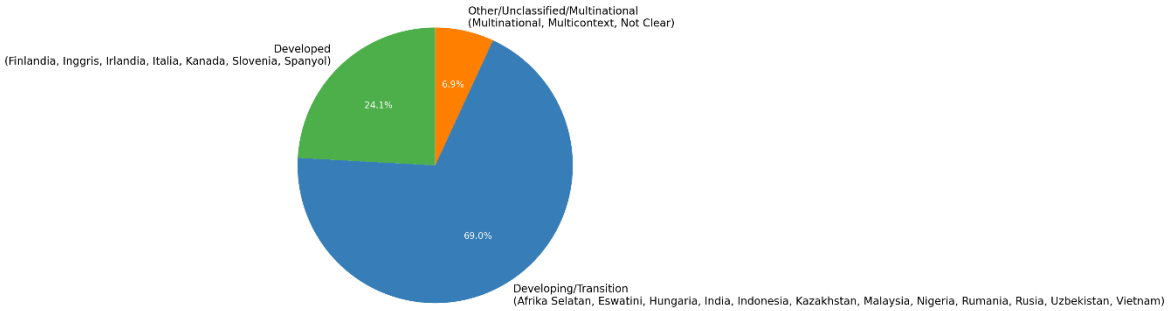


**Fig. 3.** Distribution of studies by country category

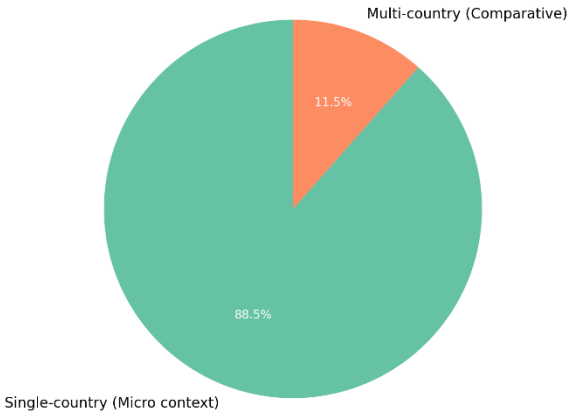


**Fig. 4.** Distribution of studies by geographical scope

### 3.1.3. Methodological Approach

Most articles employ conventional quantitative and qualitative approaches (Table 1). Quantitative studies typically focus on student/teacher perceptions of technology through surveys, while qualitative studies explore pedagogical experiences and identities in digital contexts. The use of mixed methods approaches or longitudinal studies, which are crucial for understanding long-term changes in education systems, remains limited. This suggests that Education 4.0 studies are still in the early stages of exploration and documentation, with limited evaluative or predictive aspects. Therefore, future research needs to strengthen the methodological dimension to uncover the dynamics of transformation in greater depth and sustainability.

### 3.1.4. Type and Credibility of Sources

All articles are from indexed international journals, demonstrating relatively high research quality and consistent academic standards. However, not all studies are accompanied by an explicit

theoretical framework, and most are exploratory-descriptive in nature. This reinforces the importance of the subsequent sections of this review to conceptually synthesize the findings and highlight unaddressed gaps in the literature.

**Table 1.** Distribution of methodological approaches

| Method Category | Number of Studies | Percentage |
|---|---|---|
| Qualitative | 12 | 46.2% |
| Quantitative | 8 | 30.8% |
| Mixed Methods | 5 | 19.2% |
| Conceptual/Theoretical | 1 | 3.8% |

### 3.2. Technology Focus and Pedagogical Approach in Education 4.0 Studies (RQ1)

This section aims to identify the key technologies and pedagogical approaches dominant in the Education 4.0 literature. Based on the coding results of the 26 articles reviewed, consistent patterns were found regarding the types of technologies adopted and the pedagogical orientations developed by education researchers and practitioners. In general, the technologies most frequently encountered in the studies included artificial intelligence (AI) and the Internet of Things (IoT), which are used to support personalized learning, data-driven decision-making, and the development of adaptive learning systems [43], [44]. In addition, Augmented Reality (AR), Virtual Reality (VR), and Metaverse technologies are also found in a number of studies that seek to create more immersive learning experiences, especially in the context of technical and experiential skills learning [45]. Digital platforms such as Learning Management Systems (LMS), Massive Open Online Courses (MOOCs), and distance learning systems have become an important foundation for implementing digital education, especially during the pandemic [44], [46]. Hybrid and blended learning models also occupy a central position as the most widely adopted form of integration between physical and digital learning spaces [47]. As shown in Fig. 5, hybrid learning, distance learning, and AI are the technologies with the highest frequency of occurrence. This indicates a shift from assistive technologies to transformational technologies that are changing the way learning is designed and delivered. However, more advanced technologies such as Metaverse and VR/AR are still found in exploratory studies, indicating that their implementation is uneven and still limited to experimental contexts [48], [49], [50], [51].

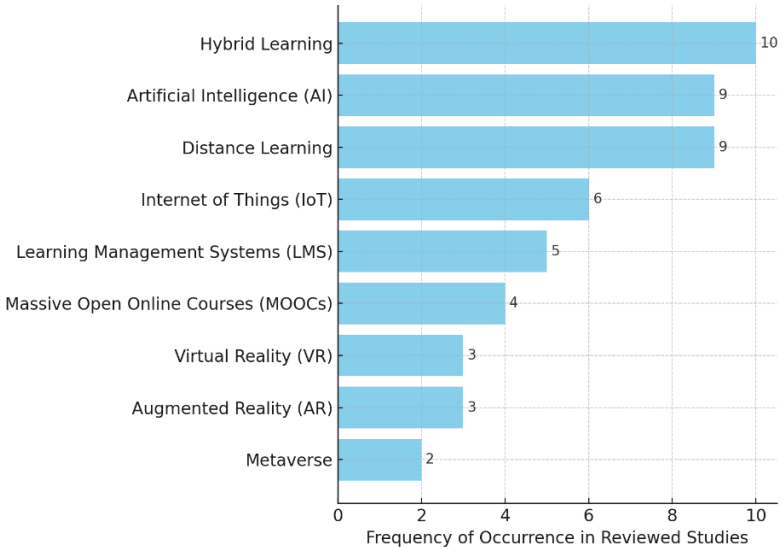


**Fig. 5.** Dominant technologies in education 4.0 literature

From a pedagogical approach perspective, there is a strong tendency towards student-centered learning [44], [52]. Some prominent approaches include personalized learning, which utilizes artificial

intelligence to tailor content and learning paths individually; project-based learning, which emphasizes collaboration and problem-solving in authentic contexts; and digital pedagogy and hybrid classrooms, which consciously integrate technology into instructional design [43], [52], [53]. In addition, there is also strengthening of 21st-century competencies such as critical thinking, collaboration, and creativity as part of the main orientation in Education 4.0-based learning practices [54], [55]. Although the term 21st-century skills frequently appears in the reviewed articles, only a small number truly integrate it into a measurable and applicable evaluative framework. Most remain conceptual or opinionated, without a clear implementation approach.

These findings confirm that in the Education 4.0 discourse, technology is no longer positioned merely as a tool, but rather as a key structural element supporting new pedagogical models. The use of AI and digital systems in learning shows significant potential for expanding access, increasing personalization, and deepening student engagement, particularly in developing countries [56], [57]. However, significant limitations remain in systematically evaluating the effectiveness of this approach. The gap between technology availability and pedagogical readiness is also a crucial issue, with many educational institutions technically capable of adopting technology but lacking a well-developed pedagogical strategy for integrating it into the learning process [58]. Although the hybrid learning model has become a popular discourse, few studies have in-depth explored how it is pedagogically implemented in real-world practice. Furthermore, the focus on the importance of 21st-century competencies has not been matched by studies that explicitly discuss how to measure, cultivate, or evaluate these skills in the context of digital learning [59]. Thus, there are still gaps that need to be filled to ensure that technology integration in education truly impacts pedagogical transformation and student learning outcomes across the board.

### 3.3. Research Contribution to Educational Transformation in the Era of Education 4.0 (RQ2)

The studies analyzed in this review not only explain the implementation of technology in education but also make tangible contributions to systemic transformation efforts. These contributions depend heavily on the country context, the methodological approach used, and the solution-oriented approach offered by each study. Geographically, the majority of articles originate from developing countries such as Nigeria, Indonesia, and India. Studies from these regions generally highlight fundamental issues such as the readiness of digital education infrastructure, the technological literacy gap among educators and students, and efforts to improve access and equity in distance learning [59]. In contrast, studies from developed countries like Ireland and Eastern Europe place more emphasis on the transformation of teachers' roles in digital contexts, technology-based professional development, and explorations of digital identity and epistemological paradigm shifts in education. Interestingly, most of the studies reviewed remain at the institutional level and have not addressed broader public policy, indicating that educational transformation is often positioned as a local responsibility, rather than a nationally or regionally coordinated, cross-level agenda [60].

The methodological approach also influences the contributions made by these studies. Qualitative studies, such as case studies, typically offer in-depth insights into the subjective experiences of teachers, students, and other stakeholders in the technology adoption process. However, these contributions tend to be narrative and contextual. Quantitative studies, on the other hand, present findings based on perception data or evaluations of the effectiveness of technology interventions, which can inform policymaking if supported by a robust evaluative methodology. Systematic studies and mixed-methods approaches, while limited in number, demonstrate significant potential for bridging practice, theory, and policy within a more holistic and multi-layered framework for educational transformation.

Analysis of the keywords contributed in the literature also shows that the most frequently emerging themes include curriculum development and digital competencies, teacher and institutional readiness in facing technology-based changes, and strengthening education policies and management of digital learning systems [61]. However, few studies explicitly address technological infrastructure and digital literacy as the foundations of transformation, despite their critical importance, particularly

in developing countries. The issue of equal access to digital-based education has also emerged in several studies from Africa and Asia, but has not yet become a primary focus in the global Education 4.0 literature [62].

In general, the contributions offered by these studies tend to be local, applicable, and sectoral. Most of the proposed solutions focus on the micro-level, such as in a particular classroom, school, or institution, without fully linking them to systemic reforms that include the integration of educational policy, pedagogical design, and technology adoption [63]. In fact, the Education 4.0 approach is ideally ecosystemic, meaning that learning innovation must be accompanied by comprehensive structural reforms, ranging from digital curriculum design, continuous teacher training, inclusive educational technology regulations, to community involvement in supporting change. The lack of studies that holistically integrate the dimensions of policy, pedagogy, and technology indicates that the current literature is still limited and needs to be expanded to respond to more complex transformative challenges in the global education system.

### 3.4. Conceptual Themes and Key Challenges in Education 4.0 Studies (RQ3)

The studies in this review not only highlight pedagogical innovation and the use of technology in the context of Education 4.0, but also reflect on the main conceptual themes and structural challenges that need to be addressed to realize a comprehensive transformation of education [64]. An analysis of the key findings in each article reveals the complexities involved in implementing technology-based education. Some of the most prominent conceptual themes include digital identity, human resource readiness, resistance to change, and digital literacy and the digital divide. Digital identity is often discussed in the context of teachers' new roles as digital educators, changes in professional identity, and new relationships between teachers and students in the digital space [1]. Several studies in Europe and Australia highlight the importance of pedagogical reflection on technology use, not just technical adoption. The readiness of human resources, both teachers and institutions, is also a central issue, encompassing digital competence, technological literacy, and attitudes toward innovation, with dimensions of readiness encompassing not only technical but also affective and pedagogical aspects [2], [3].

Resistance to change is also a key theme, with a number of studies noting that teachers show resistance to digital innovation due to lack of training, additional workloads, and unclear policy direction [1], [4]. This indicates that the success of Education 4.0 depends not only on the availability of technology but also on change management at the institutional level. Issues of digital literacy and access disparities reinforce the argument that educational transformation cannot stop at the technological aspect but must address the structural roots of inequality [5], [6]. Many studies show that the presence of technology does not necessarily guarantee meaningful participation, especially when skills, confidence, and critical understanding of technology are lacking. In this context, digital inclusion must be understood as a cognitive right, not simply physical access.

Furthermore, this study identifies a number of fundamental challenges in the Education 4.0 literature. The lack of longitudinal studies [7]. This has limited understanding of the long-term impacts of technology integration in education. Most studies are still cross-sectional, thus failing to capture the true dynamics of transformation. The literature's dominant focus on the micro-level, such as institutions or individuals, without explicit links to national policies, also weakens the potential for systemic change [8]. The lack of integration between policy, pedagogy, and technology in these studies indicates that the systemic approach required within the Education 4.0 framework has not yet been established [9]. In fact, to achieve sustainable educational transformation, alignment between policy, learning practices, and technology development is needed, known as policy-pedagogy-technology alignment.

This finding confirms that the discourse of Education 4.0 is beginning to shift from simply improving the teaching and learning process to an epistemological and ontological redefinition of how learning should be understood in the digital era [10]. Teacher and student identities are no longer formed solely through physical interactions and formal curriculum structures, but rather through a

fluid and ever-evolving digital ecosystem. This identity formation process is also not linear, as resistance to change often stems from the tension between the demands of innovation and the limitations of the field. This resistance stems not only from technical aspects but also from a sense of loss of professional control, which can arise when teachers feel their roles are being replaced by rigid digital systems [4]. Without reflective pedagogical dialogue, technology adoption can actually lead to alienation among educators.

Theoretically, the current literature on Education 4.0 also demonstrates limitations in the use of a robust conceptual framework. Many studies simply use Education 4.0 as an umbrella term without examining the concept's structure, transformative logic, or deeper implications [11]. As a result, the misconception often arises that technology is an end in itself, rather than a means to achieve broader pedagogical goals such as inclusion, equity, and learning autonomy. Therefore, more critical and reflective theoretical approaches, such as emancipatory education and critical theory, are needed to prevent technology integration from becoming a new tool for reproducing old inequalities in more sophisticated forms.

### 3.5. Thematic Synthesis and Practical Implications

This section presents a cross-thematic synthesis of the previous analysis and practical implications for teachers, educational institutions, and policymakers. The synthesis is conducted by mapping the relationships between technology, pedagogical approaches, systemic contributions, and key challenges, based on findings from the 26 reviewed studies. Table 2 illustrates the relationship between the study focus and the main findings. This synthesis demonstrates that technological innovation and learning approaches are not yet fully connected to sustainable systemic transformation efforts. Many efforts remain experimental, partial, and unsupported by structural policies.

**Table 2.** Thematic synthesis matrix across research questions

| Primary Focus (RQ) | Core Findings | Related Challenges |
|---|---|---|
| Technology and Pedagogy (RQ1) | Hybrid learning, AI, LMS, AR/VR; personalized & project-based learning | Teacher resistance, limitations of high technology adoption |
| Systemic Contribution (RQ2) | Digital curriculum, 21st century competencies, teacher & institutional readiness | Still local & micro, not cross-sectoral |
| Themes & Challenges (RQ3) | Digital identity, digital literacy, inequality, lack of longitudinal studies | Policy fragmentation, lack of national direction |

Based on the results of the thematic analysis and synthesis, a conceptual framework was developed that illustrates the key elements of the Education 4.0 transformation. This conceptual model encompasses four main, interconnected components that form a complete digital education ecosystem. First, innovative technologies such as artificial intelligence (AI), learning management systems (LMS), and augmented and virtual reality (AR/VR) act as enablers in creating adaptive and interactive learning experiences. Second, digital pedagogy serves as the foundation for new learning designs that emphasize personalized learning, project-based learning, and hybrid classroom approaches. Third, the success of technology integration is greatly influenced by the readiness of human resources and institutions, which include digital competence, technological literacy, and the formation of a collaborative mindset. Finally, supporting policies and infrastructure are needed, including aligned regulations, budget support, and equitable access for all levels of education. These four components will only produce a transformative impact if they operate synergistically and sustainably. An imbalance in any one element can weaken the effectiveness of the entire Education 4.0 system.

In practice, the results of this synthesis yield several important implications for various stakeholders. For teachers and practitioners, a pedagogical retooling approach is needed that emphasizes strengthening digital identity through critical reflection and developing communities of

practice, rather than solely technical training. For educational institutions, technological transformation needs to be accompanied by changes to curriculum, assessment, and learning governance, as well as the implementation of regular digital readiness audits. Meanwhile, for policymakers, it is necessary to develop cross-sectoral education policies involving education, communications, and the digital economy, with a national roadmap that emphasizes inclusivity, sustainability, and collaboration between the public and private sectors.

The results and discussion sections of this study demonstrate that while the literature on Education 4.0 has grown in quantity and thematic scope, significant conceptual and structural challenges remain. The thematic synthesis resulting from this study is expected to serve as a foundation for the development of more focused further research and the formulation of educational policies that adapt to the demands of ongoing digital transformation.

## 4. Conclusion

This study systematically reviewed 26 scholarly articles discussing the implementation of Education 4.0 in the context of technology, pedagogy, and education system transformation. The results indicate that the most dominant technologies used include artificial intelligence (AI), learning management systems (LMS), hybrid learning, and various digital tools that support personalized and project-based learning. However, a gap exists between technology adoption and truly transformative pedagogical implementation. Most studies remain local and applied, particularly in digital curriculum development, 21st-century competencies, and institutional readiness. Studies at the systemic level, particularly those linking policy, pedagogy, and digital infrastructure, are still very limited. Prominent conceptual themes include digital identity, technological literacy, resistance to change, and educational infrastructure gaps. The lack of longitudinal studies and the lack of policy-technology-pedagogy synthesis reinforce the indication that Education 4.0 has not been fully implemented as a complete ecosystem.

The implications of these findings include the importance of using a stronger and more consistent theoretical framework, as well as the need for an integrated conceptual model that combines pedagogical, technological, and educational policy dimensions. In practice, teachers need to be actively involved in the design of educational technology, institutions are required to design long-term digital strategies, and policymakers must develop evidence-based and sustainability-oriented regulations. For future research, longitudinal studies are needed to understand the long-term impacts of digital transformation, policy-based evaluative research, cross-contextual analysis, and exploration of ethical and humanistic AI-based learning evaluation systems. A transdisciplinary approach is also needed to build a relevant, adaptive, and sustainable Education 4.0 implementation model.

## Declarations

**Author Contribution:** All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

[1] F. Almeida and J. Simoes, “The role of serious games, gamification and Industry 4.0 tools in the education 4.0 paradigm,” *Contemp. Educ. Technol.*, vol. 10, no. 2, pp. 120–136, Apr. 2019, https://doi.org/10.30935/cet.554469.

[2] T. Shenkoya and E. Kim, “Sustainability in higher education: Digital transformation of the fourth industrial revolution and its impact on open knowledge,” *Sustainability*, vol. 15, no. 3, p. 2473, Jan. 2023, https://doi.org/10.3390/su15032473.

[3] C. M. Reigeluth, “Technology and the new paradigm of education,” *Contemp. Educ. Technol.*, vol. 1, no. 1, pp. 84–86, 2010, https://doi.org/10.30935/cedtech/5963.

[4] L. I. González-Pérez and M. S. Ramírez-Montoya, "Components of education 4.0 in 21st century skills frameworks: systematic review," *Sustainability*, vol. 14, no. 3, p. 1493, Jan. 2022, https://doi.org/10.3390/su14031493.

[5] O. Habets, J. Stoffers, B. Van der Heijden, and P. Peters, "Am i fit for tomorrow's labor market? the effect of graduates' skills development during higher education for the 21st century's labor market," *Sustainability*, vol. 12, no. 18, p. 7746, Sep. 2020, https://doi.org/10.3390/su12187746.

[6] D. Mhlanga, "Artificial intelligence in the industry 4.0, and its impact on poverty, innovation, infrastructure development, and the sustainable development goals: lessons from emerging economies?," *Sustainability*, vol. 13, no. 11, p. 5788, May 2021, https://doi.org/10.3390/su13115788.

[7] H. A. López, P. Ponce, A. Molina, M. S. Ramírez-Montoya, and E. Lopez-Caudana, "Design framework based on TEC21 educational model and education 4.0 implemented in a capstone project: A case study of an electric vehicle suspension system," *Sustainability*, vol. 13, no. 11, p. 5768, May 2021, https://doi.org/10.3390/su13115768.

[8] E. Costan, G. Gonzales, R. Gonzales, L. Enriquez, F. Costan, D. Suladay, N. M. Atibing, J. L. Aro, S. S. Evangelista, F. Maturan, E. Selerio Jr., and L. Ocampo, "Education 4.0 in developing economies: A systematic literature review of implementation barriers and future research agenda," *Sustainability*, vol. 13, no. 22, p. 12763, Nov. 2021, https://doi.org/10.3390/su132212763.

[9] S. M. Ross, G. R. Morrison, and D. L. Lowther, "Educational technology research past and present: Balancing rigor and relevance to impact school learning," *Contemp. Educ. Technol.*, vol. 1, no. 1, pp. 17–35, Mar. 2010, https://doi.org/10.30935/cedtech/5959.

[10] A. A. Khafizova, A. M. Galimov, S. R. Kharisova, L. Y. Grebenshchikova, R. I. Yagudina, and L. M. Smirnova, "The impact of healthcare digitalization on the medical education curricula and programs: Points of convergence and divergence," *Contemp. Educ. Technol.*, vol. 15, no. 4, p. ep479, Oct. 2023, https://doi.org/10.30935/cedtech/13768.

[11] J.-H. Ye, Y.-W. Hao, and Y.-F. Wu, "Effectiveness and sustainable applications of educational technology," *Sustainability*, vol. 16, no. 18, p. 8209, Sep. 2024, https://doi.org/10.3390/su16188209.

[12] X. Wen and S. M. Walters, "The impact of technology on students' writing performances in elementary classrooms: A meta-analysis," *Comput. Educ. Open*, vol. 3, p. 100082, Dec. 2022, https://doi.org/10.1016/j.caeo.2022.100082.

[13] S. Purohit and A. Dutt, "Pedagogical innovations in management education in the 21st century: A review and research agenda," *Int. J. Manag. Educ.*, vol. 22, no. 2, p. 100976, Jul. 2024, https://doi.org/10.1016/j.ijme.2024.100976.

[14] F. Toma, A. Ardelean, C. Grădinaru, A. Nedelea, and D. C. Diaconu, "Effects of ICT integration in teaching using learning activities," *Sustainability*, vol. 15, no. 8, p. 6885, Apr. 2023, https://doi.org/10.3390/su15086885.

[15] P. Rikala, G. Braun, M. Järvinen, J. Stahre, and R. Hämäläinen, "Understanding and measuring skill gaps in Industry 4.0 — A review," *Technol. Forecast. Soc. Change*, vol. 201, p. 123206, Apr. 2024, https://doi.org/10.1016/j.techfore.2024.123206.

[16] K. Sperling, C.-J. Stenberg, C. McGrath, A. Åkerfeldt, F. Heintz, and L. Stenliden, "In search of artificial intelligence (AI) literacy in teacher education: A scoping review," *Comput. Educ. Open*, vol. 6, p. 100169, Jun. 2024, https://doi.org/10.1016/j.caeo.2024.100169.

[17] A. Patiño, M. S. Ramírez-Montoya, and G. Ibarra-Vazquez, "Trends and research outcomes of technology-based interventions for complex thinking development in higher education: A review of scientific publications," *Contemp. Educ. Technol.*, vol. 15, no. 4, p. ep447, Oct. 2023, https://doi.org/10.30935/cedtech/13416.

[18] A. Visvizi and L. Daniela, "Technology-enhanced learning and the pursuit of sustainability," *Sustainability*, vol. 11, no. 15, p. 4022, Jul. 2019, https://doi.org/10.3390/su11154022.

[19] D. K. Narong and P. Hallinger, "Traversing the evolution of research on engineering education for sustainability: A bibliometric review (1991–2022)," *Sustainability*, vol. 16, no. 2, p. 641, Jan. 2024, https://doi.org/10.3390/su16020641.

[20] A. Artyukhov, T. Wołowiec, N. Artyukhova, S. Bogacki, and T. Vasylieva, "SDG 4, academic integrity and artificial intelligence: Clash or win-win cooperation?," *Sustainability*, vol. 16, no. 19, p. 8483, Sep. 2024, https://doi.org/10.3390/su16198483.

[21] E. Katsamakas, O. V. Pavlov, and R. Saklad, "Artificial intelligence and the transformation of higher education institutions: A systems approach," *Sustainability*, vol. 16, no. 14, p. 6118, Jul. 2024, https://doi.org/10.3390/su16146118.

[22] F. Kamalov, D. Santandreu Calonge, and I. Gurrib, "New era of artificial intelligence in education: Towards a sustainable multifaceted revolution," *Sustainability*, vol. 15, no. 16, p. 12451, Aug. 2023, https://doi.org/10.3390/su151612451.

[23] J. V. Pavlik, "Fueling a third paradigm of education: The pedagogical implications of digital, social and mobile media," *Contemp. Educ. Technol.*, vol. 6, no. 2, pp. 113-125, Jun. 2015, https://doi.org/10.30935/cedtech/6143.

[24] B. Bhasin, "Integration of information and communication technology in enhancing teaching and learning," *Contemp. Educ. Technol.*, vol. 3, no. 2, pp. 130-140, Jun. 2012, https://doi.org/10.30935/cedtech/6073.

[25] M. Umar and I. Ko, "E-learning: Direct effect of student learning effectiveness and engagement through project-based learning, team cohesion, and flipped learning during the COVID-19 pandemic," *Sustainability*, vol. 14, no. 3, p. 1724, Feb. 2022, https://doi.org/10.3390/su14031724.

[26] J. del R. Fernández-Velásquez, O. López-Regalado, and G. A. Fernández-Hurtado, "Educational dualism in action: Systematic review of gamification and flipped classrooms' effects on young learners," *Contemp. Educ. Technol.*, vol. 17, no. 1, p. ep557, Jan. 2025, https://doi.org/10.30935/cedtech/15749.

[27] S. McManus, D. Pendergast, and H. Kanasa, "The intersection between food literacy and sustainability: A systematic quantitative literature review," *Sustainability*, vol. 17, no. 2, p. 459, Jan. 2025, https://doi.org/10.3390/su17020459.

[28] W. C. Satyro et al., "Technology-organization-external-sustainability (TOES) framework for technology adoption: Critical analysis of models for Industry 4.0 implementation projects," *Sustainability*, vol. 16, no. 24, p. 11064, Dec. 2024, https://doi.org/10.3390/su162411064.

[29] Á. Novoa-Echaurren, A. Canales-Tapia, and L. Molin-Karakoç, "Pedagogical uses of ICT in Finnish and Chilean schools: A systematic review," *Contemp. Educ. Technol.*, vol. 17, no. 1, p. ep561, Jan. 2025, https://doi.org/10.30935/cedtech/15828.

[30] R. Afrilyasanti, Y. Basthomi, and E. L. Zen, "Fostering creativity and critical literacy: Transforming EFL classes with engaging critical media literacy integration," *Asian Educ. Dev. Stud.*, vol. 14, no. 2, pp. 133–151, Mar. 2025, https://doi.org/10.1108/AEDS-06-2024-0124.

[31] H. G. van de Werfhorst, E. Kessenich, and S. Geven, "The digital divide in online education: Inequality in digital readiness of students and schools," *Comput. Educ. Open*, vol. 3, p. 100100, Dec. 2022, https://doi.org/10.1016/j.caeo.2022.100100.

[32] N. A. Jogezai, D. Koroleva, and F. A. Baloch, "Teachers' digital competence in the post COVID-19 era: The effects of digital nativeness and digital leadership capital," *Contemp. Educ. Technol.*, vol. 15, no. 4, p. ep466, Oct. 2023, https://doi.org/10.30935/cedtech/13620.

[33] B. Amarathunga, "Work integrated learning and trending areas for future studies: A systematic literature review and bibliometric analysis," *Asian Educ. Dev. Stud.*, vol. 13, no. 2, pp. 97–116, Apr. 2024, https://doi.org/10.1108/AEDS-12-2023-0175.

[34] K. Hu and A. Raman, "Systematic literature review on the holistic integration of e-learning in universities: Policy, human, financial, and technical perspectives," *Contemp. Educ. Technol.*, vol. 16, no. 2, p. ep497, Apr. 2024, https://doi.org/10.30935/cedtech/14287.

[35] S. L. Gupta, A. Mittal, S. Singh, and D. N. Dash, "Demand-driven approach of vocational education and training (VET) and experiential learning: A thematic analysis through systematic literature review (SLR)," *Asian Educ. Dev. Stud.*, vol. 13, no. 1, pp. 45–63, Feb. 2024, https://doi.org/10.1108/AEDS-07-2023-0083.

[36] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald, L. A. McGuinness, L. A. Stewart, J. Thomas, A. C. Tricco, V. A. Welch, P. Whiting, and D. Moher, "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," *BMJ*, vol. 372, p. n71, 2021, https://www.bmj.com/content/372/bmj.n71.

[37] J. Thomas and A. Harden, "Methods for the thematic synthesis of qualitative research in systematic reviews," *BMC Med. Res. Methodol.*, vol. 8, no. 1, p. 45, Dec. 2008, https://doi.org/10.1186/1471-2288-8-45.

[38] D. Mhlanga, "Digital transformation of education, the limitations and prospects of introducing the fourth industrial revolution asynchronous online learning in emerging markets," *Discover Educ.*, vol. 3, no. 1, p. 32, Mar. 2024, https://doi.org/10.1007/s44217-024-00115-9.

[39] H. Benlhabib and A. Berrado, "Towards a digital platform for performance management and systemic improvement of education systems: Evidence from Morocco," *Discover Educ.*, vol. 4, no. 1, p. 15, Jan. 2025, https://doi.org/10.1007/s44217-024-00317-1.

[40] C. N. Akpen, S. Asaolu, S. Atobatele, H. Okagbue, and S. Sampson, "Impact of online learning on student's performance and engagement: A systematic review," *Discover Educ.*, vol. 3, no. 1, p. 205, Nov. 2024, https://doi.org/10.1007/s44217-024-00253-0.

[41] C. L. Svihus, "Online teaching in higher education during the COVID-19 pandemic," *Educ. Inf. Technol. (Dordr)*, vol. 29, no. 3, pp. 3175–3193, Feb. 2024, https://doi.org/10.1007/s10639-023-11971-7.

[42] J. F. Kalolo, "Digital revolution and its impact on education systems in developing countries," *Educ. Inf. Technol. (Dordr)*, vol. 24, no. 1, pp. 345–358, Jan. 2019, https://doi.org/10.1007/s10639-018-9778-3.

[43] S. Mhlongo, K. Mbatha, B. Ramatsetse, and R. Dlamini, "Challenges, opportunities, and prospects of adopting and using smart digital technologies in learning environments: An iterative review," *Heliyon*, vol. 9, no. 6, p. e16348, 2023, https://doi.org/10.1016/j.heliyon.2023.e16348.

[44] E. F. Okagbue, U. P. Ezeachikulo, I. S. Nchekwubemchukwu, I. E. Chidiebere, K. Obisoanya, C. A. T. Ouattara, and E. O. Nwigwe, "The effects of Covid-19 pandemic on the education system in Nigeria: The role of competency-based education," *Int. J. Educ. Res. Open*, vol. 4, p. 100219, 2023, https://www.sciencedirect.com/science/article/pii/S2666374022000954.

[45] D. Mara et al., "Are digital education resources meeting the preliminary needs of 'R.E.D. Teacher EDucation' project?," *Rev. Rom. pentru Educ. Multidimens.*, vol. 16, no. 4, pp. 70–96, 2024, https://doi.org/10.18662/rrem/16.4/908.

[46] G. Schlebusch, S. Bhebhe, and L. Schlebusch, "Technology integration in teacher education practices in two Southern African universities," *Open Educ. Stud.*, vol. 6, no. 1, p. 20220223, 2024, https://doi.org/10.1515/edu-2022-0223.

[47] B. D. Bretan, "Is the future hybrid? An analysis of opportunities for digital education," *Studia Univ. Babeș-Bolyai Philologia*, vol. 238, pp. 225–238, 2022, https://doi.org/10.24193/subbphilo.2022.4.11.

[48] H. Ullah, S. Manickam, M. Obaidat, S. U. A. Laghari, and M. Uddin, "Exploring the potential of metaverse technology in healthcare: Applications, challenges, and future directions," *IEEE Access*, vol. 11, pp. 69686–69707, 2023, https://doi.org/10.1109/ACCESS.2023.3286696.

[49] P. Onu, A. Pradhan, and C. Mbohwa, "Potential to use metaverse for future teaching and learning," *Educ. Inf. Technol. (Dordr)*, vol. 29, no. 7, pp. 8893–8924, May 2024, https://doi.org/10.1007/s10639-023-12167-9.

[50] S. Rostami and M. Maier, "The metaverse and beyond: Implementing advanced multiverse realms with smart wearables," *IEEE Access*, vol. 10, pp. 110796–110806, 2022, https://doi.org/10.1109/ACCESS.2022.3215736.

[51] C. E. George-Reyes, I. C. Peláez Sánchez, L. D. Glasserman-Morales, and E. O. López-Caudana, "The metaverse and complex thinking: Opportunities, experiences, and future lines of research," *Front. Educ. (Lausanne)*, vol. 8, p. 1166999, May 2023, https://doi.org/10.3389/feduc.2023.1166999.

[52] M. R. Mohd Jamil, N. Idris, M. M. Md Zalli, N. M. H. Nek Rakami, and Z. H. Putra, "Transforming inclusive digital pedagogy in Malaysian tertiary TVET: Adapting to a new educational landscape," *J. Tech. Educ. Train.*, vol. 16, no. 2, pp. 161–170, 2024, https://doi.org/10.30880/JTET.2024.16.02.014.

[53] L. Younie and C. Adachi, "Nurturing the human dimension in digital and medical spaces through pedagogy of care – A case of creative enquiry," *Open Praxis*, vol. 13, no. 1, pp. 307–312, 2024, https://doi.org/10.5334/pme.1147.

[54] D. Padua, "Artificial intelligence and Quality Education: The Need for Digital Culture in Teaching," *J. Educ., Cult. Psychol. Stud.* (ECPS Journal), no. 30, pp. 181-193, 2024, https://doi.org/10.7358/ecps-2024-030-padd.

[55] W. Barber, "Building creative critical online learning communities through digital moments," *Electron. J. e-Learn.*, vol. 18, no. 5, pp. 387–396, 2020, https://doi.org/10.34190/JEL.18.5.002.

[56] Z. Liu and E. Yushchik, "Exploring the prospects of using artificial intelligence in education," *Cogent Educ.*, vol. 11, no. 1, art. 2353464, Dec. 2024, https://doi.org/10.1080/2331186X.2024.2353464.

[57] M. Gentile, G. Città, I. Marfisi-Schottman, F. Dignum, and M. Allegra, "Editorial: Artificial intelligence for education," *Front. Educ. (Lausanne)*, vol. 8, p. 1276546, Nov. 2023, https://doi.org/10.3389/feduc.2023.1276546.

[58] E. du Plooy, D. Casteleijn, and D. Franzsen, "Personalized adaptive learning in higher education: A scoping review of key characteristics and impact on academic performance and engagement," *Heliyon*, vol. 10, no. 21, p. e39630, Nov. 2024, https://doi.org/10.1016/j.heliyon.2024.e39630.

[59] G. S. Olanrewaju, S. B. Adebayo, A. Y. Omotosho, and C. F. Olajide, "Left behind? The effects of digital gaps on e-learning in rural secondary schools and remote communities across Nigeria during the COVID19 pandemic," *Int. J. Educ. Res. Open*, vol. 2, p. 100092, 2021, https://doi.org/10.1016/j.ijedro.2021.100092.

[60] A. Verger, C. Fontdevila, and A. Zancajo, *The Privatization of Education: A Political Economy of Global Education Reform*. New York, NY, USA: Teachers College Press, 2016, https://download.ei-ie.org/Docs/WebDepot/The_Privatization_of_Education.pdf.

[61] Ł. Tomczyk, "Digital competence among pre-service teachers: A global perspective on curriculum change as viewed by experts from 33 countries," *Eval. Program Plann.*, vol. 105, p. 102449, 2024, https://doi.org/10.1016/j.evalprogplan.2024.102449.

[62] A. M. McCarthy, D. Maor, A. McConney, and C. Cavanaugh, "Digital transformation in education: Critical components for leaders of system change," *Soc. Sci. Humanit. Open*, vol. 8, no. 1, p. 100479, 2023, https://doi.org/10.1016/j.ssaho.2023.100479.

[63] S. Hennessy, S. D'Angelo, N. McIntyre, S. Koomar, A. Kreimeia, L. Cao, M. Brugha, and A. Zubairi, "Technology use for teacher professional development in low- and middle-income countries: A systematic review," *Comput. Educ. Open*, vol. 3, p. 100080, 2022, https://doi.org/10.1016/j.caeo.2022.100080.

[64] L. I. González-Pérez and M. S. Ramírez-Montoya, "Components of Education 4.0 in 21st century skills frameworks: Systematic review," *Sustainability*, vol. 14, no. 3, p. 1493, 2022, https://doi.org/10.3390/su14031493.