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Review

Decentralized Identity Management for Metaverse-Enhanced Education: A Literature Review

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Abstract: As we transition into the era of Web 3.0, where decentralized information and user privacy are paramount, emerging technologies are reshaping the way in which personal data are managed. This paper focuses on decentralized identity management (DID) in the metaverse, particularly within the education sector, which has rapidly embraced digital tools for e-learning, especially since the COVID-19 pandemic. Technologies such as blockchain, artificial intelligence (AI), and virtual and augmented reality (VR/AR) are increasingly integrated into educational platforms, raising questions about privacy, security, and interoperability. This literature review examines the current landscape of DID in metaverse-based educational applications. Through a systematic methodology, relevant academic papers were identified, filtered, and analyzed based on four key criteria: standardization, interoperability, application scalability, and security/privacy considerations. The paper provides a comparative analysis of these papers to assess the maturity of DID implementations, highlight existing challenges, and suggest future research directions in the intersection of decentralized identity and educational metaverse applications.

Keywords: decentralized identity management; metaverse; education; scalability; interoperability; standardization; literature review

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1. Introduction

Modern educational approaches have undergone tremendous changes as a result of the recent and drastic technology developments that have occurred over the previous years. Acknowledging the impact of COVID-19 on education, research shows that remote learning methods have become an everyday habit for faculty and students. State-of-the-art research advancements have been brought about by cutting-edge technologies, showing the potential to significantly enhance digital training and education methods using metaverse technologies (i.e., artificial intelligence—AI, virtual reality/augmented reality—VR/AR, blockchain, and the Internet of Things—IoT) [1]. However, the challenges of bringing the metaverse experience into education seamlessly surpasses the current efforts being made. One of the biggest challenges is the capability of multiple decentralized environments to cryptographically handle the identification and authentication of a single individual, without using central authority infrastructures (e.g., certificate authorities, login servers, etc.) [2].

Digital methods and tools can radically transform education processes and training in general. The prospects of exploiting the metaverse have skyrocketed, with the education sector being either at the center or one of the three most affected areas. It is also evident that the advancement of the distinct technologies comprising the metaverse has already impacted traditional educational methods at all levels of education, with the most intense and recent example being the use of ChatGPT for the writing and correction of assignments. Moreover, Hwang and Chien discuss the effect of the metaverse on social constructivism methodology concerning an individual's cognitive development [3]. Clinical and field

exercises can be improved with students' access to real-world data (e.g., the virtual digital twin of a server for computer science students) and environments (e.g., the collapse site of a building for rescuers, firefighters, etc.), removing barriers like space, time, and cost. Maheswari and others explain the impact and benefits of IoT-enhanced education through the metaverse [4]. Training and education can take place using simulations, which are based on real-world data and actual situations, however, making education even more accessible and preparing individuals for real-world situations.

Within this scope, the management of digital identities in the metaverse is fundamental for creating a secure and reliable educational environment, where individuals are able to authenticate themselves and gather their certificates and credentials digitally, in a secure and private way. The roles and entities involved in an identification system within the metaverse can exponentially increase and are related to the complexity of a use case scenario. Currently, the state of the metaverse does not offer users a way to authenticate themselves and the other entities they interact with (e.g., other users, digital twins, avatars, and data) using a standardized method. Over the past few years, efforts have been made to implement a Meta-University, reaching experimental conditions under real circumstances, such as those of the University of Nicosia in Cyprus [5] and the University of Hong Kong in China [6].

As part of these efforts, the known Role Based Access Control (RBAC) [7] model has been followed; the roles implemented are simple and distinct, with the primary ones being the educational staff and student community. Digital identity integration is not addressed, and in the case of the University of Nicosia, program attendance certification consists of a Non-Fungible Token (NFT) owned by a crypto-wallet without any authentication methods for the person who owns the wallet itself. The process of verifying the certificate takes place off-chain, disrupting any chance of interoperability with other applications or other metaverse environments.

While several experiments demonstrate the potential of the metaverse to enhance educational experiences, they also highlight significant challenges—particularly in terms of authentication and identity management. These challenges stem from the lack of a unified framework that can provide secure and seamless user experiences across different platforms [8]. For instance, decentralized technologies such as Decentralized Identifiers (DIDs), Verifiable Credentials (VCs), and Self-Sovereign Identitie (SSI) have been proposed to address these issues [9], offering promising solutions for secure user identification and privacy protection. However, as noted by recent studies such as [10], the implementation of such frameworks remains inconsistent, and no standardized approach has yet been widely adopted.

By employing a common Decentralized Identity Management (DIM) framework, vendors could enhance security, ensure interoperability, and facilitate trusted communications between users in the metaverse [11]. This raises the key question: what is the current landscape of DIM, and what progress has been made in developing a framework that supports the integration of metaverse-based educational applications? This paper intends to review the recent efforts revolving around DIM implementations based on the technologies of blockchain and the metaverse in order to define their state and their impact on the education sector. To this end, Section 2 of this paper will present the methodology used to filter and categorize the recent literature regarding the problem statement that this paper focuses on. Section 3 will analyze the main topics comprising the base of our research, which can solve our research questions, while Section 4 will present the comparative analysis of the filtered literature and our findings. Lastly, Sections 5 and 6 will conclude our inferences upon the matter and discuss our intentions for future work.

2. Methodology and Criteria

For the selection of the papers that should be included in this work, a literature review took place to comprehensively assess the intersection of the metaverse, education, and decentralized identity management. This review process consists of two phases and several steps to ensure that the selected papers meet the criteria to be included in it. More

analytically, the first phase is focused on searching popular scholarly databases for papers on related topics while the second phase includes all of the filtering and clustering processes in order to organize the finalized list of literature that was accumulated.

The methodology was meticulously designed to ensure thoroughness and academic rigor, following a structured approach as presented in Figure 1. Its stages are analyzed in the following subsections.

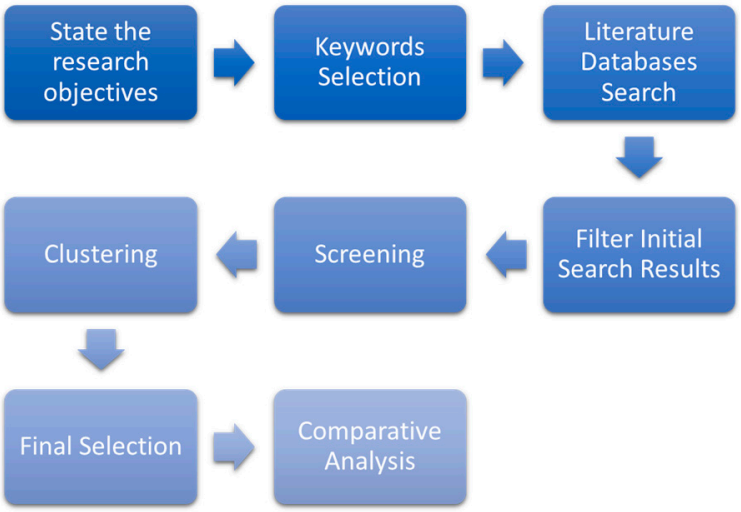


Figure 1. Methodology stages.

2.1. Research Objectives

In this literature review, we aim to take a deep dive into the current academic landscape, focusing on DIM in metaverse environments, particularly within the context of education as a use case, as illustrated in Figure 2. Keeping in mind the impact of standardization in the advancement of practical applicability for different technologies so far, this paper intends to identify whether the current state of research is moving towards the standardization of DIM and convergence into a common framework.

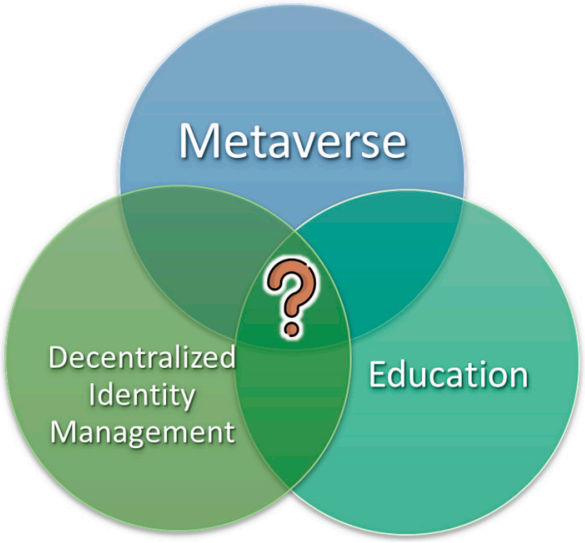


Figure 2. Target area of the literature review.

In short, the objectives of this paper are as follows: (1) to evaluate existing DIM solutions and their applicability to educational use cases within the metaverse, (2) to assess the engagement of the research community with this topic, and (3) to assess the role of

DIM standardization in supporting seamless integration and compatibility across various metaverse educational scenarios.

2.2. Keyword Selection

For the literature search, three key phrases were identified based on the previously set research objectives: "metaverse", "education", and "decentralized identity management". The search strategy involved querying these keywords individually, in pairs, and then collectively to ensure comprehensive coverage of relevant literature. The specific combinations were as follows:

- "Metaverse"
- "Education"
- "Decentralized Identity Management"
- "Metaverse" AND "Education"
- "Metaverse" AND "Decentralized Identity Management"
- "Metaverse" AND "Education" AND "Decentralized Identity Management"

2.3. Database Search

The databases utilized for this review were chosen for their extensive coverage of relevant academic fields:

- ***Google Scholar***: A broad platform providing access to a wide variety of scholarly articles across multiple disciplines.
- ***IEEE Xplore***: A digital library for scientific and technical content published by IEEE and its partners.
- ***Scopus***: A comprehensive abstract and citation database of peer-reviewed literature, including journals, books, and conference proceedings.
- ***ScienceDirect***: A leading full-text scientific database offering journal articles and book chapters.

2.4. Filtering Initial Search Results

The initial search across multiple academic databases generated a substantial number of articles. To ensure a focused and relevant selection for our literature review, we applied a multi-step filtering process based on specific criteria:

- ***Timeframe***: We restricted our search to publications from 2021 to February 2024. This timeframe was chosen to capture the most recent advancements and research developments in the field.
- ***Language***: To maintain consistency and ensure accessibility, we included only articles published in English. This criterion was essential for comprehensiveness and alignment with the target audience of our review.
- ***Type of Publication***: We focused on peer-reviewed journal articles and conference papers. This choice was made to prioritize high-quality, rigorously reviewed research. Publications such as book chapters and white papers were excluded as they do not typically meet the same standards of peer-reviewed scholarship.
- ***Subject Area***: The search was confined to the subject area of computer science to ensure relevance to our research topic.

To refine the search results, we used the advanced search features provided by each database in order to set the timeframe limitation (papers since 2021) and show only the results where all of the keywords are included in the title of the publication. It is worth noting that the number of results exponentially increases out of control when the keyword exclusiveness is not considered, resulting in a less transparent filtering and screening process. The search results for each exclusive combination of keywords are shown in Table 1.

Table 1. Literature databases search results list.

Keywords	Database	Raw Results	Timeframe Filter	Journals + Confs	Subject Area
Metaverse	Scopus	19.756	10.365	8.083	2766
	Google Scholar	16.300	13.500	N/A	N/A
	IEEE Xplore	618	618	565	N/A
	Science Direct	624	611	500	84
Decentralized Identity Management	Scopus	371	278	218	178
	Google Scholar	18	75	N/A	N/A
	IEEE Xplore	315	204	190	N/A
	Science Direct	103	71	65	45
Metaverse and Decentralized Identity Management	Scopus	0	0	0	0
	Google Scholar	0	0	0	0
	IEEE Xplore	5	5	5	N/A
	Science Direct	1	1	1	1
Metaverse and Education	Scopus	126	125	96	74
	Google Scholar	872	614	N/A	N/A
	IEEE Xplore	228	225	213	N/A
	Science Direct	59	58	45	14
Metaverse and Decentralized Identity Management and Education	Scopus	0	0	0	0
	Google Scholar	0	0	0	0
	IEEE Xplore	2	2	2	N/A
	Science Direct	1	1	1	1

2.5. Screening Process

Table 1 shows the search results from each database and the decrease in their number when applying each filtering criterion. As shown, the first keyword, "Metaverse", provides a huge number of results, which finally, after filtering the timeframe, the type of publication, and the subject area they belong to, decreases to 2766. While this number is enormous to manually review, it demonstrates the interest of academia in the topic of the metaverse within the computer science area. however, reviewing the entire metaverse landscape is out of the scope of this paper, especially considering the different definitions of the term that have occurred during the last few years.

On the other hand, with the decentralized identity management key phrase, due to the fact that it has appeared as a term over the last few years with the rise of the Web 3.0 idea, the search results are considerably lower but in most cases indirectly relevant to the metaverse or blockchain solutions in general.

Consequently, at the time of writing this paper, the search results, which are included in the next step of the review, are the ones that appeared in the combination of keywords and key phrases and a small number from the DIM search results. Figure 3 demonstrates a first impression of the search results number based on the selected keywords/key phrases. It is evident that despite the fact that Decentralized Identity and the metaverse are hot topics, with education being one of the most affected sectors, the available recent literature is considerably low, especially when one combines all of the key phrases. On the other hand, the combination of the metaverse and education has attracted the most attention over recent years, while DIM has also attracted attention independently of the other keywords.

The initial search results underwent a rigorous screening process where duplicate entries across the databases were identified and removed, and the titles and abstracts of the remaining articles were screened for relevance to the study's focus on the metaverse, education, and decentralized identity management. And finally, the articles that passed the initial screening were subjected to a full-text review to ensure that they met the inclusion criteria. During the screening process, in order for a paper to be included (or excluded by not following both of the inclusion criteria) in this research, the authors defined 3 criteria: (1) English language used throughout the paper, (2) specific publication content (literature review or solution/use case or architecture/conceptual model), and (3) address at least two

of the main keywords/key phrases in any combination possible. After this process, the list of included papers was finalized and is shown in Appendix A.

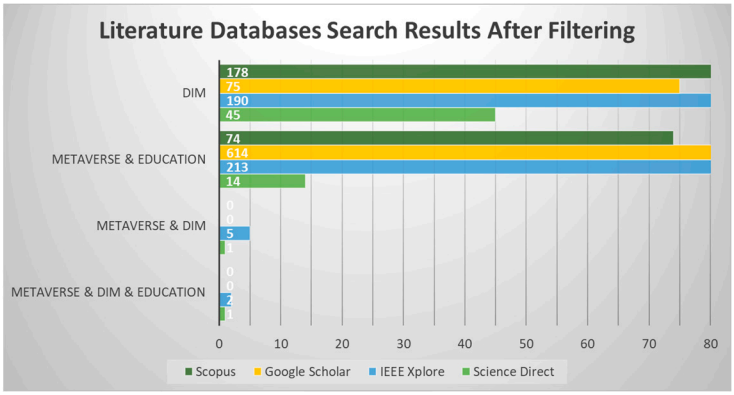


Figure 3. Literature databases search results after filtering.

2.6. Clustering

The selected articles were categorized into three clusters based on their primary focus and the keywords/key phrases they appeared from. Using these keywords, we manually grouped the papers into preliminary clusters. Each cluster represented a dominant theme or technology related to Decentralized Identity Management in the context of the metaverse and education. For instance, papers focusing on **blockchain** as the foundational technology for identity management were grouped together, while others emphasizing educational applications of DID technologies were placed in a different cluster. After the initial grouping, we refined the clusters by reviewing the full text of each paper, ensuring that each paper fit appropriately within its cluster based on both the keywords and the thematic focus of the research. Papers that spanned multiple themes were categorized into the cluster that aligned most with their primary focus.

- The final clustering was determined by the relevance of each paper to three core areas: education, decentralized identity management, and the intersection of these keywords within the metaverse. Papers were categorized into clusters based on their primary focus—those dealing primarily with decentralized identity management, those focused on educational applications, and those exploring the integration of decentralized identity management within metaverse-based educational environments. This clustering ensured that papers addressing the intersection of all three themes—education, decentralized identity management, and the metaverse—were placed in [10] a distinct cluster, while other papers were grouped based on their relevance to either education or decentralized identity management individually.

This clustering approach facilitated a structured analysis, enabling a detailed examination of the intersection between the metaverse, education, and decentralized identity management. This process ensured that each cluster was based on meaningful and consistent criteria, reflecting the main themes across the selected papers.

The final clustering comprised 31 articles that were deemed highly relevant to the study's objectives. These articles were distributed across the three clusters as follows:

- **Metaverse and Education:** 21
- **Metaverse and Identity Management:** 9
- **Metaverse, Education, and Identity Management:** 1

2.7. Comparative Analysis

Following clustering, a comparative analysis of the final list of 31 academic papers was conducted. This analysis was based on four critical parameters:

- **Contribution Type:** Identifying the nature of the contribution (e.g., literature review, proof of concept, empirical study, etc.).
- **Focus Areas Engaged:** Determining how many of the key focus areas (metaverse, education, decentralized identity management) are addressed.
- **SSI Standardization Utilized:** Assessing whether any form of Self-Sovereign Identity (SSI) standardization was employed in the study.
- **Application-level Interoperability:** Evaluating whether the topic of application-level interoperability was addressed.

The purpose of this comparative analysis was threefold. Initially, by examining the coverage of the focus areas, we aimed to identify gaps in the research, particularly in the context of decentralized identity management for metaverse education applications. Moreover, analyzing the types of contributions provided insights into the overall and holistic understanding and progress in this research domain, while, finally, evaluating the use of standardization and interoperability helped us to assess the practical applicability and maturity of the available contributions.

The above methodology ensured a comprehensive review of the literature, providing a robust foundation for the study's findings and recommendations. By following this rigorous methodology, the study aims to contribute significantly to the ***understanding of the conjunction area of the metaverse, education, and DIM***, identifying both current applications and future research directions.

3. Literature Review

Identity management is one of the most foundational challenges to be addressed when creating a consistent and secure environment in the metaverse. At the same time, all of the technologies included in a metaverse environment are capable of transforming traditional educational methods into modern ones, providing immersive learning, active engagement of students, hands-on training with safety, and many more aspects.

In this section, we conduct an in-depth survey of research works selected following the methodology described previously, aiming to highlight the importance of standardization in DIM for metaverse-based educational applications. The following subsections categorize the referenced literature based on three axes: (i) the state of research on the conjunction of metaverse and education, (ii) the state of research on DIM in Metaverse environments, and (iii) the combination of all of these research areas which forms the topic of decentralized identity management in metaverse environments for educational applications.

3.1. Metaverse and Education

Currently, there are several important research works published on the topic of the metaverse in education which underline the interest in this field and the enormous outcomes of this combination. In this subsection, we survey several published research works, aiming to present a brief description of their main objectives and outcomes, with an emphasis on their consideration and/or application of DIM methods and standards.

3.1.1. Review Articles

The research work on the metaverse and education presented in [3] examines the application of the metaverse in education, such as medical training, language learning, and virtual simulations. Considering the topic of identity management, the authors highlight the need for the adoption of blockchain-based decentralized identity management to ensure secure and traceable interactions within the metaverse.

Through a systematic literature review, the authors in [4] identify the potential benefits and applications of the IoT in creating immersive and interactive learning environments. The study highlights the role of the IoT in data mapping and the creation of digital twins, which can improve the accuracy and realism of virtual educational settings, concluding that combining the IoT and metaverse can significantly enhance the efficiency and engagement of remote learning systems, offering a more immersive and effective educational experience.

Especially in this case, both data and users need an identity management system in order to safeguard the privacy and integrity of both.

The paper in [8] focuses on the potential of the metaverse to transform education by creating immersive and interactive learning environments for education through a systematic survey of case studies. It discusses various components of the metaverse, including VR/AR, blockchain technology, and decentralized identity management, emphasizing their roles in educational applications. Key challenges were identified including technological limitations, the need for interoperability, data privacy, and security concerns, such as identity management. The paper also outlines open issues and areas for future research, such as developing technical standards, enhancing user experience, and ensuring equitable access to metaverse-based educational tools.

The authors in [9] explore the potential of the metaverse to merge physical and virtual realities through augmented and virtual reality technologies, allowing for interactions via avatars and holograms. This descriptive and organized study delves into the socio-economic impacts of the metaverse on sectors such as marketing, education, and healthcare while addressing significant societal issues like trust, privacy, data security, psychological effects, and ethical concerns. The current limitations and challenges, including scalability and interoperability are pinpointed while the opportunities for enhancing user experiences through immersive technologies are also presented. The authors conclude by proposing an interesting research agenda that calls for interdisciplinary studies and a focus on socio-technical and governance perspectives with the purpose of addressing the multifaceted challenges of the metaverse.

Similar to other papers examined in this subsection, the research work in [10], by analyzing 310 academic papers published from 2004 to 2022, identifies key contributors, cooperation patterns, and education topics in Edu-Metaverse research. Some of them include physical education, metaverse-supported simulations for health education, virtual learning environments for art education, and the use of metaverse technologies in Science, Technology, Engineering, and Mathematics (STEM) education.

The above papers approach the topic of metaverse-enhanced education from a literature review perspective, where the authors conduct thorough research, identifying key points and challenges. The papers highlight the importance of addressing challenges such as data security, balancing real and virtual identities, and shedding light on how needed the DIM is as a separate module in the metaverse for education systems. However, the authors do not explicitly address decentralized identity management or mention the use of specific standards such as DIDs or VCs in their discussion, leaving a critical point of security exposed.

3.1.2. Proof of Concept/Case Studies/Conceptual Model Articles

The authors of [11] present a smart education ecosystem based on the principles of educational ecology, proposing a new education method characterized by virtual reality symbiosis, trans-spatial fusion, and collaborative inquiry, built upon technologies like 5G, AI, VR, AR, and blockchain. Using the Analytic Hierarchy Process (AHP), the paper verifies the educational benefits and effectiveness of this ecosystem.

In [12], the authors propose a multi-agent collaborative development strategy involving government, enterprises, and individuals to promote the sustainable and balanced growth of the Edu-Metaverse. They discuss various application scenarios of the Edu-Metaverse, including school, family, and social education, emphasizing the creation of flexible teaching spaces and innovative learning experiences.

Yet another conceptual model is presented in [13] for a metaverse educational platform integrating immersive features, blockchain technology, and a safe learning environment to enhance educational outcomes. The study uses data collected from 100 educators worldwide and employs methods such as Partial Least-Squares Structural Equation Modeling (PLS-SEM), Random Forest, and thematic content analysis to analyze the impact of these

features on education. The authors address decentralized identity management using NFTs to facilitate the secure and transparent management of student identities and achievements.

In [14], the authors examine the potential applications of metaverse technologies in the field of physical education. The study distinguishes metaverse technologies into four categories and explores how these can be integrated into physical education curricula, bringing learning experiences to the next level. The paper discusses the current use of these technologies such as blockchain and XR, their benefits, and the challenges they present, concluding that the metaverse will profoundly change physical education in the future, if and when more specialized technology are developed and incorporated into physical activities as well.

The authors of [15] proposes an innovative educational system that integrates virtual reality and Web 3.0 blockchain technologies to create an immersive and interactive environment for a seamless and comprehensive learning experience. The MetaEdu framework aims to combine physical and virtual learning spaces, leveraging AI and blockchain to provide a secure, transparent, and adaptive educational experience. The system is designed to store learning trajectories and knowledge trees on the blockchain, ensuring data security and transparency. However, once again, there is no mention of identity management, in order to keep users' data private, while at the same time, the authors do not provide any kind of certification system for their users. As the paper concludes, security remains a great challenge to address.

In [16], the authors propose the concept of "metaversity"—a virtual reality campus that offers immersive and interactive learning experiences. By examining the impact of NFTs, Decentralized Autonomous Organizations (DAOs), Web 3.0, and the metaverse on educational frameworks, the paper discusses how these technologies can enhance the validity and credibility of educational assets, facilitate lifelong learning, and create educational communities, braking special barriers. On the matter of security and decentralized identity management, the "metaversity" integrates blockchain technology to secure and validate educational records and credentials, while the use of NFTs can create tamper-proof educational certificates.

The authors of [17] focus on innovation and entrepreneurship education (IEE) by exploring the perspective and opinions of teachers towards the use of metaverse technologies in higher education. The study, which was conducted at two universities, one in China and one in Spain, with the use of surveys and interviews with 40 faculty members, concluded that teachers had a generally positive attitude towards the adoption of metaverse technologies in education. The potential for high engagement and learning outcomes are the characteristics they look for in modern and technology-enhanced educational environments.

The authors of [18] provide a comprehensive overview of the metaverse's integration with the IoT, blockchain, and AI to revolutionize education. This study outlines a future roadmap, detailing how these technologies can create immersive, interactive, and secure educational environments, placing emphasis on the metaverse's potential to enhance learning experiences through extended reality.

The papers presented in this subcategory [9–16] try to examine the benefits of the metaverse in education from a theoretical perspective only. They all emphasize the need for seamless integration of the metaverse and smart education technologies to foster a dynamic, balanced, and sustainable learning environment. However, they do not address matters such as scalability and interoperability as the authors do not discuss the use of standards such as DIDs or VCs, which are of utmost importance in the case of real-world and real-time connections with the metaverse.

These studies duly note the challenges related to privacy, as well as the need for decentralized technologies to ensure security and data protection but do not delve into specific strategies or methods that could be used to address them. **The common conclusion of all authors** includes the highlighting of the need for interdisciplinary research and the development of technical standards to ensure scalability, security, and interoperability

while leveraging blockchain for secure and decentralized management of educational data and identities.

3.1.3. Solution-Proposing Articles

Another research work, [5], presents the experiment of the first on-chain and in-metaverse academic course offered as a Massive Open Online Course (MOOC), attracting 22,500 students, while NFTs were used for student registration and access to course materials, providing transparency and security. However, no high-level standards such as the SSI model or DIDs and VCs were mentioned, highlighting the lack of educational interoperability, mobility, and asset ownership. The findings reveal that the metaverse can revolutionize traditional educational paradigms, emphasizing the need for further research on the scalability, interactivity, and implementation of decentralized technologies in educational settings.

The authors of [6] present the implementation of a blockchain-driven prototype for a meta-university campus. The authors propose a three-layer architecture consisting of infrastructure, interaction, and ecosystem layers. This prototype manages to enhance student life through an interactive and immersive virtual environment, demonstrating that metaverse technologies can promote social good by improving accessibility, diversity, equality, and cultural preservation within a university setting. Although the work carried out here is extremely important in showcasing the possibilities that the metaverse can open up for education, the authors describe a token-driven monetary system for people in order to access the platform. Identity is never referred to as a term, indicating that tokens are stored in a plain decentralized wallet, exposing the users to immediate threats and system failures.

In [19], the authors aim to address the challenges of protecting and managing educational assets in the metaverse by developing a centralized model using blockchain technology to store educational assets as NFTs, ensuring their security and integrity. While tools like Scyther are used for security evaluation, demonstrating effectiveness, this work does not refer to decentralized identity management methods and standards. The authors focus on using blockchain, specifically through NFT standards like ERC-20, ERC-721, and ERC-1155, to manage and secure educational assets in the metaverse.

Research work [20] presents the CO-MATE framework for high-level education, which explores the use of emerging technologies to create a virtualized and globalized learning environment. The potential of this framework is to revolutionize the future of education through immersive, interconnected, and automated systems, with the CO-MATE framework integrating identity management through the use of VCs, although their only application considers the safety of avatars and not the users' holistic identity.

The authors of [21] examine the effectiveness of using the metaverse to support cybersecurity education and training through an immersive Capture the Flag (CTF) contest, using the metaverse environment. Conducted over two academic semesters, the study found that the metaverse environment significantly provided a deeper understanding of cybersecurity concepts and practical skills, while enhancing participants' critical thinking, creativity, problem-solving, and teamwork skills. However, once again, there seems to be a severe lack of reference to the identity management of users, creating issues for trainees regarding proving their experience and performance on a topic such as cybersecurity skills.

Quite similarly to [6], in [22], the authors propose a comprehensive metaverse architecture in order to make e-learning systems more effective and engaging for students by using cutting-edge technologies. Utilizing digital twins, blockchain, and extended reality, they manage to create a metaverse experience where many e-learning applications are able to operate over the same metaverse platform, removing barriers for students. However, once again, the authors do not address security challenges, including identity management, leaving their potential users exposed to a number of threats and failures.

The authors of [23] propose a blockchain-based architecture in an effort to enhance security, transparency, and trust in digital metaverse-based educational environments. This

framework aims to address key challenges such as data integrity, user authentication, and secure access control in the metaverse, while various blockchain mechanisms and their application in educational applications and use cases are discussed. More specifically, the authors address and highlight the challenge of decentralized identity management through the use of blockchain technology, stating that consortium blockchains are the best fit for managing access permissions in assets and data.

The work carried out by the authors of [3,4,17–21] is of the highest value to the research community, as it represents the most practical efforts towards metaverse-based educational methods. Through these solutions which were implemented and tested (either in a lab environment or in the real world), it is evident that identity management for users of the metaverse, and especially for educational content, is of utmost importance. From avatar control and ownership to proving certifications, decentralized identities are the cornerstone of metaverse education security and skills ownership. All of the aforementioned solutions avoid tackling the specific challenge of identity management or they do so only for specific purposes (e.g., article [18] which only uses avatars), creating a gap in one of the most important security topics. A holistic and practical approach is needed in order for these solutions to upgrade their implementation level.

3.2. Decentralized Identity Management (DIM) (1–2 Pages)

In the metaverse era, a major challenge highlighted by most of the previous research is secure and decentralized identity management. Blockchain technology is considered as the most promising one to provide a highly secure DIM toolset that consists of methods and protocols such as DIDs, VCs, and SSI. This subsection explores several notable research studies that underscore the growing enthusiasm for DIM, which at the same time seems to be considered by most of the authors to belong in a metaverse environment. A concise overview of these works is provided, highlighting their primary goals and findings, with a focus on how they consider and/or implement decentralized identity management methods and standards.

3.2.1. Review Articles

In [24], a comprehensive overview of the metaverse as a technology is presented. Through the review of over two hundred academic and non-academic texts, they scrutinize every aspect of the metaverse, from simple use cases to real-world implementations such as *Decentraland* and others. Of course, the matter of identity management does not miss the authors' attention, as its importance cannot be ignored, especially when one looks over the landscape of this technology in a holistic way.

The paper in [25] discusses the application of digital identity in the virtual world of the metaverse. It explores the historical development of identity verification from face-to-face interactions to digital identity certificates, while the authors recognize three categories of association between users and their digital counterparts. Moreover, naming the core characteristic of "more autonomy for individuals", they find that centralization is not going to work in a decentralized environment, especially when it comes to identity management. Even more importantly, auditing digital identity is an inevitable process, although centralized supervision may be unavoidable.

The two papers above study the topic of DIM from a theoretical approach, covering the research made so far. Their findings on this matter are that most of the active implementations use NFTs and Soulbound tokens as the basis of an identity management profile; however, such a plain approach can and does introduce limitations regarding privacy protection. Nonetheless, further innovation and development on this matter are needed. Moreover, the authors highlight the need for governance approaches to address identity trust issues and privacy concerns. Overall, they provide a comprehensive overview of the complexities and implications of digital identity in the evolving metaverse environments.

3.2.2. Solution-Proposing Articles

In [26], the authors propose a robust authentication framework aimed at ensuring the traceability of avatars within the metaverse, tracking avatars to their physical counterparts. The integration of two-factor authentication, utilizing biometric-based authentication and a chameleon signature algorithm ensures the verifiability of an avatar's virtual and physical identities. The framework also introduces decentralized authentication protocols, which allow real-time authentication without relying on a central platform, thereby protecting user privacy, reducing overheads, and removing the usual single-point-of-failure (SPOF) of centralized systems. Through security analyses and simulation experiments, the authors show how effective such a system can be, by achieving consistent and traceable avatar identity management.

The paper in [27] presents a decentralized system for managing and resolving multiple identifiers within the metaverse. The proposed Multi-Identifier System (MIS) uses a consortium blockchain to provide secure, efficient, and manageable registration, resolution, and inter-translation of various identifiers, including identities, content, services, and IP addresses. The system is designed with a four-tier architecture to ensure the secure and efficient management of identifiers across interconnected sub-metaverses and effectively address decentralized identity management by utilizing blockchain technology to create a secure and transparent system for managing multiple types of identifiers. The MIS framework inherently supports identity management, with identities serving as the anchor for all other identifiers. However, while the system leverages blockchain for decentralization and security, the paper does not explicitly mention or implement specific standards such as DIDs or VCs. The focus is on the broader application of blockchain to manage identities and other identifiers cohesively rather than detailing the adoption of standardized decentralized identity management protocols.

The authors of [28] propose a novel data scheme called IDRG (Identity-based Data Rights Governance), in an effort to address the issues of privacy and data rights governance in the metaverse, based on a privacy-preserving digital identities system. The IDRG scheme leverages identity-based encryption and chameleon hash techniques to provide comprehensive data rights management, allowing users to specify who can read or edit their data while preserving privacy policies. The system also incorporates a user accountability and revocation mechanism using proxy re-encryption to ensure that only authorized users can access and modify data.

The authors of [29], recognizing that blockchain technology has not been exploited to its full potential considering the metaverse, propose a novel trustless architecture called On-Demand Trusted Computing Environment (OTCE), for increasing security and efficiency in both hardware and software resource integration and allocation. By creating a mapping system between users and relationships with the resources, they mathematically quantify the parameter of trust within a metaverse environment using graphs, allowing its users to react to it and make decisions based on the plan they want to follow to build on that trust. The OTCE proposes the use of DIDs and VCs as a critical technique applied in the metaverse in order to map each identity to an avatar and other resources. By introducing this approach, the authors contribute to the standardization of identity management within the metaverse environment.

The authors of [30] propose a novel and secure authentication scheme for using avatars in the metaverse. Their scheme makes use of some of the most advanced and state-of-the-art tools, like the DID and VC standards for creating a base for their avatar management and authentication system and the ZoKrates tool for producing ZKP Proofs for avatars. Moreover, they fully exploit SBT functionality for ensuring KYC processes, which proceed with DID creation for each user and avatar, by binding the ZKP proof of Avatar ownership to the user's wallet. This way, the authors manage to bring the blockchain and metaverse technologies closer to the end user, providing a friendlier and simpler way for them to manage their avatars without compromising security.

In [31], the authors propose a comprehensive authentication scheme, putting into use the standards of DID and VC over a blockchain-based architecture to ensure secure, private authentication within the metaverse. The authors describe how their scheme uses DIDs for creating and managing digital identities by creating an architecture with a central Service Provider and a Certificate Authority responsible for the authenticating processes. The scheme uses ZKPs to allow users to prove their identity attributes without revealing any sensitive information. This approach is designed to prevent identity theft and unauthorized access, offering a robust solution for identity verification in virtual environments. While the authors designed and executed a series of simulation and testing trials on user data integrity, demonstrating the effectiveness and efficiency of the proposed scheme in real-world scenarios, their architecture is still endangered by the single point of failure threat. The Service Provider and the Certificate Authority are always considered to be fully trusted while their continuous functionality is supposed to be uninterrupted, leaving the current and mainstream threats unaddressed.

The XMAT (Cross-Metaverses Avatar Travel) solution, which the authors describe in [32], is an abstract protocol that aims to support the transferability of avatars into multiple metaverses without compromising privacy and security. By following the SSI principles in accordance with European policies and regulations such as GDPR, they managed to create a five-phase protocol to be used when and if a user wishes to transfer his/her avatar from one metaverse to another. DIDs, VCs, and verifiable presentations are the main tools the XMAT protocol relies upon in an effort to create a basis for future interoperability and standardization regarding developing decentralized applications in metaverse environments. The authors insist on the fact that further research as well as development is needed in order to create technical regulations to guide both hardware and software development respecting the data and operational governance rules.

The above solutions proposed by the authors of [24–30] all address the great metaverse challenge of DIM in an effort to preserve privacy and increase security for both users and the systems as well. The fact that on the topic of identity management, the focus of many authors remains on ensuring traceability and security of users' avatars and not of actual users (including data beyond their avatars), creates limitations in the adoption of such a solution in use cases where a more holistic approach to user identity management is needed. Moreover, while many authors address DIM through the use of identity-based encryption and blockchain technologies, they do so in a mathematical and theoretical way. This approach validates and proves the fundamental need for cryptographic tools for privacy-preserving identity-based data governance; however, it lacks practicality and the ability to be implemented in real-world and real-time systems to be used in large-scale applications.

Interestingly, the authors of [33], recognizing and capturing the essence of the metaverse and Web 3.0 in decentralization, anonymity, and interoperability, propose an SSI-based model aiming to fully satisfy these requirements. This solution acts within the context of the metaverse as a single, open standard that supports seamless integration of the physical world with the virtual. To this end, the authors designed an SSI-based implementation towards increased decentralization and trust regarding the users' data, where using DIDs and VCs, identities full ownership, control, and possession is given to the last ones.

By following the open standard philosophy, the authors provide metaverse interoperability, which is defined as the ability to transfer personal data (e.g., identity, avatar, assets, etc.) to different metaverses or Virtual Service Providers (VSPs). Authentication and Identity Management are tackled in the presented algorithm in a decentralized and environment-agnostic way, based on the characteristics and abilities of VCs and the cryptographic proofs that are generated from them using a ZKP mechanism. We can see that while this may seem like the perfect solution for metaverse DIM, its readiness level remains in theory and design only, while the industry needs practical solutions at the level of a product in order to provide fully secured and state-of-the-art metaverse applications.

3.3. Metaverse Education and DIM

In the previous subsections, we reviewed several significant research works on the topics of the metaverse in education and Decentralized Identity Management. The number and quality of these publications highlight the strong interest in these areas and suggest new research directions. In this section, we seek to identify high-level research in this combined field and summarize its main objectives, goals, and findings, with an emphasis on their consideration and/or implementation of decentralized identity management methods and standards. Unlike the previously examined topics, this area lacks substantial high-level publications, indicating a notable research gap and presenting numerous opportunities for future studies and publications.

The research work in [34] presents a preliminary architecture and its characteristics for avatar authentication between multiple metaverses using blockchain technology. The authors highlight an example of two universities, each one with its own version of the metaversity system. Inevitably, the issue arising is the possibility of users being able to jump from one metaverse to another while maintaining their data. The system proposed by the authors describes the characteristics for secure and traceable authentication mechanisms for avatars and users as they navigate through different virtual environments. By leveraging blockchain, the framework provides anonymous identity mechanisms, reducing risks such as impersonation, server spoofing, and replay attacks. The solution is tailored to enhance security in various applications within the metaverse, particularly focusing on educational domains where immersive and interactive learning experiences are becoming increasingly significant.

While the authors highlight that in order for interoperability to be achieved, a higher-level blockchain-enabled identity management system is needed, they do not specifically mention or implement widely recognized standards such as DIDs or VCs. The SSI model is also not referenced in their framework, and no adequate information from an actual implementation for this solution is given.

4. Comparative Analysis and Results

Following the literature review, this section provides a comparative analysis to identify the existing gaps in the research on decentralized identity management for educational metaverse-enhanced applications. We will examine the currently available contributions of the referenced literature in this paper based on four different parameters in order to gain insights into the current research landscape and pinpoint areas that need to be further addressed.

The four parameters used for comparison are the type of contributions (e.g., architecture, solution, etc.), how well they cover the aforementioned research topics, their use of DIM-related standards, and their efforts towards interoperability. By comparing these aspects, we aim to highlight the critical challenges and opportunities in creating effective, scalable, and interoperable decentralized identity management within the metaverse. This will help guide future research and practical applications in the educational metaverse. It should be noted that a comprehensive and analytical table with all the literature referenced and the parameter analysis can be found in Appendix A of this paper.

4.1. Parameter: Focus Areas—Identifying the Research Gap

To provide a balanced and comprehensive review, we evaluated the extent to which every contribution addresses its key topics (education, decentralized identity management, and the metaverse). The examination of this parameter reveals ***the level to which integrated solutions are brought forward*** while at the same time, any gaps that may exist across interdisciplinary methods are identified. To make sure that no important detail is missed, a fair assessment of each focus area is conducted while aiming to develop complete solutions that meet the specific needs of educational applications in the metaverse; this thorough coverage is essential.

Table 2 and Figure 4 summarize the ***coverage of the referenced literature*** in three categories, which are derived from our methodology's main keywords used for discovering the academic papers. The first category, which captures most researchers' attention, is the combination of the "Metaverse" and "Education" keywords, where the related results highlight the different forms. The technologies involved in the metaverse (XR, AI, IoT, and blockchain) can transform current digital and traditional educational methods by breaking the barriers of space and providing safe and realistic spaces for training.

Table 2. Referenced literature categorization based on the research areas they focus on.

Focus Areas	References
Metaverse and Education	[3–6,8–23]
Metaverse and Decentralized Identity Management	[24–33]
Metaverse, Education, and Decentralized Identity Mgmt.	[34]

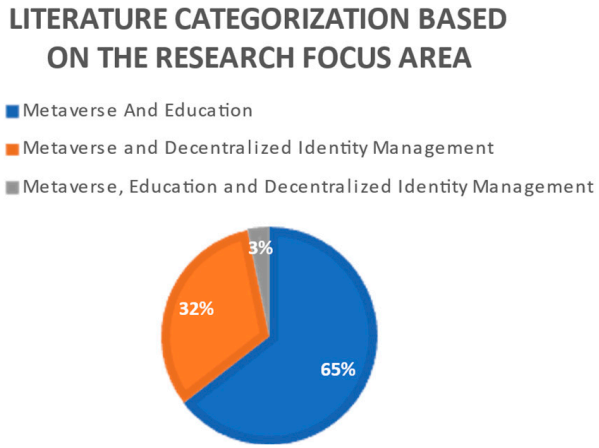


Figure 4. Focus area graph of referenced literature.

The second category of papers comes from the combination of the "Metaverse" and "Decentralized Identity Management" keywords, where the results cover about half of those of the first category. This area is much younger in age, as decentralized identity management has been a hot topic only for the last 5 to 6 years since blockchain technology has begun to evolve in ways that can support heavy cryptography and provide the security and privacy digital identities need.

The third category is the one with the fewest research results and it is the combination of the previous two categories using all three keywords of "Metaverse", "Education", and "Decentralized Identity Management". The conjunction of these three research topics lies in the benefits secure and robust digital identity management offers to educational applications operating with the help of or within one or multiple metaverse environments. We can see that this category severely lacks the research necessary for the industry to be able to provide secure digital cutting-edge tools to teachers/tutors/trainers, making education more efficient.

4.2. Parameter: Type of Contribution—Holistic Understanding of Contributions

We can easily understand ***the state of current research*** by classifying the type of contribution (e.g., solution, proof of concept, or literature review) of each academic paper. This makes it easier to identify where the majority of the work is being performed and points out areas that may require further examination or development. By pointing up cutting-edge solutions and encouraging collaboration, this analysis fosters innovation on the topic of standardized solutions supporting an open metaverse-based educational ecosystem. New research ideas and collaborations can be created through an understanding of the contributions along with the focus areas, providing guidelines for future work.

Table 3 and Figure 5 classify the referenced literature into five categories, depending on the type of contribution the authors have provided. The category with the most contributions is the "Solution" presentation, which is a result of a double-sided interpretation. On the one hand, the fact that both academia and industry are putting effort into finding innovative solutions on the topics of "Metaverse—Education" and "Metaverse—Identity Management" is crucial and most beneficial. However, on the other hand, many of these solutions are not applicable on a wider scale, as they are use-case specific, making it difficult for others to fully adopt the solution described. Modifications of each solution are needed in the best of cases for integration with interdisciplinary use cases.

Table 3. Referenced literature categorization based on their type of contribution.

Type of Contribution	References
Solution	[5,6,19–23,26–32,34]
Proof of Concept	[5,21,32]
Literature Review	[3,4,8–10,24,25]
Case Study	[11,17,22]
Conceptual Model	[12–16,18,33]

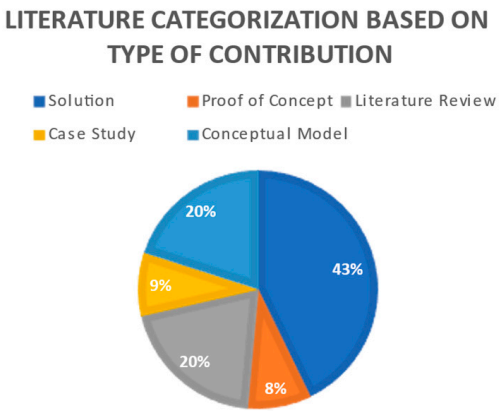


Figure 5. Type of contribution graph of referenced literature.

Moreover, the categories of "Literature Review" and "Conceptual Model" are the second in line for the research results, showing the need not only for further development on all of these topics but also the need for a more abstract solution that can be easily adopted by multiple vendors and applications. Lastly, the least attractive categories are the ones of "Proof of Concept" and "Case Study", which in combination with the outburst of solutions might indicate the fact that decentralized identity management for education in the metaverse is not yet ready for wide experimentation and adoption.

4.3. Parameters: Standardization and Interoperability—Practical Applicability

Examining whether papers apply standards (e.g., DIDs, VCs, SSI, and eIDAS) allows us to assess the ***level of maturity and usefulness*** of the suggested solutions and other contributions. These two parameters of "Standardization" and "Interoperability" stress the readiness of solutions for real-world applications and how well they could be implemented and integrated. In addition, examining the efforts to establish compatibility with alternative solutions shows the ***suggested systems' capacity for interaction and scalability***. The significance of smooth integration into the larger ecosystem is emphasized, as this is necessary for decentralized identity management to be widely used in educational metaverse applications. The analysis highlights the practical aspects, such as standards and interoperability, which demonstrate how research findings can be applied in real-world scenarios. This

guarantees the conversion of theoretical contributions into workable, practical solutions that can scale horizontally through the metaverse over multiple applications.

Table 4 and Figure 6 summarize the referenced literature into four categories: addressing either SSI standardization or interoperability between different applications, addressing both of these matters or none. The distribution of papers indicates that although academia has rushed to provide solutions and significant contributions, these are not focused or coordinated towards wider practical applicability, whereas the topics of identity management in the metaverse and the metaverse for education do not seem to be in alignment with each other just yet considering the lack of targeted efforts for practical implementations, not only academically but from industry as well.

Table 4. Referenced literature categorization based on standardization and interoperability.

Standardization and Interoperability	References
DIM Standardization	[25,30,31,33]
Application-Level Interoperability	[9,20,30,32,33]
Both of the above	[30,33]
Not addressed	[3–6,8,10–19,21–24,26–29,34]

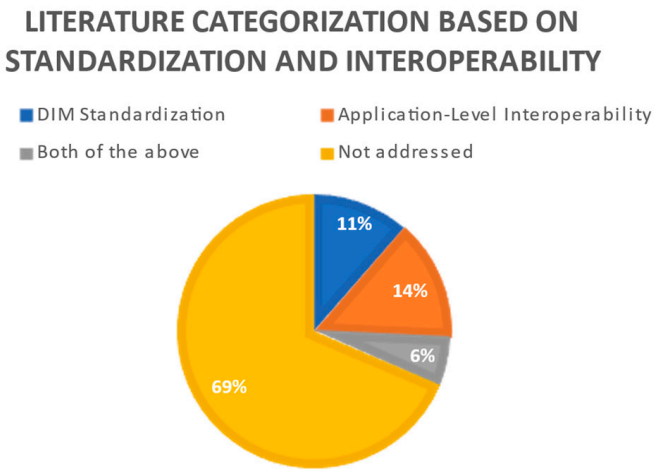


Figure 6. DIM standardization and interoperability graph of referenced literature.

5. Discussion—Future Research and Development

A development framework, if designed with consideration for its possible future use cases and implementations, can be built in such a way as to expose different interfaces, aiming to provide a basis for developer flexibility and scalability. Considering our research question, the secure and decentralized identity management for metaverse-based educational applications, one such extension can be the ability to support educational and training applications. For example, creating methods and ways for students to access their academic services and digitally own their assets (e.g., school rewards, degrees, training certifications, etc.). Following this modular design technique, another extension based on both decentralized identity and educational support can be a recruitment extension, thus allowing users to demonstrate and prove their hard skills to exclusive and targeted recruiters, without exposing their personal information and by being the digital owners and controllers of their data.

Subsequently, with such an approach, an ***open and modular development framework for decentralized identity management*** can evolve to be decentralized, even at its implementation level. Allowing developers, as well as system and application designers, to follow specific and standardized rules for their products, can lead to a horizontal and endless metaverse and Web 3.0 interoperability and scalability. The ***integration of legal***

policies and regulations such as the eIDAS or other legislations can provide seamless and guided legal compliance of applications and products. Lastly, by respecting and satisfying the core values of Web 3.0 (decentralization, self-sovereignty, and anonymity), public trust in new and emerging technologies can be exponentially increased, paving the way to a new era of safe and responsible use of technology by the people.

Some of the proposed methods and techniques (from the papers above), if combined, implemented, and standardized, can contribute to establishing an open framework for decentralized identity management within the metaverse with extensibility towards not only education but other sectors as well. By ***moving the control and ownership of users' data to their devices***, the high security and verifiability of users' digital identity and credentials are ensured, while their ***interoperability across different applications*** and metaverse environments becomes easier to implement for developers and educational application vendors. We aim to pursue the design and the creation of such a framework during our future work.

Our research highlights the potential of a modular and extensible development framework for decentralized identity management (DIM) in metaverse-based educational applications. By considering future use cases and implementing flexible interfaces, this framework can significantly enhance both developer adaptability and scalability. Moving data control and ownership to users' devices enhances the security and verifiability of digital identities and credentials. This shift not only ensures high levels of data protection but also simplifies interoperability across various applications and metaverse environments. By adhering to standardized rules and integrating legal frameworks such as the eIDAS regulations, the framework can ensure seamless legal compliance and support the growth of decentralized applications. This can contribute to widespread adoption and trust in new technologies, fostering a more secure and interconnected digital ecosystem.

6. Conclusions

In summary, our research provides a foundational perspective on decentralized identity management within the context of metaverse-enhanced education. Following the described literature review, there is now no doubt that while the metaverse can provide groundbreaking and highly adaptive educational methods, the matter of security remains in most cases unaddressed. At the same time, however, there are a number of uncoordinated efforts regarding decentralized identity management, including authorization, which provide different scopes and solutions. We believe that an intelligent and effective combination of some of the best approaches and qualities which have already been recognized by the research community can result in an open standardized solution. This can lead to the prospect of evolving into a development framework, able to be implemented in a wide variety of metaverse and Web 3.0 applications.

By integrating flexible design principles and adhering to legal standards, this framework has the potential to transform how educational and professional credentials and assets are managed in the digital age. Future research will aim to refine these concepts, develop practical implementations, and explore additional applications across different sectors. This work lays the foundation for a more secure, decentralized, and interoperable digital future.

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Appendix A. Full Summarized Table of Literature Reviewed

Title	Contribution	Focus Research Areas	Standard	Interoperability
Definition, roles, and potential research issues of the metaverse in education: An artificial intelligence perspective [3]	Literature Review	Metaverse, Education	Not Addressed	Not Addressed
Systematic Literature Review on The Usage of IoT in The Metaverse to Support the Education System [4]	Literature Review	Metaverse, Education	Not Addressed	Not Addressed
An Educational Metaverse Experiment: The First On-Chain and In-Metaverse Academic Course [5]	Solution, Proof of Concept	Metaverse, Education	ERC-721	Not Addressed
Metaverse for Social Good: A University Campus Prototype [6]	Solution	Metaverse, Education	Not Addressed	Not Addressed
A Blockchain-Based Educational Assets Management and Access Control Model for the Metaverse [19]	Solution	Metaverse, Education	ERC-20, ERC-721, ERC-1155	Not Addressed
A Collaborative Metaverse based A-La-Carte Framework for Tertiary Education (CO-MATE) [20]	Solution	Metaverse, Education	SCORM, xAPI, SIF, IEEE 1484, ISO/IEC standards, IMS Global Consortium standards	Yes
Advancing CyberSecurity Education and Training: Practical Case Study of Running Capture the Flag (CTF) on the Metaverse vs. Physical Settings [21]	Solution, Proof of Concept	Metaverse, Education	Not Addressed	Not Addressed
Advancing Education through Metaverse: Components, Applications, Challenges, Case Studies and Open Issues [8]	Literature Review	Metaverse, Education	Not Addressed	Not Addressed
Building a smart education ecosystem from a metaverse perspective [11]	Solution	Metaverse, Education	Not Addressed	Not Addressed
Edu-metaverse: Internet education form with fusion of virtual and reality [12]	Conceptual Model	Metaverse, Education	Not Addressed	Not Addressed
Elevating students' lives through immersive learning experiences in a safe metaverse [13]	Conceptual Model	Metaverse, Education	Not Addressed	Not Addressed
Exploration of educational possibilities by four metaverse types in physical education [14]	Literature Review	Metaverse, Education	Not Addressed	Not Addressed
MetaEdu: a new framework for future education [15]	Conceptual Model	Metaverse, Education	Not Addressed	Not Addressed
Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy [9]	Literature Review	Metaverse, Education	Not Addressed	Yes
Metaverse framework: A case study on E-learning environment (ELEM) [22]	Case Study, Solution	Metaverse, Education	Not Addressed	Not Addressed
Metaverse in Education: Contributors, Cooperations, and Research Themes [10]	Literature Review	Metaverse, Education	Not Addressed	Not Addressed

Title	Contribution	Focus Research Areas	Standard	Interoperability
Non-fungible tokens, decentralized autonomous organizations, Web 3.0, and the metaverse in education: From university to metaversity [16]	Literature Review	Metaverse, Education	Non-Fungible Tokens	Not Addressed
Perceptions and use of metaverse in higher education: A descriptive study in China and Spain [17]	Case Study	Metaverse, Education	Not Addressed	Not Addressed
Technological Roadmap of the Future Trend of Metaverse based on IoT, Blockchain, and AI Techniques in Metaverse Education [18]	Literature Review	Metaverse, Education	Not Addressed	Not Addressed
Toward a Secure Educational Metaverse: A Tale of Blockchain Design for Educational Environments [23]	Literature Review Conceptual Model	Metaverse, Education	Not Addressed	Not Addressed
Web3 Metaverse: State-of-the-Art and Vision [24]	Literature Review	Metaverse, Decentralized Identity Management	Not Addressed	Not Addressed
A secure authentication framework to guarantee the traceability of avatars in metaverse [26]	Solution	Metaverse, Decentralized Identity Management	Blockchain, Chameleon signature algorithm, Two-factor authentication	Not Addressed
MIS: A Multi-Identifier Management and Resolution System in the Metaverse [27]	Solution	Metaverse, Decentralized Identity Management	Not Addressed	Not Addressed
Privacy-preserving Identity-based Data Rights Governance for Blockchain-empowered Human-centric Metaverse Communications [28]	Solution	Metaverse, Decentralized Identity Management	Not Addressed	Not Addressed
A review of the application of digital identity in the Metaverse [25]	Literature Review	Metaverse, Decentralized Identity Management	DIDs, VCs	Not Addressed
A trustless architecture of blockchain-enabled metaverse [29]	Solution	Metaverse, Decentralized Identity Management	Not Addressed	Not Addressed
Digital Authentication System in Avatar Using DID and SBT [30]	Solution, Proof of Concept	Metaverse, Decentralized Identity Management	Decentralized Identifiers (DIDs), Soul Bound Tokens (SBTs)	Yes
Secure and Privacy-Preserving Authentication Scheme Using Decentralized Identifier in Metaverse Environment [31]	Solution	Metaverse, Decentralized Identity Management	DID standard	Not Addressed

Title	Contribution	Focus Research Areas	Standard	Interoperability
The Interplay Between Policy and Technology in Metaverses: Towards Seamless Avatar Interoperability Using Self-Sovereign Identity [32]	Solution	Metaverse, Decentralized Identity Management	SSI, DID, VC	Yes
Self-Sovereign Identity for Trust and Interoperability in the Metaverse [33]	Conceptual Model	Metaverse, Decentralized Identity Mgmt	Decentralized Identifiers (DIDs), Verifiable Credentials (VCs)	Yes
Blockchain Enabled Architecture for Secure Authentication in the Metaverse Environment [34]	Solution	Metaverse, Decentralized Identity Management	Not Addressed	Not Addressed

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