Industrial Metaverse as a New Component of Digital Transformation: A Bibliometric Analysis

Araştırma Makalesi/Research Article

İsmail YOŞUMAZ[1]

[1]Kütahya Dumlupınar Üniversitesi Kütahya Sosyal Bilimler MYO İşletme Yönetimi Bölümü Merkez / Kütahya / Türkiye

ismaily@dpu.edu.tr

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***Abstract*—** The digital transformation process in businesses operates within the data and knowledge cycle. Industrial metaverse technology has recently emerged as a new catalyst within this transformation. Industrial metaverse technology aims to develop a virtual space for living and working that closely resembles the physical environment, facilitated through collaboration with multiple technologies. In this context, this study aims to identify the technologies or processes that industrial metaverse technology interacts with and to provide a framework for researchers and businesses engaging in this field. A bibliometric analysis was conducted on studies using the keyword "industrial metaverse" in the Web of Science and Scopus databases to accomplish this aim. A total of 44 studies were identified from the Scopus database and 16 from the Web of Science database, amounting to 60 studies. A complete census was performed based on these 60 studies, which constituted the research sample. Data were manually collected, and a keyword analysis was conducted using the VOSviewer application. The study's findings suggest that industrial metaverse technology is connected to processes such as smart production, employee-technology collaboration, employee training, and environmental sustainability. Additionally, technologies such as digital twins, blockchain, non-fungible tokens (NFTs), virtual reality, augmented reality, the industrial internet of things, and artificial intelligence were identified as forming the infrastructure of industrial metaverse technology.

***Keywords*—** digital transformation, industrial metaverse, knowledge management, technology and innovation management, Industry 5.0

Dijital Dönüşümün Yeni Bileşeni Olarak Endüstriyel Metaverse: Bibliyometrik Analiz

***Özet*—** İşletmelerde dijital dönüşüm süreci veri ve bilgi döngüsü içerisinde işleyen bir süreçtir. Son zamanlarda dijital dönüşüm sürecine Endüstriyel metaverse teknolojisi yeni bir katalizör olarak dahil olmuştur. Endüstriyel metaverse teknolojisi birçok teknoloji ile iş birliği içerisinde, sanal ortamda fiziksel ortama benzer yeni bir sanal yaşam ve çalışma alanı oluşturmayı hedefleyen teknolojidir. Bu kapsamda, bu çalışmanın amacı, Endüstriyel metaverse teknolojisinin hangi teknoloji veya süreçlerle iş birliği içerisinde olduğunu belirleyebilmek ve bu sayede bu alanda çalışma yapacak araştırmacılara ve işletmelere bir vizyon sunabilmektir. Bu amaca ulaşabilmek için Web of Science ve Scopus veritabanlarında endüstriyel metaverse anahtar kelimesi kapsamında yapılan çalışmaların bibliyometrik analizi yapılmıştır. Scopus veritabanından 44, WoS veritabanından 16 ve toplamda 60 çalışmaya ulaşılmıştır. Araştırmanın evrenini oluşturan bu 60 çalışma kapsamında tam sayım yapılmıştır. Veriler manuel derlenmiş ve çalışmaların anahtar kelime analizleri VOSviewer uygulaması ile yapılmıştır. Çalışma sonucunda Endüstriyel metaverse teknolojisinin akıllı üretim, çalışan ve teknoloji iş birliği, çalışan eğitimi, çevresel sürdürülebilirlik gibi süreçlerle ilişkili olduğu sonucuna varılmıştır. Ayrıca bu ilişkinin sağlanabilmesi için dijital ikiz, blok zinciri, Nun-fungible token (NFT), sanal gerçeklik, arttırılmış gerçeklik, endüstriyel nesnelerin internet, yapay zekâ gibi teknolojilerin endüstriyel metaverse teknolojisinin altyapısını oluşturduğu görülmüştür.

***Anahtar Kelimeler*—** digital dönüşüm, endüstriyel metaverse, bilgi yönetimi, teknoloji ve yenilik yönetimi, Endüstri 5.0

1. INTRODUCTION

With the advent of Industry 4.0, businesses have begun automating all their processes to optimise data and knowledge through technological contributions, thereby initiating efforts within the scope of digital transformation. Before the Industry 4.0 process, digitalisation efforts were generally carried out in the context of injecting technology and automation into businesses. However, with the Industry 4.0 process, the data and knowledge needs of technologies such as big data, internet of things (IoT), cloud computing, artificial intelligence (AI), metaverse, blockchain, and NFTs have brought digital transformation efforts within the purview of the data and knowledge cycle [1].

Despite these advancements, the role of employees in the technology-supported digital transformation within the data and knowledge cycle during Industry 4.0 was not fully elucidated. The emergence of Industry 5.0, building on the technological foundations of Industry 4.0 and incorporating advanced technologies like productive artificial intelligence and industrial metaverse, has clarified the status of employees in the digital transformation process. Employees are now recognised as valuable assets in digital transformation. Alongside employees, environmental sustainability and business resilience against cyber security breaches, ecological disasters, and supply chain disruptions have become key components of Industry 5.0. Thus, the essential elements of a digital transformation suitable for Industry 5.0 are technology, employees, environmental sustainability, and business resilience.

A literature review reveals that industrial metaverse technology is interconnected with all components of the digital transformation process appropriate for Industry 5.0. Specifically, Kumar et al. [5] explore the relationship between the industrial metaverse and organisational agility and business performance, while Kshetri [6] examines the economic returns of the industrial metaverse. Additionally, Ren et al. [7], Xiang et al. [8], and Yang, Wang, and Zhao [9] investigate the link between industrial metaverse and smart manufacturing. Kshetri and Dwivedi [10] study the relationship between the industrial metaverse and environmental sustainability, and Huang et al. [11] and Zheng et al. [12] address the challenges and opportunities the industrial metaverse presents to businesses. Gattullo et al. analyse the relationship between the industrial metaverse and knowledge sharing, while Opperman et al. [13] focus on the relationship between the industrial metaverse and remote support and training. Furthermore, Muller, Bohne, and Jamboula [14] examine the scope and components of industrial metaverse, Bharti and Sharma [15] discuss the interaction between avatars and humans in decision-making processes, and Aromaa et al. [16] explore the relationship between industrial metaverse and human factors.

This study aims to identify the technologies and processes with which industrial metaverse technology collaborates, thereby providing insights for researchers and businesses interested in this field. A bibliometric analysis of studies indexed under the "industrial metaverse" keyword in the Web of Science and Scopus databases was conducted to achieve this goal. The analysis encompassed 44 studies from Scopus and 16 from WoS, totaling 60 studies. A comprehensive census of these 60 studies was performed, with data manually compiled and analysed using the VOSviewer application. To further support the study's objectives, figures (Figures 1 and 2) were included to illustrate the conceptual framework and infrastructure of the industrial metaverse.

In this context, the study's research question was determined as follows: Which technologies or processes are most closely aligned with the industrial metaverse?

The study concluded that industrial metaverse technology is associated with processes such as smart processes, employee-technology collaboration, maintaining the functionality of the data and knowledge cycle infrastructure, employee training, and environmental sustainability. Furthermore, technologies like digital twins, blockchain, NFT, virtual reality (VR), augmented reality (AR), the industrial internet of things (IIOT), and AI form the foundational infrastructure of industrial metaverse technology.

A limitation of this study is that only the studies indexed in the Web of Science (WoS) and Scopus databases were examined. Future research encompassing different databases could enhance the findings of this study.

2. CONCEPTUAL FRAMEWORK

This section aims to explain the digital transformation process of enterprises within the scope of the data and knowledge cycle. Following this, conceptual knowledge will be provided on metaverse technology and industrial metaverse technology, which are key technological infrastructures required to establish the data and knowledge cycle. The conceptual understanding is supplemented with figures drawn explicitly for this topic.

2.1. Digital Transformation

The digital transformation process in enterprises accelerated and took on a new dimension with the announcement of Industry 4.0 in 2011. This initiative introduced a new wave of digital transformation focused on the data and knowledge cycle in the industry [17], [18]. Digital transformation has evolved from merely focusing on technology and automation to emphasising the data and knowledge cycle, which these technological advancements support. By integrating and analysing data obtained from physical and virtual environments, enterprises generate new data and insights, aiming to make processes such as production, marketing, and finance more transparent and efficient. This approach seeks to improve decision-making, predictive maintenance, customer relationship management, employee skill enhancement, production processes, and waste reduction [19], [20].

The data and knowledge cycle involves the acquisition, storage, analysis, sharing, and preservation of data within enterprises and is considered within the context of technological collaboration [21]. Establishing this cycle requires the development of technological infrastructure for each process within the cycle. Figure 1 illustrates the data and knowledge cycle underpinning businesses' digital transformation.

While the Industry 4.0 process explained digital transformation within a technology-supported data and knowledge cycle, it did not fully address the role of employees. The subsequent Industry 5.0 process expanded on this by incorporating employees, environmental sustainability, and business resilience against various threats into the data and knowledge-oriented digital transformation [22], [23]. This approach builds on the Industry 4.0 foundation by emphasising collaboration between technology and human factors, ensuring a more holistic and sustainable transformation.

Humans interact with their physical environment through the five senses. To fully leverage the metaverse infrastructure, human sensory organs need to be stimulated [27]. This stimulation allows people to experience the virtual environment in the metaverse as if it were real. The technology that facilitates this experience is known as VR technology [28]. Currently, metaverse infrastructures can stimulate the senses of sight and hearing, while research on olfactory stimulation is ongoing. Additionally, no special equipment is necessary to access the metaverse; interactions can occur via computer, tablet, or phone screens using keyboards, mouse, or voice commands. However, technologies such as VR and AR are essential to fully immerse in the metaverse and experience the virtual environment realistically [29].

The technologies underpinning the metaverse infrastructure have gained prominence in the digital transformation of enterprises within the Industry 4.0 framework. Digital twin technology generates analogs of

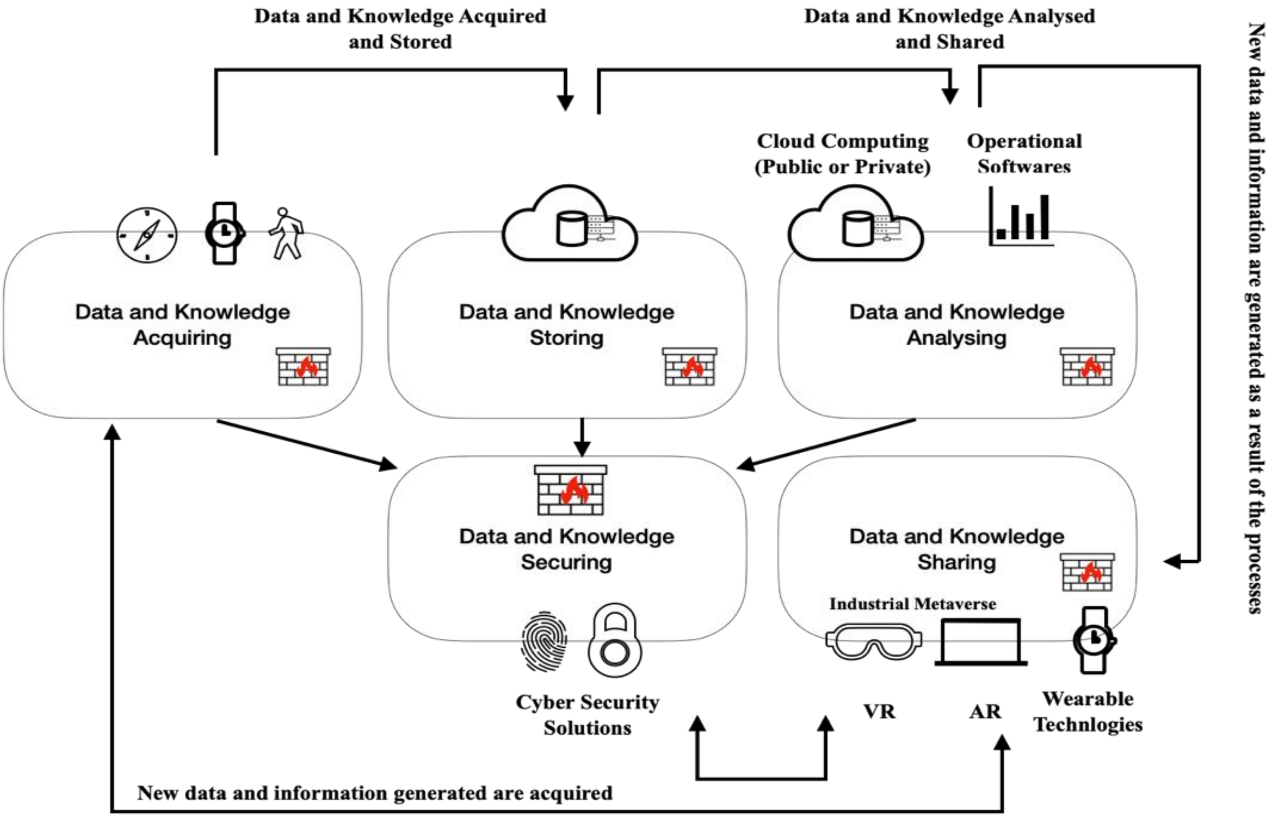

Figure 1. Data and Knowledge Cycle (Source: Author Elaboration)

2.2. Metaverse

The term "metaverse" first appeared in the novel “Snow Crash” in 1992, describing a virtual world where users from the physical environment interact with avatars through cyber components [24]. The metaverse can be defined as a virtual environment that emerges from the interaction between the physical and cyber environments through technological infrastructure [25], [26].

physical objects in the virtual environment. The interfaces connecting the metaverse to the physical world are VR and AR technologies. AI and three-dimensional (3-D) modelling solutions configure objects and facilitate user interaction in the metaverse. Blockchain-based digital currencies support the trade infrastructure within the metaverse, and blockchain technology also secures metaverse data. Ownership of virtual objects is managed through NFT technology, closely related to the blockchain infrastructure [30].

The primary application areas for metaverse technology include sectors such as production, marketing, healthcare, and education. Adopting metaverse technology in manufacturing, engineering, and related processes has given rise to the concept of the industrial metaverse. As the industrial metaverse has emerged, the broader concept of the metaverse has expanded to address issues relevant to individuals and society. In contrast, the industrial metaverse has begun to focus on topics pertinent to various industries.

2.2. Industrial Metaverse

The industrial metaverse refers to the application of metaverse technologies for industrial purposes. To fully define the industrial metaverse, it is necessary to explain the technologies used in the industry conceptually. These technologies are generally categorised into two groups: operational technologies and information technologies.

i. Operational technologies: This category encompasses all the hardware, software, and technologies required to structure, maintain, and ensure the efficiency of operational business processes such as production, procurement, logistics, and finance [31], [32]. Included within operational technologies are wearable technologies, cobots, IIOT (sensors and related technologies), autonomous vehicles, machinery, equipment, and associated software. Technologies such as AI, generative AI, and digital twins are employed to maximise efficiency. The benefits from these technologies can be measured through improvements in predictive maintenance, decision-making processes, and the emergence of new business models [32].

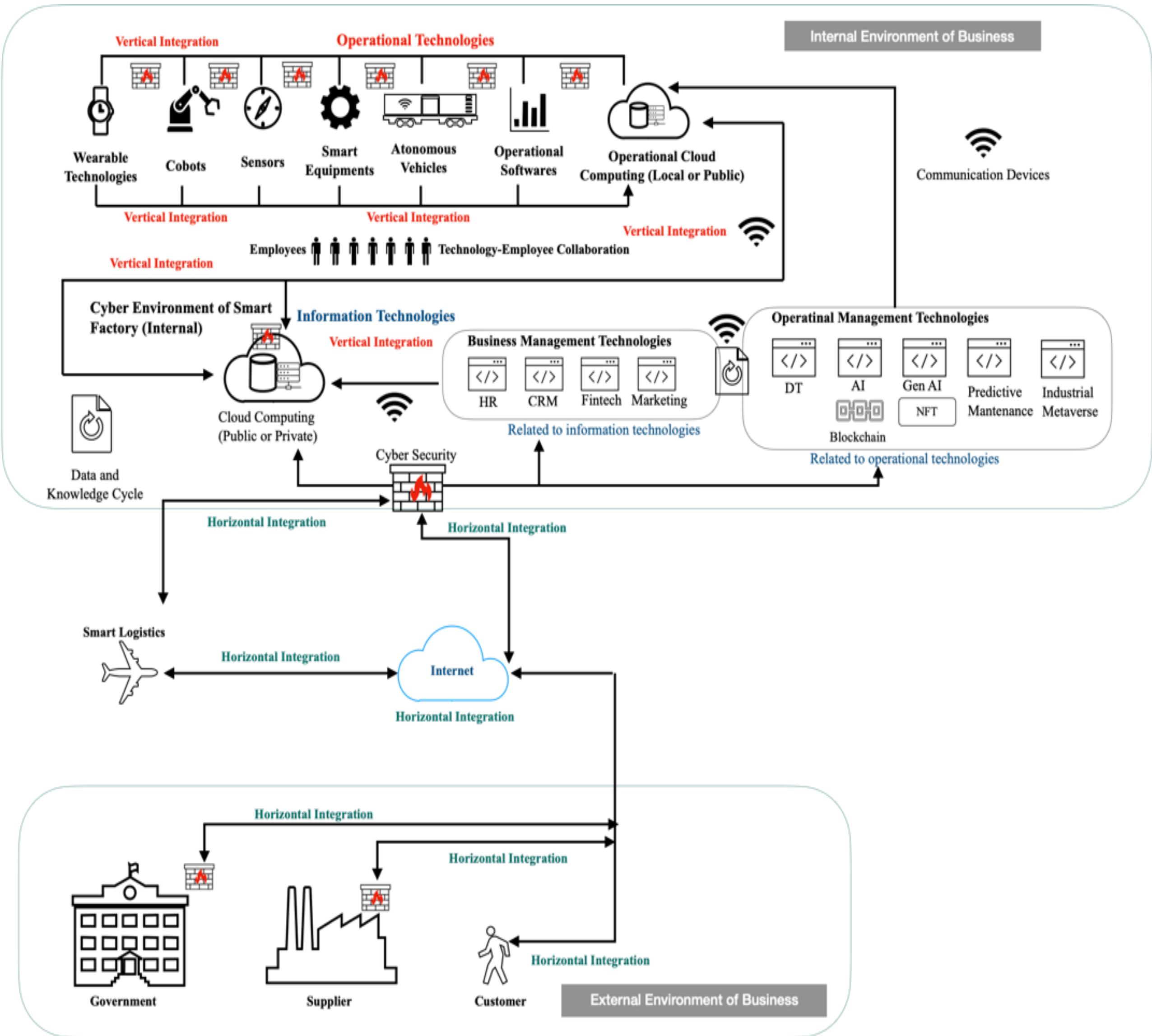

Figure 2. Operational and Information Technologies (Source: Author Elaboration)

ii. Information technologies: This category forms the communication and information system infrastructure necessary for establishing the data and knowledge cycle, enabling all business functions to collaborate. The data and knowledge cycle involves integrating data obtained from

operational technologies with other data sources within the business, transforming this data into knowledge, and sharing the transformed knowledge with the necessary systems within the business [19]. Technologies such as cloud computing, cybersecurity equipment, and communication equipment (such as Wi-Fi v6 and 5G) are all considered within the scope of information technologies. Additionally, technologies and software used in human resources, marketing, finance, and accounting processes fall under information technologies. These technologies also support the benefits derived from operational technologies and help eliminate silos between departments within the business [33].
Operational and information technologies play a crucial role in achieving vertical integration within the internal environment of a business and horizontal integration in the external environment. Vertical integration involves the collaboration among departments, machines, employees, and all other internal components within the business. Horizontal integration, on the other hand, refers to the cooperation between the business and its external environment, including suppliers, government units, and customers. This cooperation can lead to the creation of new value networks and innovative business models, thereby significantly contributing to the digital transformation efforts of enterprises [22], [34], [35]. The interplay between operational technologies, information technologies, and the concepts of horizontal and vertical integration is illustrated in Figure 2.

Upon explaining these concepts, industrial metaverse technology can be defined as follows: Industrial metaverse is a technology that integrates various technologies, such as digital twin, blockchain, VR, and AR, through operational and information technologies, involving the transfer of data and knowledge obtained from cobots, autonomous vehicles, employees, machinery, and equipment used in the industry to information technologies via an IIOT infrastructure, to make the operations of enterprises in the physical environment traceable, configurable, and sustainable in the virtual environment, thereby enhancing operational efficiency.

The industrial metaverse concept collaborates with multiple technologies, including IIOT [37], digital twin [38], blockchain, NFTs [39], simulation and modelling software, and AI [14]. VR and AR technologies facilitate interaction between the industrial metaverse environment and employees [13].

By implementing an industrial metaverse infrastructure, enterprises can achieve various benefits, such as improved decision-making processes [11], structured predictive maintenance activities, increased efficiency in production processes, enhanced collaboration between employees and technology [36], more effective marketing activities through a better understanding of customer demand [6] and strengthened customer relations.

Industrial metaverse technology has been studied in the literature since 2021. No bibliometric analysis study has been identified in this field. Existing studies generally focus on the application areas of industrial metaverse technology [4-5], [9], [11]. However, this study aims to fill the gap in the literature by providing an overview of the components of industrial metaverse technology and its related technologies. This will be achieved by analysing all relevant studies published in the Web of Science (WoS) and Scopus databases. Given its novelty, the following research question (RQ) has been posed to determine which technologies or processes it collaborates with:

RQ1. Which technologies or processes are most closely aligned with the industrial metaverse?

3. METHODOLOGY

This study aims to conduct a bibliometric analysis of the studies undertaken in the scope of the keyword “industrial metaverse” in the Web of Science and Scopus databases to address the research question and identify the technologies or processes most frequently collaborated with Industrial metaverse technology. Keywords include those chosen by the authors. For this purpose, studies in the WoS and Scopus databases were analysed from January 1, 2022, to May 15, 2024. The concept of the industrial metaverse began gaining prominence in 2021. For this reason, the first studies on this subject have been included in WoS and Scopus academic databases since 2022. There were no relevant studies in the WoS or Scopus databases before this date. The 60 documents examined are provided in the appendix section of the study.

The study population consists of 44 studies from the Scopus database and 16 studies from the WoS database, totaling 60 studies under the keyword “industrial metaverse”. A complete census was conducted, and no sample was selected. The data were compiled manually and VOSviewer application.

The bibliometric analysis, which reveals the technologies and processes related to industrial metaverse technology, was conducted using the VOSviewer application. In this context, the frequency of word repetition in the article titles and abstracts of the examined studies and the frequency of keyword co-occurrence were analysed. A total of 250 keywords from the related studies (authors’ keywords) and the title and abstract of each study were analysed separately. According to the frequency of co-occurrence of keywords, 22 keywords were selected. In the title and abstract analysis, the words used at least seven times in total in all titles and abstracts were selected to identify the areas related to industrial metaverse technology. The Linear-Logarithmic (Lin/Log Modularity) normalisation method was used to analyse keywords, article titles, and abstracts. Lin/Log modularity can help to visualise more clearly the relationships between research areas, keywords or clusters of topics [40]. The findings of the analysis and the discussion of these findings are presented in the findings and discussion section.

Additionally, four publications were published in both WoS and Scopus databases. These joint publications are shown in dark colours in tables in the Appendix.

4. Findings and Discussions

The findings were analysed in two parts. In the first part, a frequency analysis was performed based on the number of studies and citations, distinguishing between year and database. Additionally, frequency analysis was conducted according to the field of study of the documents within each database. The discrepancy between the number of studies and the number of fields of study is that some studies pertain to multiple fields.

In the second part, the frequency of word occurrences in the article titles and abstracts of the studies and the co-occurrence of the keywords entered by the authors were analyzed using the VOSviewer application. This analysis aims to identify which technologies or processes the Industrial metaverse collaborates with the most.

4.1. Frequency Analysis

The frequency analysis showing the total number of studies related to the analysed studies based on years is presented in Table 1. In contrast, the frequency analysis related to the total number of citations is presented in Table 2.

In Table 1 and Table 2, the colouring is done in white/black tones based on the number of studies in the databases. While the black tone indicates the highest number of studies or citations, the lightening of the tone colour shows a decrease in the number of studies.

Table 1. Frequency Analysis of Studies Published in Wos and Scopus Databases (01.01.2022-05.15.2024)

DATABASES	*SCOPUS*		*WoS*	
YEARS	***Document Count***	***Percent***	***Document Count***	***Percent***
2022	**5**	11,37	**4**	25
2023	**18**	40,91	**8**	50
2024		47,72	**4**	25
Total	**44**		**16**	

Table 1 shows that there are more studies in the Scopus database than in the WoS database. The document density in the Scopus database in 2024 is particularly notable. By mid-2024, the highest number of documents was reached compared to previous years.

Table 2. Citations Count by Years

YEARS	***SCOPUS***	***WoS***	***Total Citiations by years***
2022		**11**	108
2023	**34**	**55**	89
2024 (Until 05.15.2024)	**47**	**35**	82
Total		**101**	279

The table shows that the Scopus database surpasses the WoS database in terms of the number of citations. Evaluating Table 1 and Table 2 together indicates that studies on the industrial metaverse are expected to intensify in 2024.

Figure 3. Frequency Analysis Graph of Studies Published in Scopus Database (01.01.2022-05.15.2024) by Study Area

Figure 3 shows that the physical sciences category in the Scopus database, with 31 studies, represents the highest number of works. Additionally, 5 studies in the social sciences indicate that the topic is also being explored within this field.

Figure 4. Frequency Analysis Graph of Studies Published in WoS Database (01.01.2022-05.15.2024) by Study Area

Figure 4 shows that the physical sciences category in the WoS database, with 12 studies, represents the highest number of works. Additionally, 2 studies in the social sciences indicate that the topic is also being explored within this field.

4.2. Term Co-occurrence Analysis of Study Titles and Abstracts

To understand the relationship between the words in the titles and abstracts of the 44 studies examined from the

Scopus database, the relationship visualisation of 14 words that occur at least seven times in the titles and abstracts of all studies is shown in Figure 5. The lowest repetition frequency is for “artificial intelligence” with seven occurrences, while the highest is for the term "industrial metaverse" with 103 occurrences.

According to Figure 5, two distinct groups emerged from the analysis. The red cluster includes the terms “industrial metaverse”, “digital twin”, “system”, “technology”, “manufacturing”, “smart manufacturing”, and “artificial intelligence”. This group predominantly consists of technologies related to smart manufacturing processes.

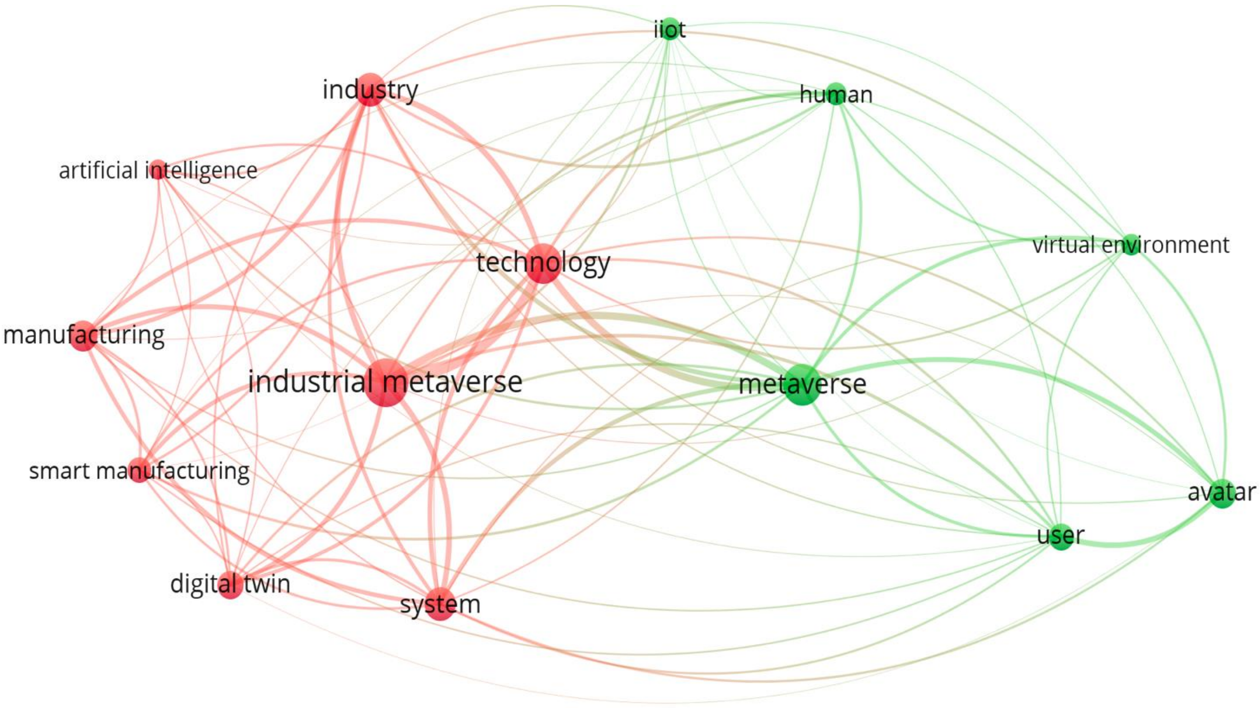

Figure 5. Network Visulation of the Co-occurrence of 14 Terms that Appear at Least 7 Times in the Titles and Abstracts of Documents Obtained from the Scopus Database.

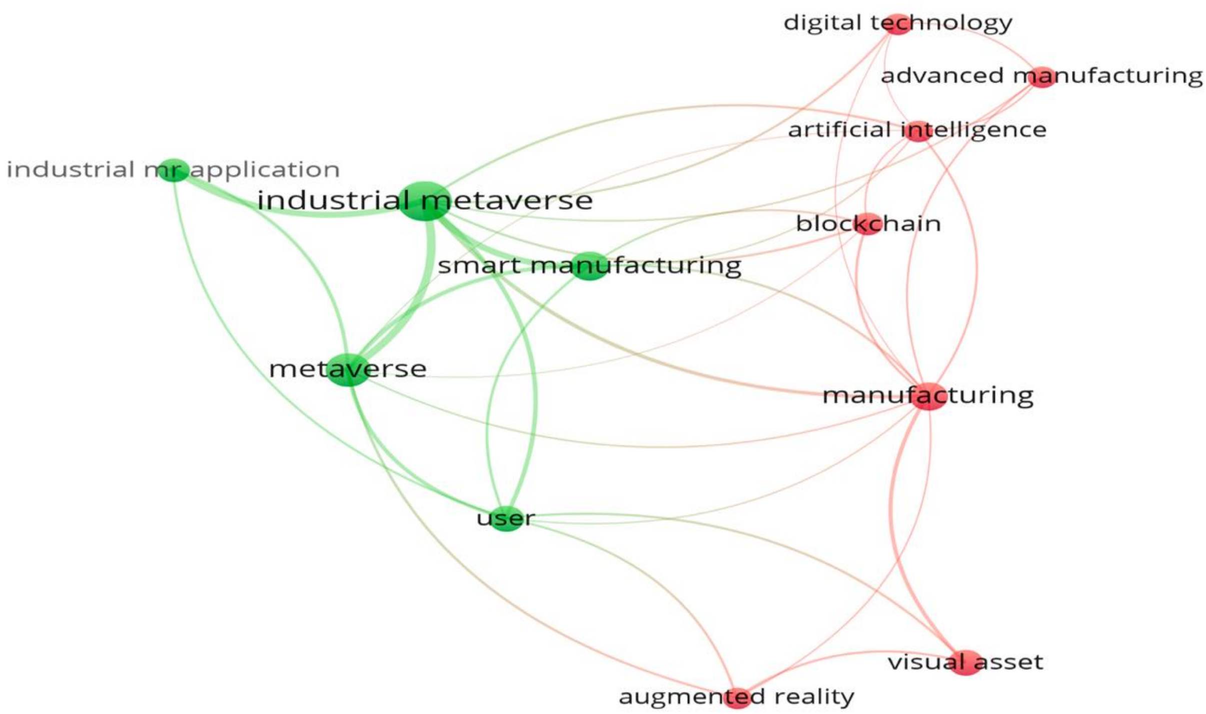

Figure 6. Network Visulation of the Co-occurrence of 14 Terms that Appear at Least 7 Times in the Titles and Abstracts of Documents Obtained from the WoS Database.

Digital twin technology models objects in the physical environment within a virtual environment, forming the infrastructure for industrial metaverse technology. The industrial metaverse environment is generated using these modelled objects, and AI technologies can further streamline this process, significantly contributing to the creation of smart production infrastructure.

The green cluster includes the terms “metaverse”, “human”, “avatar”, “user”, “IIOT”, and “virtual environment”. This group primarily consists of technologies related to the data collection infrastructure of industrial metaverse technology and the representation of employees in the virtual environment. In the industrial metaverse, an employee or person is represented by an avatar, a visual entity depicted as digital knowledge in the virtual environment. Both objects and workers need to have equivalent visual entities in the virtual environment, with their data and knowledge transferred via IIOT. When these technologies are applied to production processes, a twin of the production process is generated in the virtual environment. Together, the technologies in the red and green clusters form the smart manufacturing infrastructure. These findings are supported by the findings of Ren et al. [7], Xiang et al. [8], and Yang, Wang, and Zhao [9] investigate the link between industrial metaverse and smart manufacturing.

To understand the relationship between the words in the titles and abstracts of the 16 studies examined from the WoS database, the relationship visualisation of 14 words that occur at least seven times in the titles and abstracts of all studies is shown in Figure 5. The lowest repetition frequency is for the term “industrial mr application”, with 5 occurrences, while the highest is for "industrial metaverse", with 35 occurrences.

According to Figure 6, two different clusters emerged from the analysis. The red cluster includes terms such as augmented reality, visual asset, manufacturing, blockchain, artificial intelligence, advanced manufacturing, and digital technology. This cluster generally comprises technologies that form the infrastructure of industrial metaverse technology. In the metaverse, objects in the physical environment are represented as visual assets. Similarly, the equivalent of an employee (user) in the metaverse is an avatar, also a visual entity. These visual entities are represented as digital data or knowledge in the virtual environment. Maintaining this information within a blockchain-based data storage infrastructure is crucial for security in the industrial metaverse. Additionally, the relationship between blockchain infrastructure, digital currency, and NFTs indicates the potential for commerce within the industrial metaverse infrastructure.

The green cluster includes terms such as industrial metaverse, metaverse, user, smart manufacturing, industrial MR (mixed reality) application, and IIOT. This cluster primarily consists of technologies related to the data collection infrastructure of industrial metaverse technology and the representation of employees in a virtual environment. MR applications combining VR and AR are integral to the industrial metaverse infrastructure. A data and knowledge cycle-based infrastructure is necessary to use industrial metaverse technology through MR technology effectively. IIOT technology, which connects the physical environment to the virtual environment for data and knowledge acquisition, is a key component of this infrastructure. This technology enables the transfer of data and knowledge from the physical to the virtual environment, thus preparing the infrastructure for a smart production environment. These findings are consistent with those of Zheng et al. [12] and Kumar et al. [5]. However, it is important to note that industrial metaverse technology extends beyond smart manufacturing. According to Opperman et al., industrial metaverse also supports processes such as marketing, supply chain management, financial applications, and on-the-job employee training [13].

4.3. Keyword Co-occurrence Analysis

Within the scope of the keyword co-occurrence analysis, the frequency of two keywords appearing together in the same article among 168 from the examined studies from the Scopus database was analysed. The density map resulting from the analysis is shown in Figure 7. The lowest co-occurrence frequency value is 3 for the keyword “smart manufacturing”, while the highest co-occurrence value is 44 for the keyword “industrial metaverse”.

When analysing the keyword co-occurrence in the WoS database, a relationship is observed between industrial metaverse technology and keywords such as digital twin, blockchain, metaverse, IIOT, VR, AR, XR (Extended Reality), and cyber-physical systems. Notably, these technologies are prominent in the Industry 4.0 process and form the infrastructure of the Industry 5.0 process [1]. Environmental sustainability, employee training, and smart manufacturing have emerged as processes related to industrial metaverse technology.

The more significant number of studies in the Scopus database has made the technologies and processes related to industrial metaverse technology more evident in the keyword co-occurrence analysis. These technologies constitute the infrastructure of industrial metaverse technology, and the processes interact with industrial metaverse technology. These findings are supported by Lyu and Fridenfalk [38], Ren et al. [7], Agalwar and Alathur [3], Xiang et al. [8], and Muller et al. [14].

Within the scope of the keyword co-occurrence analysis, the frequency of two keywords appearing together in the same article among 82 keywords from the examined studies was analysed. The density map resulting from the analysis is shown in Figure 8. The lowest co-occurrence frequency value is 2 for the keyword “digital twin”, while the highest is 16 for “industrial metaverse”.

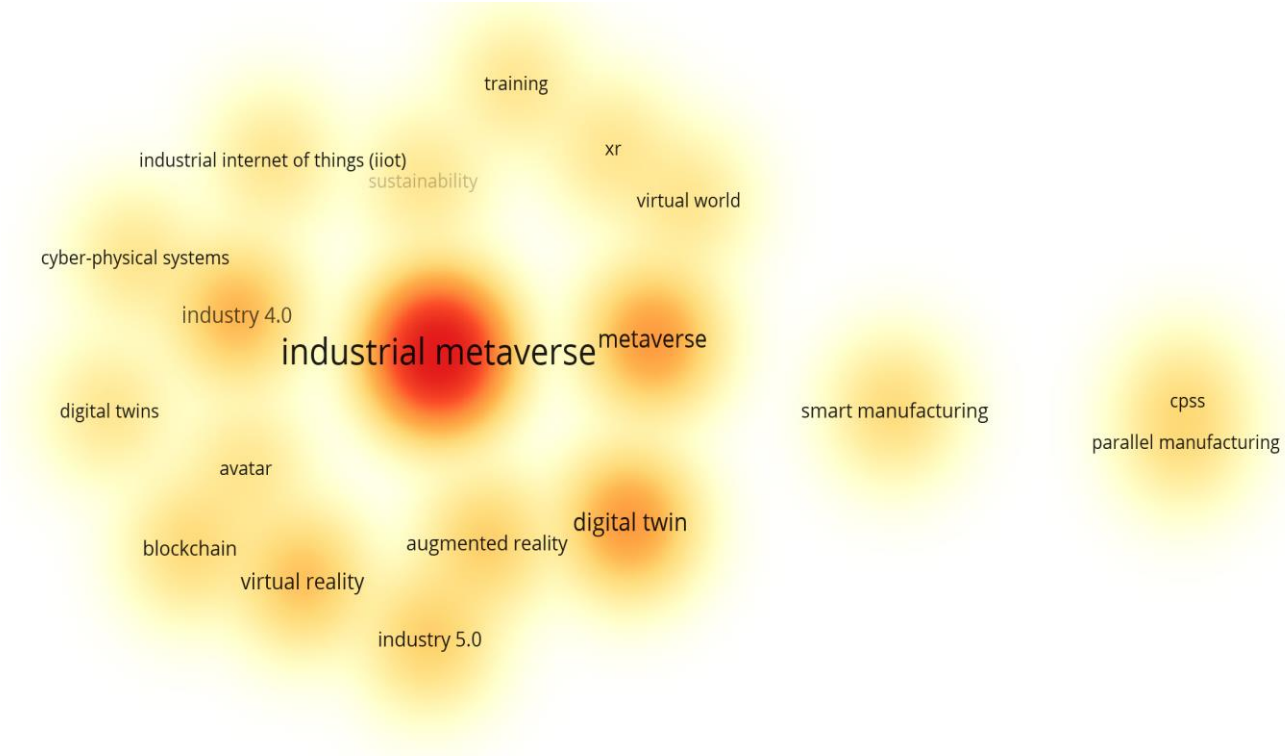

Figure 7. Keyword Co-Occurrence of Studies in the Scopus Database
Note: cpss is an abbreviation of Cyber Physical System Security

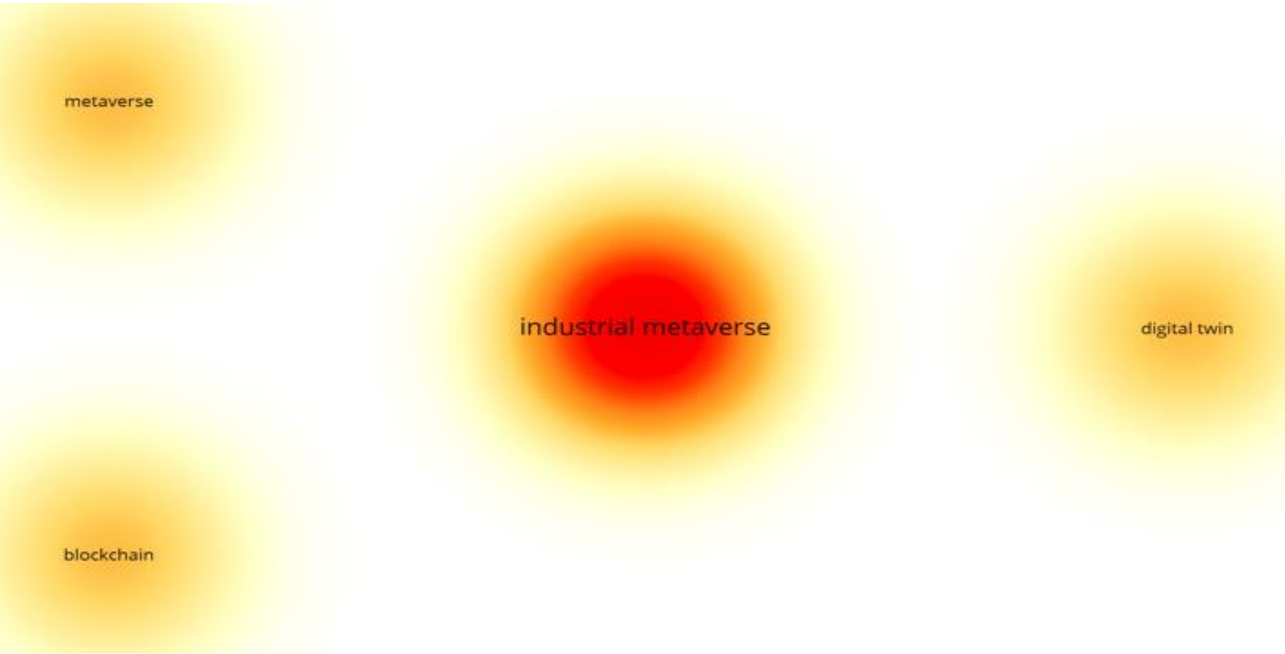

Figure Figure 8. Keyword Co-Occurrence of Studies in the WoS Database

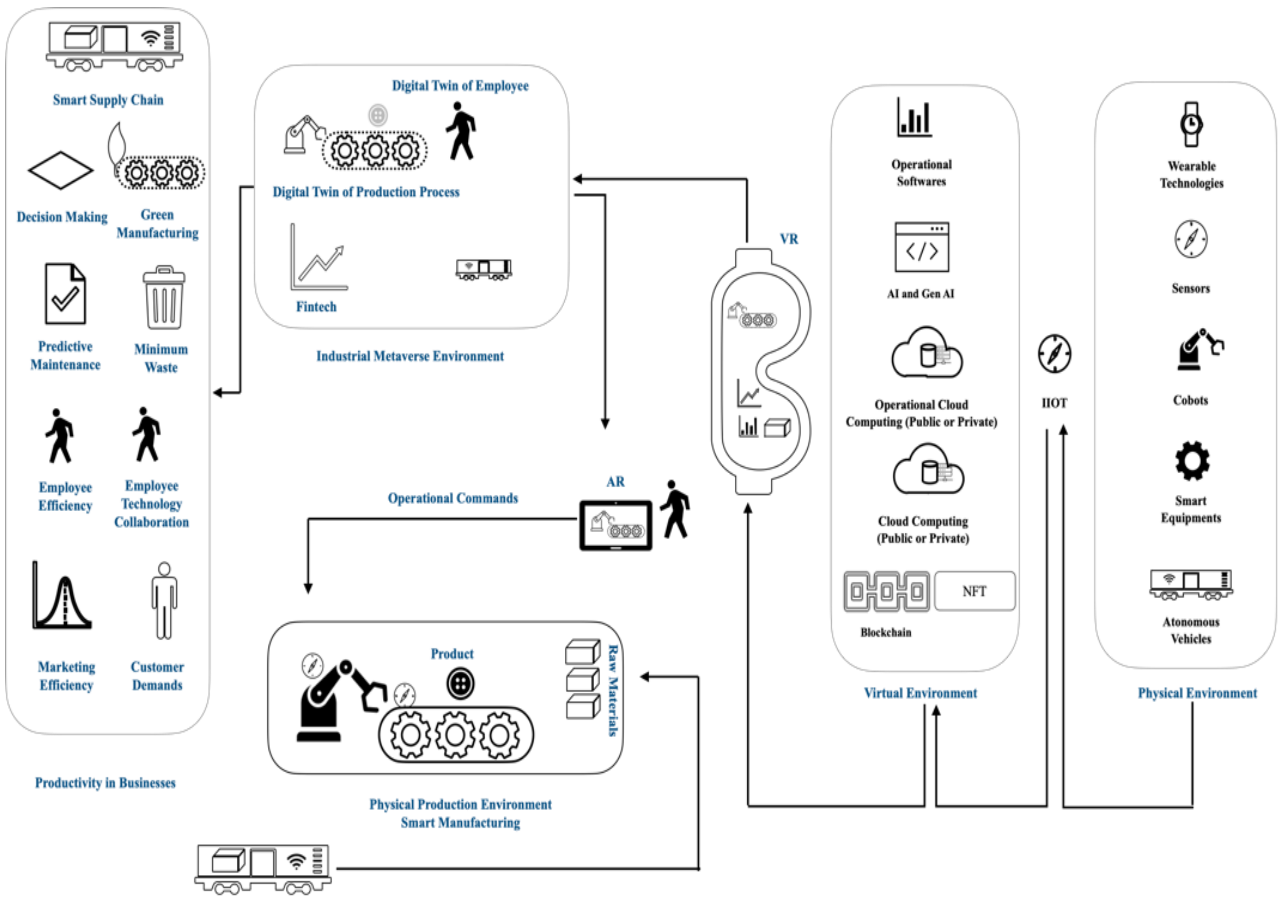

Figure 9. Industrial Metaverse Environment (Source Author Elaboration)

When examining the keyword co-occurrence in the WoS database, a relationship between industrial metaverse technology and the keywords digital twin, blockchain, and metaverse is observed. This relationship indicates that industrial metaverse technology leverages blockchain and digital twin technologies to bring the benefits of metaverse technology to the industrial sector. These findings are supported by the studies of Lyu and Fridenfalk [38] and Ren et al. [7]. Lyu and Fredenfalk examined the relationship between the industrial metaverse and the digital twin. Ren et al. focused on how the industrial metaverse infrastructure can be structured with digital twin, IIoT, and blockchain technologies and how smart manufacturing can be built.

The findings of this study highlight the intricate relationship between various technologies and processes associated with industrial metaverse technology. Industrial metaverse technology is deeply intertwined with smart manufacturing processes, digital twin technology, AI, IIoT, blockchain, and other advanced technologies. The visualisations of keyword relationships in the titles and abstracts of the studies reveal distinct clusters of technologies and concepts. These technologies are driving significant advancements not only in smart manufacturing but also in areas such as marketing, supply chain management, financial applications, and on-the-job employee training. These advancements underscore industrial metaverse technology's versatility and potentialimpact across diverse sectors and business processes. Overall, this study contributes to the existing literature by providing a comprehensive overview of the technologies and processes associated with industrial metaverse technology. The findings offer valuable insights for researchers, businesses, and policymakers looking to understand and leverage the potential of industrial metaverse technology in the digital transformation era. As a result of these findings, Figure 9 is drawn to more clearly illustrate which technologies and processes industrial metaverse technology collaborates with, addressing RQ1.

5. CONCLUSION

The concept of the industrial metaverse encompasses the application of metaverse technology within the industrial sector. A synergy between various technologies, such as digital twins, VR, AR, blockchain, and IIoT, is required to harness industrial metaverse technology effectively. These technologies are pivotal for configuring enterprises' digital transformation processes in alignment with the Industry 5.0 framework. Industrial metaverse technology presents an opportunity to maximise the benefits derived from these technologies by enabling employees and business stakeholders to achieve optimal efficiency in the digital transformation process. This is accomplished by visualising data and knowledge gathered during digital transformation using technologies like VR and AR.

This study conducted a bibliometric analysis of studies on the industrial metaverse added to the Scopus and WoS databases since 2021. This analysis aims to identify the technologies and processes associated with industrial metaverse technologies and provide insights for academics and businesses working in this field. The results indicate that the number of studies and citations in the Scopus database is higher than in the WoS database. The technologies associated with industrial metaverse technology include digital twins, IIoT, VR, AR, XR, blockchain, and AI. Industrial metaverse technology is related to smart manufacturing, employee training, the Industry 5.0 process, and environmental sustainability (green manufacturing) processes.

The findings align with existing literature, which has explored various dimensions of industrial metaverse technology. For instance, Kumar et al. have examined the relationship between the industrial metaverse and organisational agility and business performance, while Kshetri has analysed its economic returns. Ren et al., Xiang et al., and Yang, Wang, and Zhao have investigated the link between the industrial metaverse and smart manufacturing. Kshetri and Dwivedi have studied its relationship with environmental sustainability, and Gattullo et al. have focused on knowledge sharing. Furthermore, Opperman et al. have explored the relationship between the industrial metaverse and remote support and training, while Muller, Bohne, and Jamboula have examined its scope and components. Bharti and Sharma discussed the interaction between avatars and humans in decision-making processes, and Aromaa et al. explored the relationship between the industrial metaverse and human factors.

This study contributes to the literature by offering a comprehensive bibliometric analysis, thereby identifying the core technologies and processes associated with the industrial metaverse. As research on the industrial metaverse continues to grow, more use cases and potential benefits are expected to emerge. The current focus of studies from both databases is on the relationship between industrial metaverse applications and the smart manufacturing process. However, future research exploring the applications of the industrial metaverse in different areas and the technologies that can structure these applications will broaden the scope of this field. For instance, investigating how industrial metaverse technology can be leveraged to enhance remote collaboration, optimise supply chain management, or advance predictive maintenance practices could provide valuable insights and further solidify its role in digital transformation. The potential for real-time data processing and decision-making through like IIoT, digital twins, AI, VR AR, blockchain and NFT advanced technologies and smart processes, combined with the immersive and interactive capabilities of the metaverse, could reshape industrial operations.

A limitation of this study is that only the studies indexed in the Web of Science (WoS) and Scopus databases were examined. Future research encompassing different databases, as well as longitudinal studies tracking the evolution of industrial metaverse applications over time, could enhance the findings of this study. Additionally, case studies and real-world implementations of industrial metaverse technology could provide practical insights and validate the theoretical frameworks developed through bibliometric analysis.

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APPENDIX

Table 3. Study Lists in the WoS Database

Author	Title	Year
Kshetri, N	The Economics of the Industrial Metaverse	2023
Kumar, A; Shankar, A; Behl, A; Gupta, BB; Mavuri, S	**Lights, Camera, Metaverse! Eliciting Intention to Use Industrial Metaverse, Organizational Agility, and Firm Performance**	**2023**
Kshetri, N; Dwivedi, YK	Pollution-reducing and pollution-generating effects of the metaverse	2023
Ren, L; Dong, JB; Zhang, L; Laili, Y; Wang, XK; Qi, Y; Li, BH; Wang, LH; Yang, LT; Deen, MJ	**Industrial Metaverse for Smart Manufacturing: Model, Architecture, and Applications**	**2024**
Laviola, E; Gattullo, M; Manghisi, VM; Fiorentino, M; Uva, AE	Minimal AR: visual asset optimization for the authoring of augmented reality work instructions in manufacturing	2022
Tantawi, K; Fidan, I; Huseynov, O; Musa, Y; Tantawy, A	Advances in industry 4.0: from intelligentization to the industrial metaverse	2024
Jaimini, U; Zhang, TT; Brikis, GO; Sheth, A	iMetaverseKG: Industrial Metaverse Knowledge Graph to Promote Interoperability in Design and Engineering Applications	2022
Gattullo, M; Laviola, E; Evangelista, A; Fiorentino, M; Uva, AE	Towards the Evaluation of Augmented Reality in the Metaverse: Information Presentation Modes	2022
Liu, SG; Xie, JC; Wang, XW	QoE enhancement of the industrial metaverse based on Mixed Reality application optimization*	2023
Hou, J; Chen, G; Li, ZJ; He, W; Gu, SD; Knoll, A; Jiang, CJ	**Hybrid Residual Multiexpert Reinforcement Learning for Spatial Scheduling of High-Density Parking Lots**	**2024**
Patterson, EA	Engineering design and the impact of digital technology from computer-aid engineering to industrial metaverses: A perspective	2024
Siriweera, A; Naruse, K	QoS-Aware Federated Crosschain-Based Model-Driven Reference Architecture for IIoT Sensor Networks in Distributed Manufacturing	2023
Xiang, W; Yu, K; Han, FL; Fang, L; He, DH; Han, QL	**Advanced Manufacturing in Industry 5.0: A Survey of Key Enabling Technologies and Future Trends**	**2024**
Aromaa, S; Heikkilä, P; Kaasinen, E; Lammi, H; Tammela, A; Salminen, K	Human factors and ergonomics considerations in the industrial metaverse	2024
Yao, XF; Ma, NF; Zhang, JM; Wang, KS; Yang, EF; Faccio, M	Enhancing wisdom manufacturing as industrial metaverse for industry and society 5.0	2024
Camacho-Muñoz, GA; Franco, JCM; Nope-Rodríguez, SE; Loaiza-Correa, H; Gil-Parga, S; alvarez-Martínez, D	6D-ViCuT: Six degree-of-freedom visual cuboid tracking dataset for manual packing of cargo in warehouses	2023

Table 4. Study Lists in the Scopus Database

Author	Title	Year
Khanna P.; Karim R.; Kumari J.	Issues and Challenges in Implementing the Metaverse in the Industrial Contexts from a Human-System Interaction Perspective	2024
Lyu Z.; Fridenfalk M.	Digital twins for building industrial metaverse	2023
Liu S.; Xie J.; Wang X.	QoE enhancement of the industrial metaverse based on Mixed Reality application optimization	2023
Bellalouna F.; Puljiz D.	Use case for the Application of the Industrial Metaverse Approach for Engineering Design Review	2023
Martínez-Gutiérrez A.; Díez-González J.; Perez H.; Araújo M.	Towards industry 5.0 through metaverse	2024
Yao X.; Ma N.; Zhang J.; Wang K.; Yang E.; Faccio M.	Enhancing wisdom manufacturing as industrial metaverse for industry and society 5.0	2024
Bharti P.; Sharma V.K.	Avatars in the Metaverse: From Social Interaction to Collaborative Work and Beyond	2024
Endres H.; Indulska M.; Ghosh A.	Unlocking the potential of Industrial Internet of Things (IIOT) in the age of the industrial metaverse: Business models and challenges	2024
Kshetri N.; Dwivedi Y.K.	Pollution-reducing and pollution-generating effects of the metaverse	2023
Ren L.; Dong J.; Zhang L.; Laili Y.; Wang X.; Qi Y.; Li B.H.; Wang L.; Yang L.T.; Deen M.J.	**Industrial Metaverse for Smart Manufacturing: Model, Architecture, and Applications**	**2024**
Wenzheng L.	ConceptĶ Technology Features and System Architecture of Industrial Metaverse	2023
Aung N.; Dhelim S.; Chen L.; Ning H.; Atzori L.; Kechadi T.	Edge-Enabled Metaverse: The Convergence of Metaverse and Mobile Edge Computing	2024
Liu C.; Tang D.; Wang Z.	AR-Driven Industrial Metaverse for the Auxiliary Maintenance of Machine Tools in IoT-Enabled Manufacturing Workshop	2023
Wang X.; Wang Y.; Yang J.; Jia X.; Li L.; Ding W.; Wang F.-Y.	The survey on multi-source data fusion in cyber-physical-social systems: Foundational infrastructure for industrial metaverses and industries 5.0	2024
Kumar A.; Shankar A.; Behl A.; Gupta B.B.; Mavuri S.	**Lights, Camera, Metaverse! Eliciting Intention to Use Industrial Metaverse, Organizational Agility, and Firm Performance**	**2023**
Schultheiß A.; Polovoj E.; Dolanovic S.; Gutsche K.	Digital Service Twin - Design Criteria, Requirements and Scope for Service Management	2023
Kim D.B.; Bajestani M.S.; Shao G.; Jones A.; Noh S.D.	CONCEPTUAL ARCHITECTURE OF DIGITAL TWIN WITH HUMAN-IN-THE-LOOP - BASED SMART MANUFACTURING	2023
Ahr P.; Dreyer J.; Reski M.; Lipps C.; Tönjes R.; Schotten H.D.	Industry 4.0 Security Trust Anchors: Considering Supply Voltage Effects on SRAM-PUF Reliability	2023
Siriweera A.; Naruse K.	QoS-Aware Federated Crosschain-Based Model-Driven Reference Architecture for IIoT Sensor Networks in Distributed Manufacturing	2023
Nateghi A.; Mosharraf M.	Architecting the Future: A Model for Enterprise Integration in the Metaverse	2023
Bharti P.; Sharma V.K.	Enhancing Decision-Making: The Significance of Humanized Avatars in Complex Scenarios	2024
Rosilius M.; Wilhelm M.; von Eitzen I.; Decker S.; Damek S.; Braeutigam V.	Sustainable Solutions by the Use of Immersive Technologies for Repurposing Buildings	2023
Hou J.; Chen G.; Li Z.; He W.; Gu S.; Knoll A.; Jiang C.	**Hybrid Residual Multiexpert Reinforcement Learning for Spatial Scheduling of High-Density Parking Lots**	**2024**
Zhou Y.; Li T.; Li B.; Wu G.; Meng X.; Guo J.; Wan N.; Zhu J.; Li S.; Song W.; Su C.; Chen N.; Xing Y.; Wang Q.; Lin Y.; Li R.	Research on Intelligent Manufacturing Training System Based on Industrial Metaverse	2024
Salminen K.; Aromaa S.	Industrial metaverse - company perspectives	2024
Huang S.; Luo H.; Zheng P.; Ma N.; Chen J.; Mo G.; Jing S.	Towards Industrial Metaverse: Opportunities and challenges	2023
Ullrich M.; Thalappully R.; Heieck F.; Lüdemann-Ravit B.	Virtual Commissioning of Linked Cells Using Digital Models in an Industrial Metaverse	2024
Ullrich M.; Heller J.; Knüpper J.; Lüdemann-Ravit B.	A Reference Architecture for an Industrial Metaverse; [Eine Referenzarchitektur für das Industrial Metaverse]	2024
Jiang Y.; Kaynak O.; Yin S.; Luo H.; Liu M.	Industrial Metaverse: Solutions from a Higher-Dimensional World	2024
Laviola E.; Gattullo M.; Manghisi V.M.; Fiorentino M.; Uva A.E.	Minimal AR: visual asset optimization for the authoring of augmented reality work instructions in manufacturing	2022
Oppermann L.; Uzun Y.; Buchholz F.; Riedlinger U.; Fuchs S.; Stenzel H.; Odenthal L.; Altepost A.; Bau M.	Industrial Metaverse? Human-Centred Design for Collaborative Remote Maintenance and Training Using XR-Technologies	2024
Yang J.; Wang X.; Zhao Y.	Parallel Manufacturing for Industrial Metaverses: A New Paradigm in Smart Manufacturing	2022
Aromaa S.; Heikkilä P.; Kaasinen E.; Lammi H.; Tammela A.; Salminen K.	Human factors and ergonomics considerations in the industrial metaverse	2024
Muller M.; Bohne T.; Jamboula T.	Identifying key factors for the development of the Industrial Metaverse	2023

Tantawi K.; Fidan I.; Huseynov O.; Musa Y.; Tantawy A.	Advances in industry 4.0: from intelligentization to the industrial metaverse	2024
Huang J.	Control and Decision Theory in the Metaverse: A Survey; [元宇宙下的控制与决策综述]	2023
Gattullo M.; Laviola E.; Evangelista A.; Fiorentino M.; Uva A.E.	Towards the Evaluation of Augmented Reality in the Metaverse: Information Presentation Modes	2022
Xiang W.; Yu K.; Han F.; Fang L.; He D.; Han Q.-L.	**Advanced Manufacturing in Industry 5.0: A Survey of Key Enabling Technologies and Future Trends**	**2024**
Patterson E.A.	Engineering design and the impact of digital technology from computer-aided engineering to industrial metaverses: A perspective	2024
Xie J.; Zheng Z.; Wang X.; Meng H.; Liu S.; Li S.	Preliminary research on the operation mode of virtual-real integration in fully-mechanized mining face based on industrial metaverse; [基于工业元宇宙的综采工作面虚实融合运行模式初步探索]	2023
Zheng Z.; Li T.; Li B.; Chai X.; Song W.; Chen N.; Zhou Y.; Lin Y.; Li R.	Industrial Metaverse: Connotation, Features, Technologies, Applications and Challenges	2022
Zhao S.X.; Qiao L.; Zhang R.J.; Zhang H.H.; Ye F.Y.	The Theoretical Principles and Practical Scenarios for Exploring Metaverse	2022
Prummer M.; Regnath E.; Singh S.; Kosch H.	From Virtual Worlds to Real-World Impact: An Industrial Metaverse Survey	2024
Camacho-Muñoz G.A.; Franco J.C.M.; Nope-Rodríguez S.E.; Loaiza-Correa H.; Gil-Parga S.; Álvarez-Martínez D.	6D-ViCuT: Six degree-of-freedom visual cuboid tracking dataset for manual packing of cargo in warehouses	2023