PUXplore: Multidisciplinary Journal of Engineering, Vol 2 , Issue 2, Apr – Jun 2026 || Online (ISSN 3108-2106)

INTEGRATING BLOCKCHAIN FOR METAVERSE OF MANUFACTURING SYSTEM: BIBLIOMETRIC ANALYSIS, AND FRAMEWORK

Utkarsh Kumar[1], Pravin Vadhel[2], Pragyan Nanda[3], Amit Sata[4,] Minal Shukla[5], Chirag R. Trivedi[6]

[1,3]Department of Information Technology, PIET, Parul University, Vadodara, Gujarat, India
[2,5,6]Department of Applied Science and Humanities, PIET, Parul University, Vadodara, Gujarat, India
[4]Department of Mechanical Engineering, Marwadi University, Rajkot, Gujarat, India
E-mail: [1]uk4061999@gmail.com, [2]pravin.vadhel43055@paruluniversity.ac.in, [3]n.pragyan@gmail.com, [4]amit.sata@marwadieducation.edu.in, [5]shuklaminal19@gmail.com, [6]chiragtrivedi867@gmail.com
ORCID: [1]https://orcid.org/0009-0000-2629-7082, [2]https://orcid.org/0000-0002-0345-2649, [3]https://orcid.org/0000-0001-6193-9204, [4]https://orcid.org/0000-0002-0945-3095, [5]https://orcid.org/0000-0002-2880-3046, [6]https://orcid.org/0000-0001-9611-2573

Keywords: METAVERSE, BLOCKCHAIN, BIBLIOMETRIC ANALYSIS, DIGITAL TWINS, INDUSTRIAL METAVERSE.

Abstract

The combination of blockchain and Metaverse is progressing toward future beyond its current paradigm, promising to be a game-changing technology in area of Next-Generation Manufacturing Industry 4.0 and Smart Factory concepts. world of Industry 4.0, or Industrial part of Metaverse, defined by concept of virtual, immersive and collaborative environments in which digital twins, IoT devices other Cyber-Physical-System objects communicate at the speed of light; however, trust and security remain major barriers to mainstream adoption. Current research examines integration of blockchain its junction with concept and implementation of Metaverse through lens of bibliometrics and literature survey. Based on Scopus and Web of Science data, the bibliometric trend evaluation revealed a significant growth in blockchain-based Metaverse application research, albeit with few manufacturing applications. The review highlighted important uses of decentralized identification, secure data exchange, digital twin synchronization, and smart contract-based automation. Despite the advances achieved in development of Metaverse technology, a few major difficulties remain in the sector. As deficiencies indicated above exist, study provides a framework combines potential of blockchain, digital twins and decentralized governance concepts in industrial Metaverse setting, as demonstrated by results. Article bridges gap between theoretical discoveries real-world implementation of blockchain-based industrial Metaverse platforms.

1 Introduction

The Metaverse is a social and permanent digital world that unites physical and virtual space. It's a vision for the future Internet, which will bring many virtual worlds together in a single ecosystem that allows for interaction, trade, and work through a digital avatar." The need for achieving such a concept has been identified in the context of the following essential aspects: interoperability, persistence, scalability, real-time interaction, digital ownership, and security [1]. It is a full-fledged socio-technical system with good governance and data protection; it is not just a visualization system. The development of the Metaverse has a strong relationship with the future of the Internet. The current Internet architecture cannot fulfill the demands of the future Internet which will require low latency, distributed computing environments as well as smart networking and decentralized data management; all of which fit well with the notion of a blockchain system for improved trust within the Metaverse eco-system [2]. The concept of the rise of digital financial systems is significant in the emerging Metaverse. Blockchain has been used to represent values in the form of tokens, in addition to automating transactions and minimizing the use of intermediaries. However, the Metaverse growth is also suffering from the instabilities and complexities due to the price value of the tokens, hence the need to accurately tokenize for trust [3]. The Metaverse is allowing for the emergence of new form of digital business model as well as new method of creating value with blockchain based applications allowing for decentralized marketing, NFTs and smart contracts which enable user economy formation. The emergence of blockchain enterprises has been beneficial for users who can enjoy shared enterprise ownership, although challenges in scalability, technology and regulations persist. [4]. Technologically the Metaverse is the outcome of the convergence of technical advances such as virtual reality, augmented reality, artificial intelligence and blockchain. A complete analysis of the Metaverse reveals that immersive technology play a significant role in various sectors such education, healthcare, entertainment and industries. Blockchain technologies help build trust, facilitating reliable data integration while limiting central control However as mentioned in [5]. However several factors inhibit the adoption of the Metaverse on a wider scale. Research indicates even though immersive experiences are enabled

by VR tools like blockchain technologies and other decentralized tools can greatly help the Metaverse realize its full potential [6]. Recent discussions have connected the Metaverse and business performance The discussion on the Metaverse has increasingly been connected to CSR however, the recent move to virtual business has added another element to CSR digital responsibility in use of ethical data within business operations Research indicates immersive technology and blockchain have potential to improve both CSR and performance however it also reveals that the governance problems within the use of the Metaverse could indicate challenges in balancing ethics with the potential use of the technology [7]. Cybersecurity plays a significant role in Web 3.0 and Metaverse systems. Although the decentralized nature of Web 3.0 systems provides the user with the power to manage the data, vulnerability also exists. Cybersecurity tools like cryptography and intrusion detection software play a significant role in controlling the risks, proving that the use of a secure blockchain is a must-have for a secure Metaverse [8].

2 Bibliometric

It is observed that popularity of *Blockchain for Metaverse* has been increased in last few years however an integration of *Blockchain for Metaverse* especially for manufacturing system is yet to be fully explored especially in the Indian scenario. Detailed analysis of prior work related research and development has been conducted using two most promising databases including Scopus® and Web of Science®. Meaningful insights achieved from these databases are highlighted herewith. These databases were searched with keyword related to *Blockchain for Metaverse*, and various types of documents were studied. Methodology adopted for this study of bibliometrix analysis on *Blockchain for Metaverse* conducted using open source platform, RStudio®, and is highlighted in Table 1.

Table 1: Methodology adopted for bibliometric analysis

Bibliometric Analysis on *Blockchain for Metaverse Using RStudio®*		
Scopus	**Database searched for documents published**	Clarivate Web of Science™
2015-2025	**Duration**	2015-2025
Articles, book chapter, review, conference paper, book, editorial	**Type**	Articles, review articles, book chapter, early access, proceeding papers
1585	**Total number**	769
English	**Language**	*English*

It is observed little research and development work in this domain has been conducted in last few years, and seems to have very high potential for an integration of metaverse and blockchain technology. This analysis helped in deciding the direction for development of appropriate Blockchain for Metaverse technology especially in the context of manufacturing system. Detailed discussion on bibliometrix analysis is presented next followed by framework for development and proposed work based on this framework.

Overview

Table 2 represents the overview about bibliometric analysis carried out on documents published in both of databases. Distribution of overall documents published in Web of Science® and Scopus® are also shown in Figure 1 and 2. Documents were also merged in order to eliminiate repeated documents using program executed on *RStudio®*, and their distribution is also represented in Figure 3.

Table 2: Overview of bibliometric analysis

Total documents (*after removing 598 duplicated and retracted documents*)	1756
Total number of sources (i.e., journal, conference, publishers) in which documents were published	637
Annual growth rate (*in percentage*)	14.7
Average citation per document	~11.4
Total number of authors contributed	4072
International co-authorship (*in percentage*)	18.56

Distribution of overall documents published in Web of Science® is also shown in Figure1.

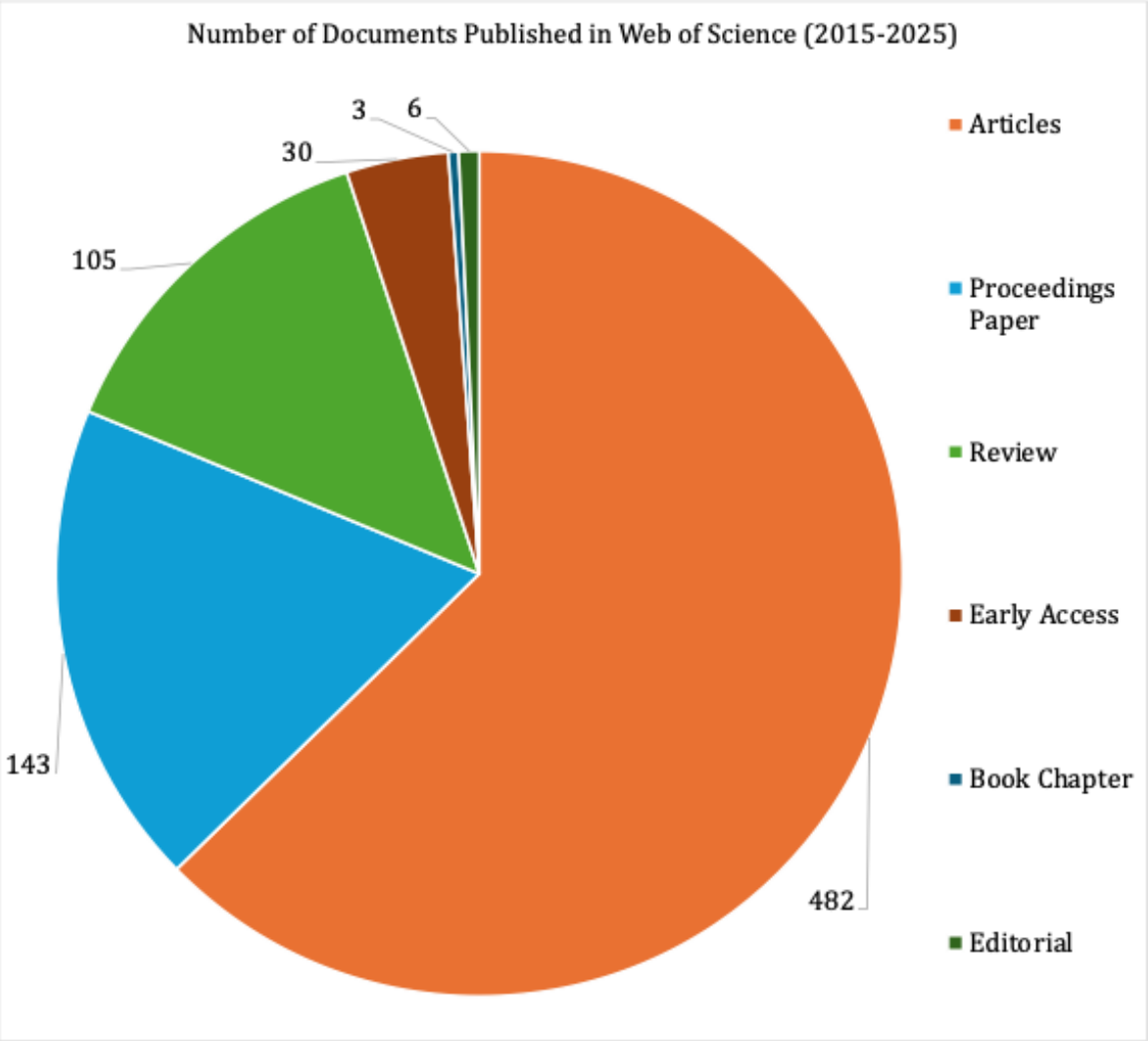

Figure 1: Type of documents published in Web of Science®

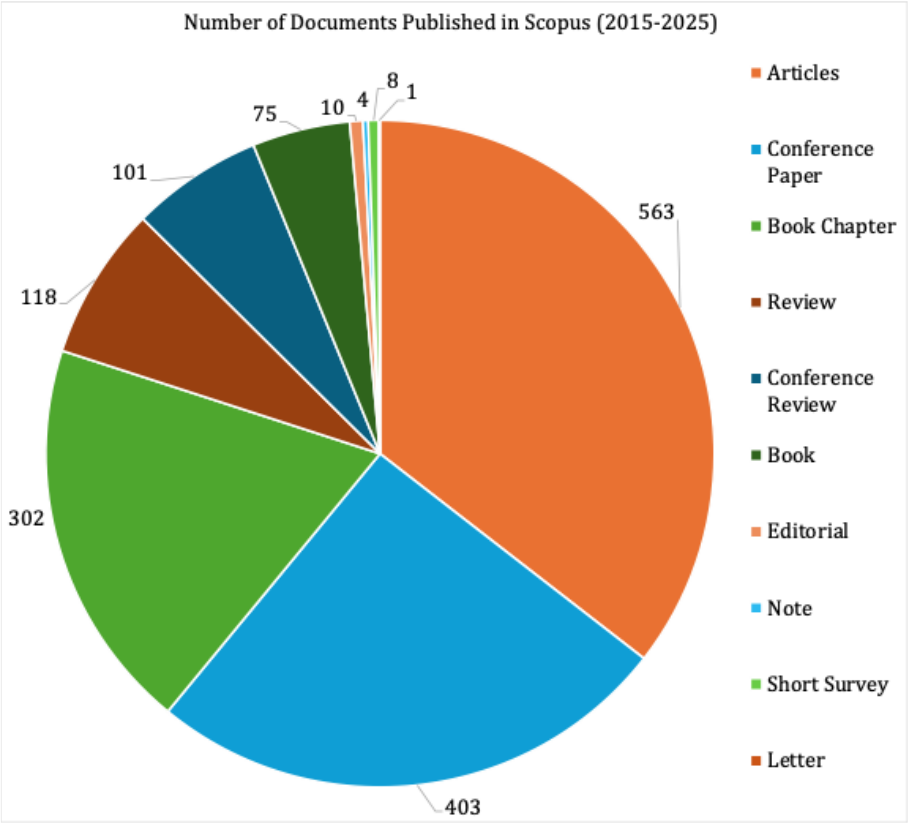

Figure 2: Type of documents published in Scopus®

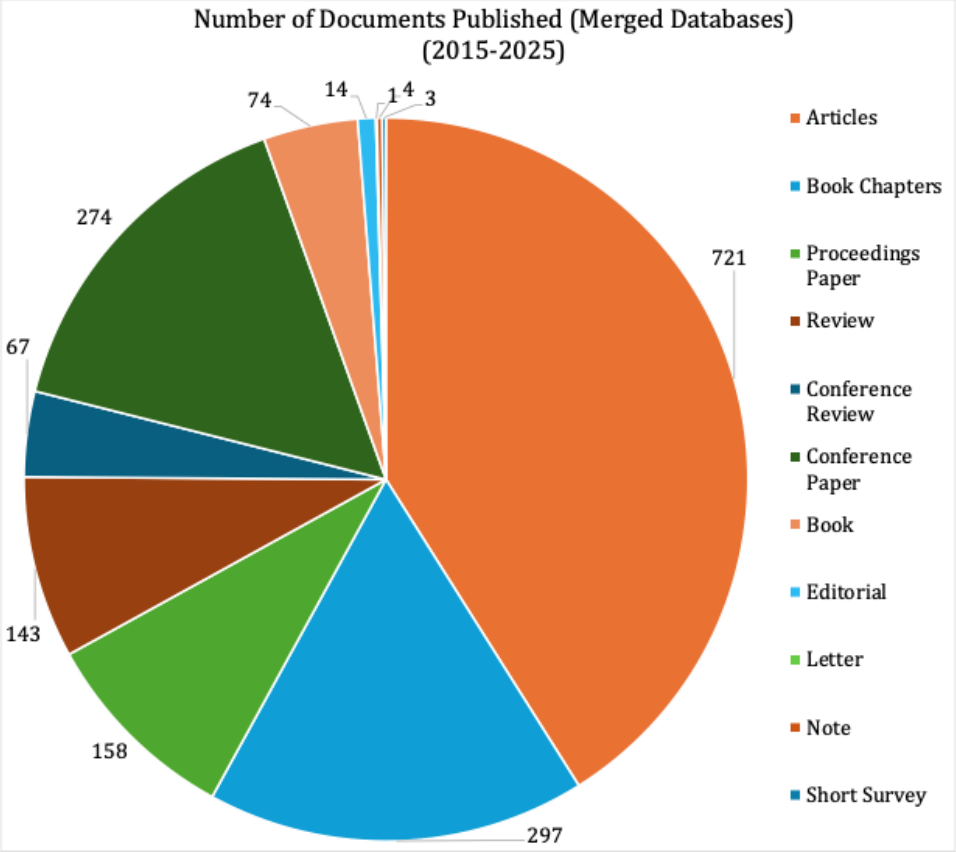

Figure 3: Distribution of documents in merged databases

Year-wise publication is also checked (Figure 4), and it was observed that number of documents published in the domain of *Blockchain for Metaverse* is increased since 2015 with average increasing rate of 14.7%, and nearly 588 documents published in the year of 2024. However, slight reduction in number of publication is happened in the year of 2025 (till December 2025).

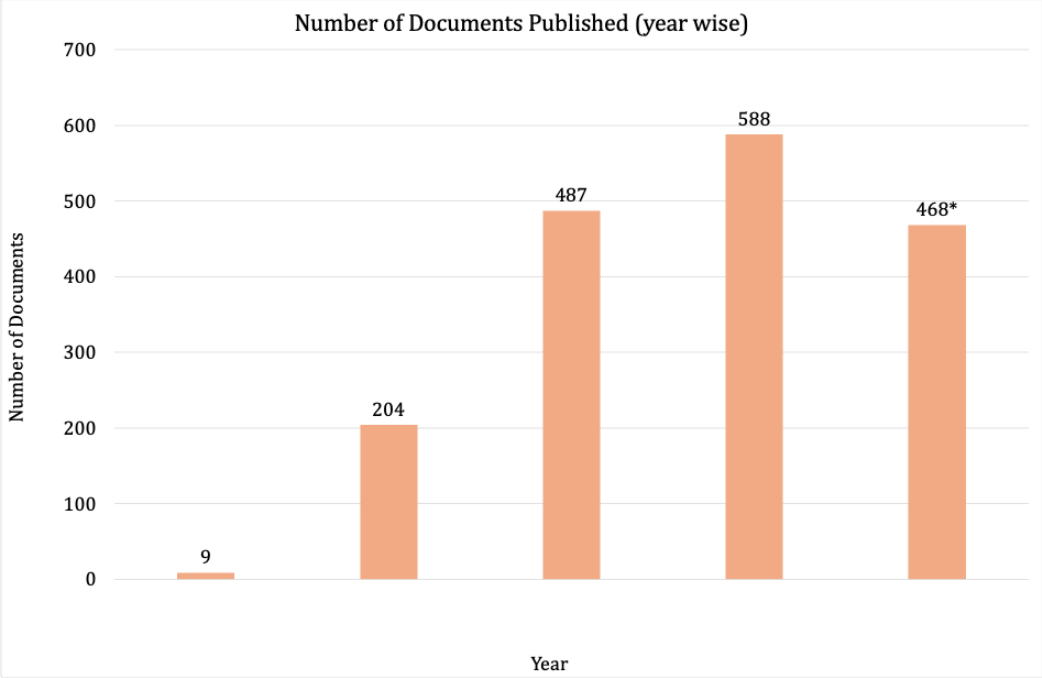

*Figure 4: Year wise publication of documents (*data is till December 2025)*

Major contributors including reseachers, their affliations, countries, sources, etc. are also found out using systematic bibliometric analysis, and is highlighted herewith.

Contributors and Collaboration

Authors conducted remarkable research in the domain of extending an appliation of *Blockchain for Metaversein Manfacturing*, and their publication, as well as h-index are represented in Figure 5. Dr. Wang Y has highest number of documents published (i.e., 30) and *h-index* (=10) in this domain. Also, most cited country and their average citations per document are shown in Figure 6. It is observed that China has maximum number of citations followed by USA, UK, Korea, India, and Australia. However, average citations per article is highest for Somalia (i.e., 108) followed by Singapore (i.e., 42.80). Average citations per article is for India is relatively low, and in the range of 6.6.

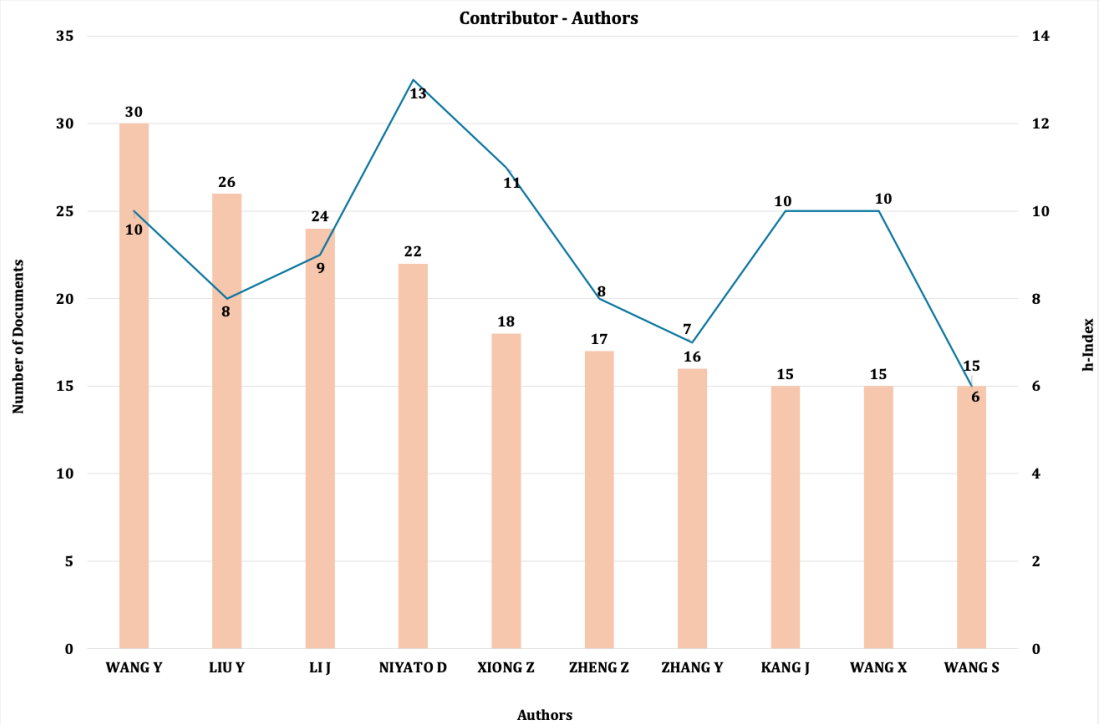

Figure 5: Top 10 Authors, and Their h index

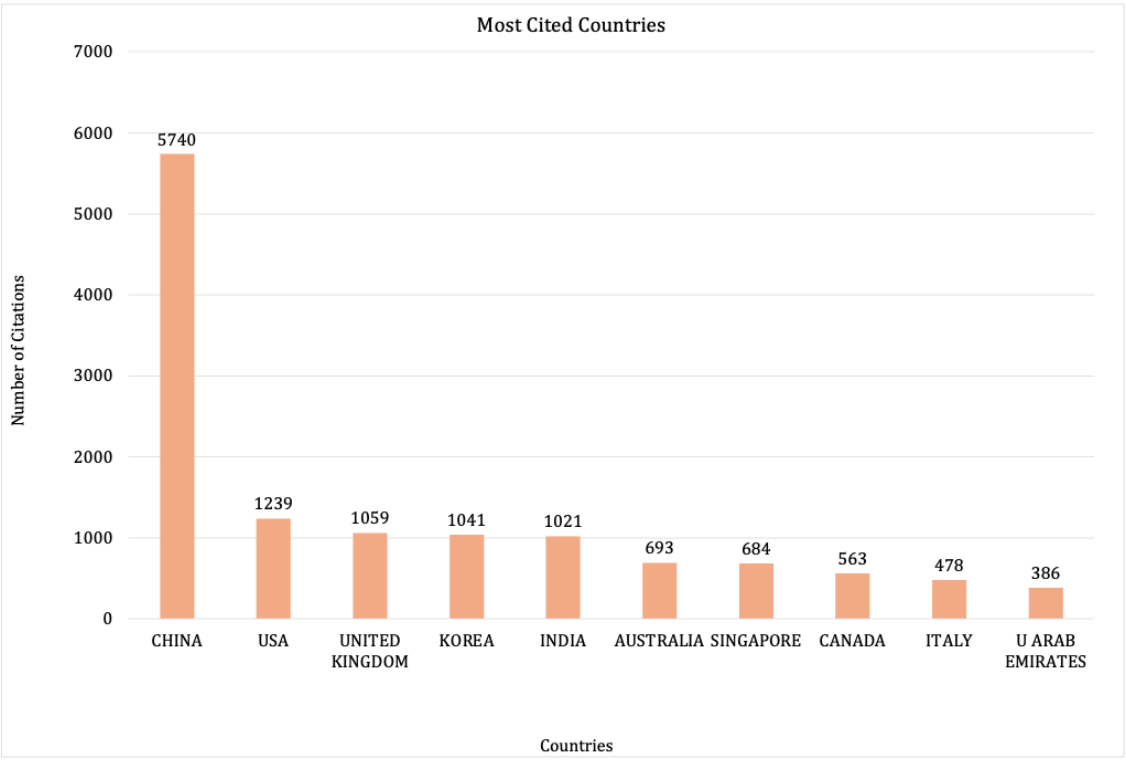

Figure 6: Most cited Countries

Specific three-field plot is generated highlighting authors, affliated institutes and countries to highlight contribution, and is illustrated in Figure 7. It is observed that Dr Niyato D from Guangzhou University – China have remarkably contributed in this domain.

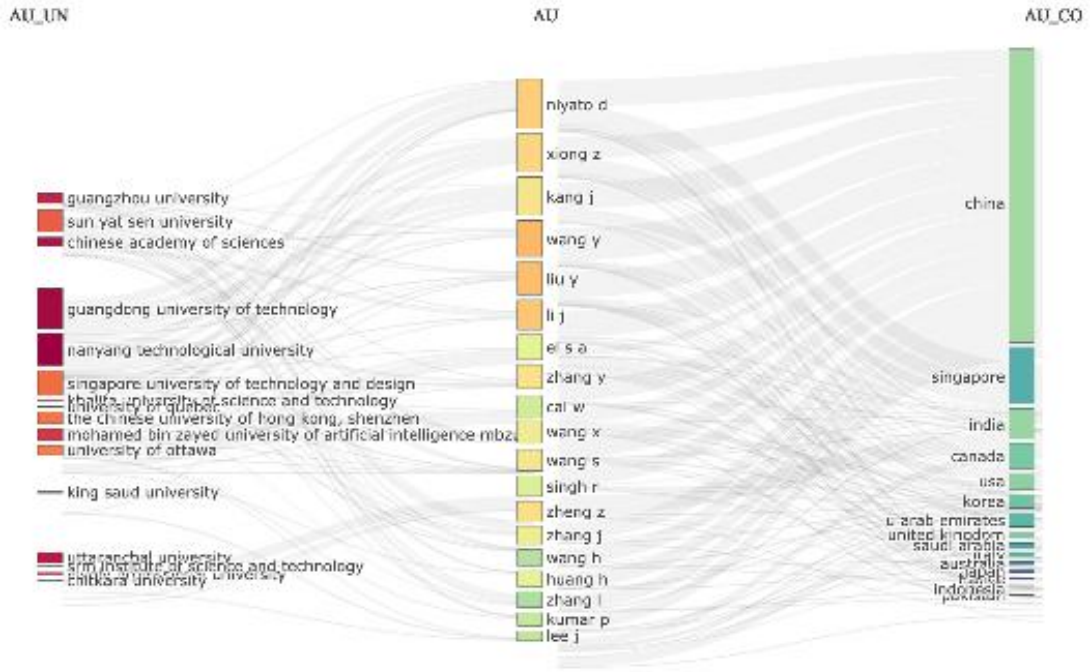

Figure 7: Three field plot highlighting institutes, authors and countries working in this domain

Collaborative research plays very important role especially in this domain. It was observed that 18.56% of documents has international co-authorship, and overview of collaboration between various countries is shown in Figure 8. China has developed strong collaboration with USA for 27 documents and with Canada for 24 documents. India has published 17 documents with UAE; 16 with UK; and 12 with USA. However, collaboration of India with USA, China, Germany, Korea, etc. can be strengthen in this domain. Various keywords used other than in these documents were also studied, and observed that keyword related to manufacturing, metal casting, etc. are not fully explored especially for an integration of Blockchain with Metaverse. It was found that *Blockchain for Metaverse in Manfacturing* especially for metal casting, and investment casting are relatively not explored. Various Blockchain for Metaversete chniques can be explored for an integreation of Metaverse enabled system specifically for metal casting. Detailed technical literature highlighting application of Blockchain for Metaverse enabled manufacturing system is summarized next.

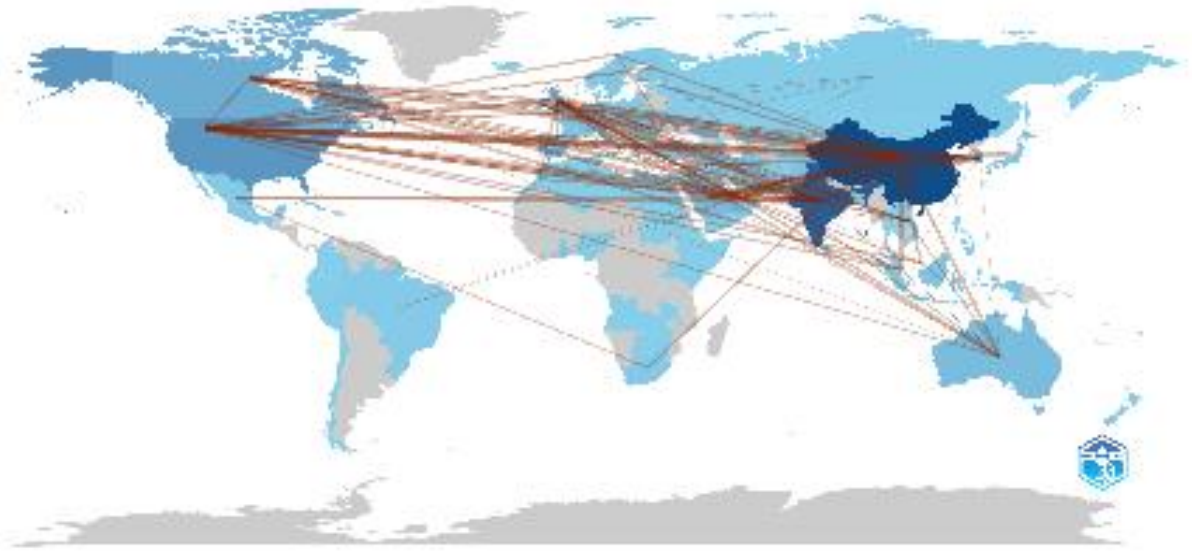

Figure 8: Collaboration between various countries for research in the domain of Image Processing for Manufacturing

Specific methodology is proposed to develop Blockchain integrated Metaverse for Manufacturing System specially for metal casting. It can further be tested in an industrial environment. This has been discussed in subsequent sections.

3 Prior Work

This paper develops blockchain based authentication method for Metaverse space which can verify user identity and ownership. It leverages smart contracts and similarity comparison to verify spaces and experiments show its reliability [9]. the Identity management allows for customization and biometric feature integration however, voluminous data generates interoperability and privacy issues [10]. This study aims to use digital twins and big data analytics to optimize smart surroundings. while the paper establishes the scalability benefits of the research based systems another challenge is ensuring privacy. The research emphasize the importance of governance and encryption to ensure a secure work environment [11]. The present study offered a detailed exploration of the security risks that exist in Metaverse, which includes identity theft, surveillance, and data leakage. The key shortcomings highlighted were a lack of security requirements. It is used as a reference base for Metaverse security research [12]. This paper offers a trustless Metaverse architecture that relies on decentralized computing. It takes use of the hypergraph model and dynamic trust. It maintains the integrity of the system and eliminates the possibility of centralized control. It demonstrates the use of the blockchain concept in trust automation [13]. This article introduces new DID authentication mechanism that relies on verified credentials. Impersonation and replay attacks are also successfully defended. In new method enhances users privacy and freedom. It is facilitates that creation of a decentralised identification infrastructure [14]. In study investigate that role of NFTs identity carriers in a metaverse. NFTs ensure the uniqueness and traceability of digital identities. It open up new avenues in decentralized identity [15]. This work suggests combining DID with Soulbound Tokens to verify avatars. It utilizes cryptographic proof for authentication to the user while preserving privacy based on regulations. This increases the trust for the avatar based interactions [16]. Study focuses on forensic science through interactive world and proof collection by means of virtual reality device and blockchain records; the study further includes a segment on cybersecurity under virtual world [17]. In this paper, blockchain protected IoT Metaverse communication is introduced and encryption combined with proximity authentication for improved privacy، integrity، and scalability for use in a smart city [18]. This article suggests the use of a blockchain with searchable encryption that provides safe content trading and the use of a smart contract to make reasonable payments and ensure system compatibility, thereby improving digital asset systems [19]. it integrates IoTfog, cloud, and blockchain to support major distributed city services for better security with traceability and connects virtual and physical systems for smart Metaverse cities [20]. in the research, it is noticed that a blockchain-based neural network is used for increasing trust in virtual and regulated supply chains through the detection of irregulate behavior using graph theory and Proof of Relation, outperforming traditional deep learning techniques [21]. The Meta Block combines blockchain and immersive healthcare technology, protect storing medical data decentralization makes records accessible, blockchain value in Metaverse healthcare [22]. In this study, the concept of XAI and Blockchain will be integrated to provide transparency in healthcare. The study will ensure accurate diagnosis through Grad-CAM and LIME models. Strong synergy has been shown to exist between AI and Blockchain [23]. However, the paper discussed block chain for artificial intelligence and IoT to safeguard privacy and data integrity. The metaverse makes remote care feasible, which is helpful in ensuring full involvement and improving individual healthcare futures [24]. Research develops quantum-safe blockchain security system incorporating AES, CRYSTALS-Kyber, Dilithium, and layered encryption along with DAO governance as proposed in reference [25]. This clinical trial looks at a Metaverse-based healthcare platform. The study includes both virtual consultations and gaming-based therapy. This study provides validation. It exhibits the Metaverse's practical applications [26]. It includes diagnosis using a combination of MobileNet V2 and blockchain, digital twin techniques, minimizing hardware usage, and facilitating real-time decision-making processes [27]. The present review is on DID and the self-sovereign identity system and emphasizes the importance of standards [28]. This paper examines the acceptance of AI-based ‘Metaverse Learning’ with TAM and behavioral theory, showing that usability and involvement lead to acceptance, while concerns over cyber risk are low, and experience is vital [29]. Also, this research shows that Metaverse platforms promote entrepreneurial activities through simulations, which improve learning, teamwork, and communication, making participation more accessible and creativity higher [30]. This review on Metaverse learning adhered to the PRISMA method and stated that the long-term impacts remain uncertain, hence a need for further investigation. [31]. The review here covers VR, AR, blockchain, and big data, showing that interactivity has improved, but problems related to accessibility, hardware inequality, and the digital divide persist [32]. MetaEdu has presented an immersive learning platform based on blockchain. This promotes fair grading and credential openness. Web3 tools enable collaboration in education. Blockchain prohibits record manipulation. It increases trust in digital learning [33]. This longitudinal study intends to assess immersive ICT education. The adoption of Blockchain and Metaverse tools led to increased student satisfaction. Students learned technical skill sets. The findings support its practical viability. This study highlights the long-term advantages of immersive learning [34]. This article investigates the use of Metaverse in India. including cybersecurity, are also discussed. In addition, public-private partnerships are encouraged. Accessibility is a source of concern, particularly [35]. This is a review of the business ecosystem in the metaverse. Blockchain technology enables NFTs and digital markets. New revenue streams are being established. Scalability and governance difficulties. Sustainable revenue models are required [36]. report establishes links between the Metaverse and the gig economy/data economy, demonstrating how blockchain facilitates the digital economy, smart contracts facilitate crypto markets, and how governance evolves over time and its significance [37]. The present

qualitative research investigates how firms experiment with innovation, where NFTs and virtual identities facilitate creativity, phygital environments enable testing, and blockchain ensures protection of ownership, all examples of factors that drive companies to embrace new models [38]. This review looks at blockchain, AI, and digital rights. Blockchain technology can improve traceability. AI can aid in moderation efforts. The regulatory process is still lacking. The governance of a DAO is suggested [39]. This study identifies decentralization and UX as significant variables. It enables for asset ownership. Governance has obstacles. There are concerns with energy. It focuses on sustainability [40]. This work is a theoretical paper that examines and/or defines Metaverse Structures, openness, and decentralization; an enabling feature is Blockchain, asset digitalization, legal governance, and its conceptual foundations [41]. This study uses both IoT sensor technologies and the Metaverse. Blockchain technology is used to secure data transfer. There is an option to allow real-time digital twins. Concerns concerning privacy and ethics are expressed [42]. This survey examines Metaverse in industries. Blockchain enhances trust. The digital twin improves monitoring. NFTs enable asset tracking. Industrial adoption is on the upswing [43]. This study proposes a blockchain-based authentication method for social cars. This approach establishes safe key agreements while maintaining anonymity. Also, verification is completed. This is appropriate for the vehicular Metaverse [44]. The study employs quantum-resistant blockchain. This helps to safeguard virtual environments. The study also employs multiparty computation. Additionally, it prepares for a quantum threat. Security improved [45]. The research in this paper focuses on virtual tourism, which demonstrates that immersive marketing can be positive while social effects still need to be understood, as sustainability is a problem [46]. The study examined virtual assets in accounting where conventional valuation is not effective, with emphasis on traceability and the changing nature of regulations regarding financial standards [47]. The legal analysis hereby aimed at property disputes with intelligent contract legal resolution and blockchain-based, observing unclear cross-border laws with the need for reforming the laws [48]. The study covers VAT and NFT taxation, citing that the buyer's identification is a challenge, and there is a need to have harmonized tax laws and regulations [49]. This study examines volatility in cryptocurrency markets and identifies the rise of cybersecurity threats, legal challenges, speculative dangers, and the need to establish a stable system of governance. [50]. This research has also examined the role of behavioral aspects in the use of NFT, which includes trust, transparency, AI, choices, ownership, and social influences, etc. [51]. This is an overview of anonymity in Bitcoin networks. A review is provided on privacy benchmarking. Multiple-criteria models are proposed. Improvements to security measures. Evaluation standards are unavailable [52]. This article investigates the transformation of government. Blockchain promotes transparency. It also raises legal difficulties. Ethical safeguards will be well-planned out. Digital governance will continue to evolve [53]. This work proposes models of a human-centered digital society. Blockchain ensures trust, cloud integration facilitates sharing, and it prioritizes privacy. Metaverse is a future layer [54]. This study focuses on digital memorialization, and blockchain ensures a genuine archive. Communities have authority over narratives, decentralized preservation is possible, and culture meets technology [55]. This is a review of the FM integration procedure. Digital twins provide for lifecycle management. Blockchain promotes transparency. Adoption is now in its early phases. Framework development is necessary [56]. Recent studies have explored the application of IIoT in manufacturing processes, such as vertical centrifugal casting, to create immersive interactive environments [57]. Digital twinning has also been applied to vertical centrifugal casting, enabling real-time monitoring and optimization [58]. Blockchain technology has been evaluated for Industrial IoT applications, with a comparative study of various consensus mechanisms [59]. The Metaverse has been leveraged to enhance learning experiences in manufacturing, with a focus on development and demonstration [60]. Furthermore, blockchain-integrated IoT devices have been developed for advanced inspection of casting defects [61].

4 Methodology

In study uses a hybrid research methodology that combines bibliometric analysis and a systematic literature review to evaluate integration to blockchain technology in Metaverse for industrial systems. goal of this methodology is to systematically discover analyze and synthesize existing research trends technology breakthroughs, and application domains for blockchain-enabled industrial Metaverse environments. The process is intended to assure transparency, reproducibility and thorough coverage of the relevant literature. In initial step is to identify relevant literature and collect data. Scientific papers were obtained from major academic databases like Scopus, Web of Science and IEEE Xplore which index high quality peer reviewed journals and conference proceedings are included. The structure keyword search technique was used combining terms such as Blockchain, Metaverse, Industrial Metaverse, Smart Manufacturing Industry 4.0, and Digital Twins. The search was limited to English-language publications and concentrated on recent works that captured developing technological breakthroughs. The second stage screening and selection criteria were applied to the collected literature. in example the literature inclusion criteria were based on study themes that discussed blockchain technology applications Metaverse environments or manufacturing related virtual system applications. Papers were omitted if they did not address industrial applications were not technically relevant to blockchain technology integration. duplicates were also removed to improve study quality. The third stage is the bibliometric analysis, in which selected articles were quantitatively examined to interpret publishing trends, key researchers, hotspots, and topic development in the blockchain based Metaverse. Results in terms of publishing year, keyword incidence, and thematic clustering were examined to gain the better understanding of the growth of the Metaverse facilitated by blockchain. A bibliometric review

allows for the identification of key topics and emerging trends in industrial Metaverse research, extended by a stage of qualitative content analysis. The found research articles were organized into themes such as identity management, safe data interchange, digital twins, decentralized governance, and industrial applications. This approach was also useful for comparing and identifying technology trends, difficulties, and limitations. Finally, ideas from both quantitative and qualitative data were combined to create a conceptual framework for blockchain-based Metaverse in manufacturing systems. The suggested framework includes important aspects such as decentralization, trust, safe information sharing, and digital twin. This is a methodical technique to harmonizing existing knowledge with the creation of a feasible framework.

5 Research Gap

Despite tremendous advances some significant research gaps remain in the context of blockchain-based Metaverse applications in manufacturing systems. First, the majority of past research has concentrated on conceptual models or industry specific domains such as healthcare, education or virtual commerce, whereas the manufacturing domain has received insufficient attention. Real time data transfer machine-to-machine connection and high dependability are all required in the industrial industry, yet most contemporary Metaverse applications do not address these needs. Second, scalability and latency are two of the most significant issues in this setting. The manufacturing process occurs in real time situations, and any delay can disrupt the operation. Existing blockchain networks frequently suffer from scalability concerns, rendering them unsuitable for large-scale Metaverse applications. The manufacturing ecosystem is made up of various devices and legacy systems that require standardized communication protocols, The second major gap concerns the privacy and security of industrial data. Although blockchain promotes transparency, industries require controlled information sharing to maintain their strategic possessions of intellectual property and business secrets. The balance between the equality of Transparency and confidentiality is not yet resolved. Governance and legal systems related to the industrial Metaverse are in their early stages, with few researchers conducting studies focused on compliance, standards, and risk control; even fewer tested their findings in pilot applications.

6 Future Work

Future research should focus on establishing scalable blockchain architectures suitable for various industrial Metaverse contexts. Layer-2 blockchain designs data storage that combines on-chain and off-chain techniques, and edge based blockchain architectures can all help to address latency and throughput challenges. Another interesting path is the combination of artificial intelligence-based digital twinning and blockchain-based secure data sharing. Intelligent digital twinning has the potential to improve predictive maintenance autonomous decision-making and adaptive production in the Metaverse. An merger of cognitive analysis with blockchain-based trust mechanisms has the potential to change industrial reliability. Furthermore standardization and interoperability frameworks must be prioritized. Universal protocols for cross platform digital twins and industrial IoT will be required, particularly to achieve widespread adoption of industrial IoT. Zero-knowledge proofs and homomorphic encryption, together with secure multi-party computation, are such privacy enhanced technologies that could keep sensitive industrial data safe while catering to the benefits of blockchain. DAOs also enhance coordination and decision-making in industries. In addition to future work, smart factories should be tested in the real world because this provides practical insights their performance, security and cost efficiency.

7 Conclusion

This paper presents an investigation on blockchain technology in industrial Metaverse using bibliometric and literature analysis methods. It is shown that blockchain technology is beneficial for trust, security, transparency, and coordination in smart manufacturing. It is observed that digital twins and Industry 4.0 have growing interests, while challenges include scalability, privacy, regulations and standardizations. It also presents a framework for blockchain, digital twins and smart contracts in smart manufacturing and reveals new trends and challenges.

8 References

[1] A. Abilkaiyrkyzy, A. Elhagr, F. Laamarti, and A. El Saddik, “Metaverse key requirements and platforms survey,” *IEEE Access*, vol. 11, pp. 117765–117787, 2023.

[2] S. A. Mohammed and A. L. Ralescu, “Future internet architectures on an emerging scale—A systematic review,” *Future Internet*, vol. 15, no. 5, p. 166, 2023.

[3] O. Marin, T. Cioara, L. Toderean, D. Mitrea, and I. Anghel, “Review of blockchain tokens creation and valuation,” *Future Internet*, vol. 15, no. 12, p. 382, 2023.

[4] A. V. Tran and B. T. Khoa, “Systematic review of blockchain business applications and the metaverse,” *SAGE Open*, 2025.

[5] S. Dong, M. Liu, and K. Abbas, “The metaverse review: Exploring the boundless realm of digital reality,” *Computers, Materials & Continua*, 2024.

[6] C. A. Gómez-Cano, A. J. Pérez Gamboa, and V. Sánchez Castillo, “Virtual reality in the metaverse: A Scopus literature review,” *Metaverse Basic and Applied Research*, vol. 3, p. 99, 2024.

[7] S. E. Uwhejevwe-Togbolo *et al.*, "Corporate social responsibility and the metaverse in the digital era: Implications for firm performance," *Data and Metadata*, vol. 4, p. 822, 2025.
[8] B. Alotaibi, "Cybersecurity attacks and detection methods in Web 3.0 technology: A review," *Sensors*, vol. 25, p. 342, 2025.
[9] J. Seo, H. Ko, and S. Park, "Space authentication in the metaverse: A blockchain-based user-centric approach," *IEEE Access*, vol. 12, pp. 18703–18713, 2024.
[10] P. Ruiu, M. Nitti, V. Pilloni, M. Cadoni, E. Grosso, and M. Fadda, "Metaverse & human digital twin: Digital identity, biometrics, and privacy in the future virtual worlds," *Multimodal Technologies and Interaction*, vol. 8, no. 6, p. 48, 2024.
[11] R. Li, H. B. Abdalla, M. Gheisari, and H. Rabiei-Dastjerdi, "Digital twins and big data in the metaverse: Addressing privacy, scalability, and interoperability with AI and blockchain," *ISPRS International Journal of Geo-Information*, vol. 14, no. 8, p. 318, 2025.
[12] J. Singh, P. Singh, R. Kaur, A. Kaur, and M. Hedabou, "Privacy and security in the metaverse: Trends, challenges, and future directions," *IEEE Access*, vol. 13, pp. 120209–120230, 2025.
[13] M. Xu, Y. Guo, Q. Hu, Z. Xiong, D. Yu, and X. Cheng, "A trustless architecture of blockchain-enabled metaverse," *High-Confidence Computing*, vol. 3, p. 100088, 2023.
[14] M. Kim and J. Ryou, "Digital authentication system in avatar using DID and SBT," *Mathematics*, vol. 11, no. 20, p. 4387, 2023.
[15] S. Banaeian Far and S. M. H. Bamakan, "NFT-based identity management in metaverses: Challenges and opportunities," *SN Applied Sciences*, vol. 5, p. 260, 2023.
[16] G. Liang, J. Xin, Q. Wang, X. Ni, X. Guo, and P. Chen, "Research on metaverse security and forensics," *Computers, Materials & Continua*, vol. 77, no. 1, pp. 799–816, 2023.
[17] M. Kim *et al.*, "Secure and privacy-preserving authentication scheme using decentralized identifier in metaverse environment," *Electronics*, vol. 12, no. 19, p. 4073, 2023.
[18] R. Patan and R. M. Parizi, "Securing data exchange in the convergence of metaverse and IoT applications," in *Proc. 18th Int. Conf. Availability, Reliability and Security (ARES)*, 2023, pp. 1–8.
[19] J. Oh, M. Kim, Y. Park, and Y. Park, "A secure content trading for cross-platform in the metaverse with blockchain and searchable encryption," *IEEE Access*, vol. 11, pp. 120680–120694, 2023.
[20] Y. Ghaderi and M. R. Ghaderi, "Integration of IoT, fog, and cloud in a blockchain network for future smart cities," *Metaverse*, vol. 6, no. 2, p. 3367, 2025.
[21] H.-C. Han and D.-C. Huang, "The blockchain neural network superior to deep learning for improving the trust of supply chain," *Computer Modeling in Engineering & Sciences*, vol. 143, no. 3, pp. 3921–3945, 2025.
[22] S. Anwar and A. Sanober, "MetaBlock: A revolutionary system for healthcare industry fusing metaverse and blockchain," *Journal of Metaverse*, vol. 4, no. 2, pp. 116–125, 2024.
[23] S. Ali, Abdullah, T. P. T. Armand, A. Athar, A. Hussain, M. Ali, M. Yaseen, M.-I. Joo, and H.-C. Kim, "Metaverse in healthcare integrated with explainable AI and blockchain: Enabling immersiveness, ensuring trust, and providing patient data security," *Sensors*, vol. 23, no. 2, p. 565, 2023.
[24] M. A. I. Mozumder, T. P. T. Armand, S. M. I. Uddin, A. Athar, R. I. Sumon, A. Hussain, and H.-C. Kim, "Metaverse for digital anti-aging healthcare: An overview of potential use cases based on artificial intelligence, blockchain, IoT technologies, its challenges, and future directions," *Applied Sciences*, vol. 13, no. 8, p. 5127, 2023.
[25] R. Benaich, Y. Gahi, and S. El Mendili, "Pioneering the security of EHRs using an immersive blockchain conceptual framework," *Emerging Science Journal*, vol. 9, no. 1, pp. 161–177, 2025.
[26] Y. Zheng, Y. Chen, Y. Chen, L. Lin, T. Xue, C. Chen, J. Wen, W. Lin, and G. Chen, "Metaverse clinic for pregnant women with subclinical hypothyroidism: Prospective randomized study," *Journal of Medical Internet Research*, vol. 27, e64634, 2025.
[27] O. Moztarzadeh, M. B. Jamshidi, S. Sargolzaei, F. Keikhaee, A. Jamshidi, S. Shadroo, and L. Hauer, "Metaverse and medical diagnosis: A blockchain-based digital twinning approach based on MobileNetV2 algorithm for cervical vertebral maturation," *Diagnostics*, vol. 13, no. 8, p. 1485, 2023.
[28] M. Polychronaki, M. G. Xevgenis, D. G. Kogias, and H. C. Leligou, "Decentralized identity management for metaverse-enhanced education: A literature review," *Electronics*, vol. 13, no. 19, p. 3887, 2024.
[29] S. Dhingra, A. Gupta, K. Chaudhry, A. Kumar, and H. Falwadiya, "Unlocking learning potentials: Understanding user intentions in AI-fueled metaverse education," *Computers & Education: X Reality*, vol. 8, p. 100131, 2026.
[30] P.-K. A. Chen, "Influence of metaverse on building entrepreneurship education ecosystems," *Engineering Proceedings*, vol. 103, p. 3, 2025.
[31] F. De Felice, A. Petrillo, G. Iovine, C. Salzano, and I. Baffo, "How does the metaverse shape education? A systematic literature review," *Applied Sciences*, vol. 13, no. 9, p. 5682, 2023.
[32] M. Garlinska, M. Osial, K. Proniewska, and A. Pregowska, "The influence of emerging technologies on distance education," *Electronics*, vol. 12, no. 7, p. 1550, 2023.
[33] L. Cui, C. Zhu, R. Hare, and Y. Tang, "MetaEdu: A new framework for future education," *Discover Artificial Intelligence*, vol. 3, p. 10, 2023.

[34] H. S. Park and J. H. Kim, "An analysis of the demonstration of five-year-long creative ICT education based on a hyper-blended practical model in the era of intelligent information technologies," *Sustainability*, vol. 15, no. 6, p. 4821, 2023.
[35] N. Chauhan, N. Z. Jhanjhi, F. Ashfaq, and Jasmansyah, "Metaverse as a catalyst for digital transformation in India's education sector: Implementation perspectives," *Engineering Proceedings*, vol. 107, p. 96, 2025.
[36] K. Kostelić and D. Etinger, "Metaverse business models and framework: A systematic search with narrative synthesis," *Systems*, vol. 13, p. 968, 2025.
[37] K. Kraus and N. Kraus, "Institutionalization of the metaverse based on the development of the exabyte economy and gig economy," *Journal of Vasyl Stefanyk Precarpathian National University*, vol. 12, no. 2, pp. 6–13, 2025.
[38] C. Mele, T. R. Spena, and S. P. Russo, "Experimenting on the metaverse to foster innovation," *Spanish Journal of Marketing – ESIC*, vol. 29, no. 3, pp. 270–292, 2025.
[39] J. H. Puente and G. Contreras-Piña, "Technological convergence in the metaverse: Challenges and solutions from blockchain, AI, and digital rights," *Metaverse Basic and Applied Research*, vol. 3, p. 108, 2024.
[40] R. Aria, N. Archer, M. Khanlari, and B. Shah, "Influential factors in the design and development of a sustainable Web3/metaverse and its applications," *Future Internet*, vol. 15, no. 4, p. 131, 2023.
[41] C. Song, S.-Y. Shin, and K.-S. Shin, "Exploring the key characteristics and theoretical framework for research on the metaverse," *Applied Sciences*, vol. 13, no. 13, p. 7628, 2023.
[42] R. Asif and S. R. Hassan, "Exploring the confluence of IoT and metaverse: Future opportunities and challenges," *IoT*, vol. 4, no. 3, pp. 412–429, 2023.
[43] P. Bhattacharya *et al.*, "Towards future internet: The metaverse perspective for diverse industrial applications," *Mathematics*, vol. 11, no. 4, p. 941, 2023.
[44] T.-Y. Wu, H. Wu, M. Tang, S. Kumari, and C.-M. Chen, "Unleashing the potential of metaverse in social IoV: An authentication protocol based on blockchain," *Computers, Materials & Continua*, vol. 84, no. 2, pp. 3175–3192, 2025.
[45] E. AraTuli, J.-M. Lee, and D.-S. Kim, "Leveraging quantum blockchain for secure multiparty space sharing and authentication on specialized metaverse platform," *Scientific Reports*, vol. 14, p. 25776, 2024.
[46] S. Monaco and G. Sacchi, "Travelling the metaverse: Potential benefits and main challenges for tourism sectors and research applications," *Sustainability*, vol. 15, no. 4, p. 3348, 2023.
[47] I. Akin and M. Akin, "Valuation, accounting principles, and classification of assets in the metaverse," *Journal of Metaverse*, vol. 4, no. 1, pp. 43–53, 2024.
[48] A. M. López Rodríguez, "Virtual real estate and innovative conflict resolution perspectives in the metaverse," *Cuadernos de Derecho Transnacional*, vol. 16, no. 1, pp. 319–343, 2024.
[49] M. Bernad Furest, "Tax challenges in the digital era: NFTs and their implications for VAT, IGIC, and IPSI," *European Public & Social Innovation Review*, vol. 9, pp. 1–18, 2024.
[50] P. Radanliev, "The rise and fall of cryptocurrencies: Defining the economic and social values of blockchain technologies, assessing the opportunities, and defining the financial and cybersecurity risks of the Metaverse," *Financial Innovation*, vol. 10, no. 1, p. 1, 2024.
[51] S. V. Jin, "'In metaverse cryptocurrencies we (dis)trust?': Mediators and moderators of blockchain-enabled non-fungible token (NFT) adoption in AI-powered metaverses," *AI*, vol. 6, p. 286, 2025.
[52] Z. K. Mohammad, S. B. Yousif, and Y. B. Yousif, "Modelling Bitcoin networks in terms of anonymity and privacy in the metaverse application within Industry 5.0: Comprehensive taxonomy, unsolved issues and suggested solution," *Journal of Intelligent Systems*, vol. 33, p. 20230117, 2024.
[53] S. Torreblanca Gómez de las Heras, "The impact of disruptive technologies in public administration: New challenges in management models," *European Public & Social Innovation Review*, vol. 9, pp. 1–21, 2024.
[54] Y. Ghaderi and M. R. Ghaderi, "Society 5.0 in the cloud: Harnessing the power of modern information technologies," *Metaverse*, vol. 6, no. 1, p. 3232, 2025.
[55] D. H. Mutibwa, "Radical left culture and heritage, the politics of preservation and memorialisation, and the promise of the metaverse," *Heritage*, vol. 7, no. 2, pp. 537–575, 2024.
[56] A. El Jaouhari, J. Arif, A. Samadhiya, A. Kumar, and V. Trinkūnas, "Are we there or do we have more to do? Metaverse in facility management and future prospects," *International Journal of Strategic Property Management*, vol. 27, no. 3, pp. 159–175, 2023.
[57] D. Anadkat, A. Sata, M. Shukla, S. Jarboui, and D. Mobarsa, "Designing an immersive interactive environment for IIoT-enhanced vertical centrifugal casting," *Frontiers in Education*, 2024.
[58] D. Anadkat, A. Dave, A. Sata, M. Shukla, and S. Jarboui, "Digital twinning of vertical centrifugal casting," *Concurrent Engineering: Research and Applications*, 2024, doi: 10.1177/1063293X241296463.
[59] M. Shukla, A. Sata, and D. Mobarsa, "Comparative evaluation of various blockchain consensus mechanisms for industrial IoT applications," *Security and Privacy*, vol. 9, no. 1, e70150, 2026.
[60] D. Anadkat, M. Sama, and A. Sata, "Enhancing learning experience of manufacturing through metaverse—development and demonstration," *Mechanical Engineering Advances*, vol. 3, no. 4, 2025.

[61] N. Yousef, A. Sata, M. Shukla, S. Jarboui, and D. Mobarsa, “Blockchain-integrated IoT device for advanced inspection of casting defects,” *Scientific Reports*, vol. 15, p. 5300, 2025.