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Postgraduate Dissertation

Exploring the Integration of the Metaverse in Supply Chain
Management: A Literature Review

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Patras, Greece, June 2024

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Abstract

The integration of metaverse technologies into supply chain management (SCM) represents a groundbreaking shift towards a more interconnected and efficient system. This master thesis conducts a comprehensive literature review on the transformative potential of metaverse technologies in SCM, exploring the application of virtual reality (VR), augmented reality (AR), blockchain, and digital twins. These technologies offer enhanced operational efficiencies, transparency, and resilience in SCM by facilitating real-time data sharing, immersive simulations, and improved collaboration among stakeholders.

The study reveals significant advancements in key SCM domains such as logistics, inventory management, and distribution. Metaverse technologies enable better visibility and traceability, optimize logistics operations, and enhance inventory accuracy through digital twins and AR-based systems. Furthermore, the secure and immutable nature of blockchain technology provides a robust framework for transaction authentication and fraud prevention, contributing to more reliable and transparent supply chains.

Despite these promising developments, the integration of metaverse technologies in SCM faces several challenges, including technological interoperability, data security, regulatory compliance, and high implementation costs. The literature highlights a need for standardized protocols and frameworks to ensure seamless integration across diverse systems and regions.

This thesis identifies a gap in the existing research regarding the comprehensive assessment of the economic, environmental, and social impacts of metaverse technologies in SCM. Future research should focus on developing scalable solutions and addressing legal and ethical considerations to support the sustainable deployment of these technologies. Additionally, practical case studies and empirical research are essential to demonstrate the real-world benefits of metaverse integration in SCM, such as cost reduction and enhanced sustainability.

By addressing the current challenges and exploring innovative applications, metaverse technologies can significantly contribute to the evolution of more agile, resilient, and efficient supply chains capable of meeting the dynamic demands of the global market.

Keywords

Metaverse, supply chain management, virtual reality, smart contracts, blockchain, supply chain digitalization, Digital Twins

Εξερευνώντας την ενσωμάτωση του Metaverse στη Διαχείριση Εφοδιαστικής Αλυσίδας: Βιβλιογραφική Ανασκόπηση

Σπυρίδων Α. Μπακατσέλος

Περίληψη

Η ενσωμάτωση των τεχνολογιών metaverse στη διαχείριση της εφοδιαστικής αλυσίδας (SCM) αντιπροσωπεύει μια πρωτοποριακή στροφή προς ένα πιο διασυνδεδεμένο και αποτελεσματικό σύστημα. Αυτή η μεταπτυχιακή διατριβή διεξάγει μια περιεκτική βιβλιογραφική ανασκόπηση σχετικά με το μετασχηματιστικό δυναμικό των τεχνολογιών μετασχηματισμού στη διοίκηση εφοδιαστικής αλυσίδας, διερευνώντας την εφαρμογή τεχνολογιών του metaverse όπως της εικονικής πραγματικότητας (VR), της επαυξημένης πραγματικότητας (AR), του Blockchain και του Digital Twins. Αυτές οι τεχνολογίες προσφέρουν βελτιωμένη λειτουργική αποτελεσματικότητα, διαφάνεια και ανθεκτικότητα στις εφοδιαστικές αλυσίδες διευκολύνοντας την ανταλλαγή δεδομένων σε πραγματικό χρόνο, τις καθηλωτικές προσομοιώσεις και τη βελτιωμένη συνεργασία μεταξύ των ενδιαφερομένων. Η μελέτη αποκαλύπτει σημαντικές προόδους σε βασικούς τομείς, όπως ο εφοδιασμός, η διαχείριση αποθεμάτων και η διανομή. Οι τεχνολογίες Metaverse επιτρέπουν καλύτερη ορατότητα και ιχνηλασιμότητα, βελτιστοποιούν τις λειτουργίες των logistics και ενισχύουν την ακρίβεια του αποθέματος μέσω ψηφιακών δίδυμων συστημάτων και συστημάτων που βασίζονται σε AR. Επιπλέον, η ασφαλής και αμετάβλητη φύση της τεχνολογίας blockchain παρέχει ένα ισχυρό πλαίσιο για τον έλεγχο ταυτότητας των συναλλαγών και την πρόληψη της απάτης, συμβάλλοντας σε πιο αξιόπιστες και διαφανείς αλυσίδες εφοδιασμού. Παρά αυτές τις ελπιδοφόρες εξελίξεις, η ενσωμάτωση των τεχνολογιών metaverse στο SCM αντιμετωπίζει πολλές προκλήσεις, όπως η τεχνολογική διαλειτουργικότητα, η ασφάλεια δεδομένων, η κανονιστική συμμόρφωση και το υψηλό κόστος εφαρμογής. Η βιβλιογραφία υπογραμμίζει την ανάγκη για τυποποιημένα πρωτόκολλα και πλαίσια για την εξασφάλιση απρόσκοπτης ενοποίησης σε διάφορα συστήματα και περιοχές. Αυτή η διατριβή εντοπίζει ένα κενό στην υπάρχουσα έρευνα σχετικά με την ολοκληρωμένη αξιολόγηση των οικονομικών, περιβαλλοντικών

και κοινωνικών επιπτώσεων των τεχνολογιών μετασύνδεσης στην εφοδιαστική αλυσίδα. Η μελλοντική έρευνα θα πρέπει να επικεντρωθεί στην ανάπτυξη επεκτάσιμων λύσεων και στην αντιμετώπιση νομικών και ηθικών ζητημάτων για την υποστήριξη της βιώσιμης ανάπτυξης αυτών των τεχνολογιών. Επιπλέον, οι πρακτικές περιπτώσιολογικές μελέτες και η εμπειρική έρευνα είναι απαραίτητες για την επίδειξη των πραγματικών πλεονεκτημάτων της ενσωμάτωσης μετασυμπτώσεων στην εφοδιαστική αλυσίδα, όπως η μείωση του κόστους και η βελτιωμένη βιωσιμότητα. Αντιμετωπίζοντας τις τρέχουσες προκλήσεις και εξερευνώντας καινοτόμες εφαρμογές, οι τεχνολογίες metaverse μπορούν να συμβάλουν σημαντικά στην εξέλιξη πιο ευέλικτων, ανθεκτικών και αποτελεσματικών αλυσίδων εφοδιασμού ικανών να ανταποκριθούν στις δυναμικές απαιτήσεις της παγκόσμιας αγοράς.

Λέξεις – Κλειδιά

Μετασύμπαν, διοίκηση εφοδιαστικής αλυσίδας, ψηφιακή πραγματικότητα, έξυπνα συμβόλαια, blockchain, ψηφιοποίηση εφοδιαστικής αλυσίδας, τεχνολογία ψηφιακών διδύμων

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List of Abbreviations & Acronyms

1. ABS Agent-Based Simulation, used for simulating complex systems.
2. AI Artificial Intelligence, used for predictive analytics and process optimization.
3. AIOT Artificial Intelligence of Things, combining AI and IoT for advanced data analytics.
4. AR Augmented Reality, blockchain, and digital twins, offering enhanced operational efficiencies.
5. BI Business Intelligence, technologies for analyzing data and presenting actionable information.
6. BIG Refers to Big Data, crucial for analyzing large datasets in supply chain management.
7. BLOCKCHAIN Blockchain, providing secure, transparent, and immutable transaction records.
8. CAD Computer-Aided Design, used for creating digital models in engineering.
9. CCPS Cognitive Cyber-Physical Systems, contributing to sustainable and efficient supply chains.
10. CPS Cyber-Physical System, integrating computation with physical processes.
11. DL Deep Learning, a subset of machine learning using neural networks with many layers.
12. DLT Distributed Ledger Technology, enabling secure decentralized transactions.
13. DT Digital Twin, creating virtual models of physical assets for improved management.
14. ERP Enterprise Resource Planning, software for managing business processes.
15. GIS Geographic Information System, used for mapping and analyzing spatial data.
16. GPS Global Positioning System, used for navigation and location tracking.
17. HTTPS Hypertext Transfer Protocol Secure, used for secure communication over the internet.
18. ICT Information and Communication Technology, key for enabling real-time data sharing.
19. IIOT Industrial Internet of Things, applying IoT in industrial contexts.
20. IOMT Internet of Medical Things, applying IoT to healthcare.
21. IoMT Internet of Medical Things, an application of IoT in the healthcare industry.
22. IOT Internet of Things, integrating physical assets into digital networks.
23. JIT Just-In-Time, an inventory management strategy to increase efficiency and decrease waste.

- 24. KPI Key Performance Indicator, a measurable value that demonstrates how effectively a company is achieving key business objectives.
- 25. MILP Mixed-Integer Linear Programming, a method used in logistics optimization.
- 26. ML Machine Learning, a key component in digital transformation in supply chains.
- 27. NTF Non-Fungible Token, a digital asset used for ownership verification.
- 28. PLC Programmable Logic Controller, used in automation for industrial control systems.
- 29. RFID Radio Frequency Identification, used for tracking and identifying objects.
- 30. ROI Return on Investment, a measure of profitability.
- 31. SCM Supply Chain Management, representing a shift towards a more interconnected and efficient system.
- 32. SCOM Supply Chain and Operations Management, proposing frameworks for digital integration.
- 33. SDC Software-Defined Cloud, a cloud infrastructure management technology.

- 34. TQM Total Quality Management, a management approach for long-term success through customer satisfaction.
- 35. VR Virtual Reality, including augmented reality (AR), blockchain, and digital twins.
- 36. VRAR Virtual Reality and Augmented Reality, technologies for creating immersive user experiences.
- 37. VSC Virtual Supply Chain, enhancing supply chain visibility and performance.
- 38. XR Extended Reality, enhancing immersive experiences.

1. Introduction

The emergence of the metaverse as an interconnected, virtual environment where digital and physical realities converge has initiated profound transformations across multiple industries, including supply chain management (SCM). The metaverse is not merely a concept of virtual worlds but encompasses a wide array of technologies such as blockchain, digital twins, augmented reality (AR), virtual reality (VR), and the Internet of Things (IoT). These technologies collectively offer novel opportunities to enhance operational efficiencies, transparency, and resilience in supply chain processes.

Supply chain management, which involves the coordination and management of activities from raw material procurement to product delivery to end consumers, is a complex and dynamic field that stands to benefit significantly from metaverse technologies. The integration of metaverse technologies into SCM can revolutionize traditional practices by facilitating real-time data sharing, immersive simulations, and enhanced collaboration among stakeholders. The application of these technologies can improve supply chain visibility, optimize logistics operations, and enhance inventory management, leading to more agile and responsive supply chains.

1.1 Research Problem

Despite the significant potential of metaverse technologies to transform supply chain management, the implementation of these technologies presents several challenges. These include technological, economic, and regulatory barriers, as well as issues related to data security and user acceptance. Currently, there is a lack of comprehensive research that addresses the practical implications of integrating metaverse technologies into supply chain processes. This research aims to bridge this gap by exploring the impact of metaverse technologies on SCM, identifying key applications, and evaluating the benefits and challenges associated with their adoption.

1.2 Objectives of the Study

The primary objective of this study is to investigate the integration of metaverse technologies into supply chain management, providing a comprehensive overview of their implications and potential benefits. The specific objectives include:

- To identify and analyze the key metaverse technologies relevant to supply chain management and their applications across different domains.
- To assess the impact of these technologies on supply chain processes, focusing on logistics, inventory management, and customer relations.
- To explore the challenges and barriers to the successful adoption of metaverse technologies in SCM.
- To propose practical recommendations for supply chain professionals and policymakers on leveraging metaverse technologies to enhance operational efficiency and resilience.

1.2.1 Structure of the Thesis

This thesis is structured into six chapters, with each chapter focusing on a different aspect of the research:

Chapter 1: Introduction – Provides an overview of the research background, problem, objectives, scope, and structure.

Chapter 2: Methodology – Describes the research methodology, including the criteria for literature selection and the analytical framework used.

Chapter 3: Literature Review – Reviews existing research on the integration of metaverse technologies in supply chain management, identifying key themes and trends.

Chapter 4: Discussion – Discusses the practical implications of the findings, exploring the benefits, challenges, and strategies for integrating metaverse technologies into supply chains.

Chapter 5: Conclusion and Recommendations – Summarizes the key findings, offers practical recommendations, and suggests areas for future research

2. Supply Chain Digitalization and Metaverse Technologies

2.1 Supply Chain Digitalization

In the contemporary business landscape, the digitalization of supply chains stands out as a pivotal trend that is reshaping the way organizations operate. This transformation involves the integration of digital technologies into every facet of supply chain management, resulting in enhanced efficiency, transparency, and agility. Digitalization is not merely a technological upgrade but a fundamental shift that necessitates a strategic overhaul of supply chain processes and systems. This paper provides a comprehensive overview of the digitalization of supply chains, drawing on insights from various sources to explore its impacts, benefits, challenges, and future prospects (37).

2.1.1 Impact on Supply Chain Management

Digitalization has a profound impact on supply chain management by enabling real-time data access and facilitating more informed decision-making (47). The integration of digital tools allows for seamless communication and coordination among supply chain stakeholders, reducing inefficiencies and enhancing operational effectiveness. For instance, digital platforms provide real-time tracking of goods and inventory, which mitigates risks such as stockouts or overstocking and allows for more accurate demand forecasting. This capability is particularly important in today's globalized market, where supply chains are becoming increasingly complex and dynamic.

Digitalization also supports the optimization of supply chain processes through the use of predictive analytics. These tools can analyze vast amounts of data to identify trends and patterns, helping organizations to anticipate changes in demand and adjust their supply chain strategies accordingly. This level of foresight is critical for maintaining competitive advantage in a rapidly changing market environment. Moreover, digitalization enables more efficient resource management by providing greater visibility into supply chain operations, allowing for better allocation of resources and reduction of waste.

2.1.2 Enhancing Supply Chain Resilience

One of the key advantages of digitalization is its role in enhancing supply chain resilience. In an era marked by frequent disruptions, ranging from natural disasters to geopolitical uncertainties, the ability to anticipate and respond to these disruptions is crucial. Digital tools enable organizations to create digital twins of their supply chains, which are virtual replicas of physical assets, processes, and systems. These digital twins allow for the simulation of different scenarios and identification of potential risks, enabling organizations to develop more robust strategies for managing disruptions and maintaining continuity of operations.

Furthermore, digital platforms provide greater visibility into supply chain operations, allowing organizations to quickly identify and address issues. This increased agility and responsiveness are critical for minimizing the impact of disruptions and ensuring that supply chain activities continue smoothly. For example, real-time monitoring of supply chain activities can help organizations to quickly identify bottlenecks or delays and take corrective action to prevent further disruptions. This capability is particularly important in industries with complex and time-sensitive supply chains, such as the agri-food sector, where delays can result in significant financial losses and impact the quality and safety of products.

2.1.3 Improving Supply Chain Efficiency

Digitalization significantly enhances the efficiency of supply chain operations by streamlining processes and improving coordination among supply chain partners. Digital tools such as automated inventory management systems and real-time tracking platforms enable more precise control over supply chain activities, reducing lead times and minimizing costs. This leads to improved operational efficiency and better customer service, which are critical for maintaining a competitive edge in the market.

In addition, digital platforms facilitate better communication and collaboration among supply chain stakeholders, enabling more effective management of supply chain activities. For example, cloud-based platforms allow for real-time data sharing and collaboration among supply chain partners, which helps to streamline processes and reduce lead times.

This capability is particularly important in industries where supply chains are complex and involve multiple stakeholders, such as the automotive industry, where coordination among suppliers, manufacturers, and distributors is critical for ensuring the timely delivery of products to customers.

Digitalization also supports more flexible and scalable supply chain models, allowing organizations to quickly ramp up or down their operations as needed. This flexibility is crucial in today's fast-paced business environment, where market conditions can change rapidly and demand can fluctuate unpredictably. For example, digital tools can enable more efficient management of inventory levels, allowing organizations to quickly adjust their stock levels in response to changes in demand. This capability is particularly important in industries with perishable products, such as the agri-food sector, where maintaining the right balance of inventory is critical for minimizing waste and ensuring the timely delivery of fresh products to customers.

2.1.4 Challenges in Implementing Digitalization

Despite its numerous benefits, the implementation of digitalization in supply chains is fraught with challenges. One of the primary obstacles is the significant investment required in technology and infrastructure. Organizations must invest in digital tools, data management systems, and the training of personnel to effectively leverage these technologies. This can be a significant financial burden, particularly for smaller organizations with limited resources. Moreover, the integration of digital technologies into existing supply chain systems can be complex and requires careful planning and execution to ensure compatibility and interoperability.

There is also the issue of data security and privacy. The increased use of digital tools exposes supply chains to potential cyber threats, which can compromise sensitive data and disrupt supply chain operations. Organizations must implement robust security measures to protect their data and ensure the integrity of their supply chain operations. This includes investing in cybersecurity tools and technologies, as well as developing comprehensive data security policies and procedures.

Another challenge is the need for a cultural shift within organizations. The successful implementation of digitalization requires a change in mindset, where organizations move away from traditional ways of working and embrace a more data-driven and collaborative approach. This requires the support and buy-in of all stakeholders, from senior management to front-line employees. Organizations must invest in training and development to ensure that their workforce has the necessary skills and expertise to effectively use and manage digital tools.

2.2 The Metaverse: An In-depth Analysis

The metaverse represents a pioneering frontier in digital innovation, encapsulating a virtual, three-dimensional, shared environment that amalgamates a range of advanced technologies to enable realistic personal and business interactions online. As a sophisticated digital ecosystem, the metaverse leverages augmented reality (AR), virtual reality (VR), blockchain, and artificial intelligence (AI), offering an immersive experience that transcends traditional boundaries of online interaction. Originally coined in a science fiction narrative in the early 1990s, the concept of the metaverse has significantly evolved, reflecting contemporary advancements in digital transformation (35).

2.2.1 Definitional Framework and Conceptual Underpinnings

Fundamentally, the metaverse is an interconnected digital space where users, represented by avatars, can interact with one another and with the environment using various smart devices, including smartphones and VR headsets. This virtual realm offers a continuum of experiences that mimic and extend real-world interactions, thereby creating an intricate digital universe that integrates multiple virtual environments. The metaverse is characterized by its persistence, interoperability, and immersive nature, enabling seamless transitions between different virtual spaces and continuity of digital identity and assets.

This virtual ecosystem is not merely a collection of disparate digital spaces but a comprehensive platform that facilitates a diverse range of activities, from social interaction and business meetings to educational training and entertainment. The persistent and interconnected nature of the metaverse ensures that users can carry their digital presence

across various platforms, fostering a cohesive and immersive experience that is revolutionizing digital engagement.

2.2.2 Technological Foundations

The realization of the metaverse is underpinned by a confluence of cutting-edge technologies, each contributing to its comprehensive and immersive nature:

Augmented Reality (AR): AR enhances the real-world environment by overlaying it with computer-generated sensory inputs, creating a hybrid experience that enriches user interactions.

Virtual Reality (VR): VR creates entirely virtual spaces where users can interact with digital environments and objects, providing a fully immersive experience.

Blockchain Technology: This technology ensures secure, transparent transactions and supports the creation and exchange of digital assets, which are fundamental to the metaverse's economic infrastructure.

Artificial Intelligence (AI): AI drives various aspects of the metaverse, including personalized user experiences, environment interactivity, and dynamic avatar behavior.

Cloud Computing: Cloud infrastructure supports the extensive data processing and storage needs of the metaverse, facilitating real-time interaction and data continuity across platforms.

These technologies converge to create a digital infrastructure that supports the metaverse's expansive and interconnected environments, providing a platform for continuous innovation and interaction.

2.2.3 Applications and Strategic Implications

The metaverse holds transformative potential across multiple sectors, offering new paradigms for interaction and engagement:

- **Commerce and Business:** The metaverse enables businesses to create virtual storefronts, conduct meetings, and engage with customers in a highly immersive and interactive manner. Major corporations like Amazon, Google, and Apple are heavily investing in metaverse

technologies, recognizing the potential for enhanced customer engagement and operational efficiency.

- **Education:** Educational institutions can leverage the metaverse for virtual classrooms, simulations, and interactive learning, making education more accessible and engaging while providing students with experiential learning opportunities.
- **Healthcare:** The metaverse offers innovative applications in telemedicine, medical training, and therapy, expanding the scope of healthcare delivery and patient engagement through immersive digital experiences.
- **Entertainment and Social Interaction:** The metaverse provides new avenues for entertainment and socialization, such as virtual concerts, digital worlds exploration, and community engagement, redefining the landscape of entertainment and social interaction.
- **Operations and Supply Chain Management (O&SCM):** In O&SCM, the metaverse is poised to revolutionize the way goods are sourced, manufactured, and distributed by enhancing collaboration, improving supply chain visibility, and enabling real-time data sharing and decision-making. Despite its nascent stage in this field, the metaverse presents significant opportunities for operational optimization and innovation.

2.3 Foundational Technologies and Innovations Driving the Metaverse

The metaverse represents a convergence of multiple advanced technologies, each contributing uniquely to the creation of an expansive, immersive, and interconnected virtual universe. This chapter delves into the critical technological pillars that underpin the metaverse, providing a comprehensive overview of their roles, functionalities, and impacts. The metaverse is not a singular technological advancement but a complex ecosystem where Virtual Reality (VR) and Augmented Reality (AR) serve as the sensory interfaces that immerse users in digital realms and overlay digital enhancements onto the physical world. Blockchain technology and Non-Fungible Tokens (NFTs) establish the infrastructure for a secure and decentralized digital economy, ensuring ownership, scarcity, and monetization of virtual assets.

The advent of 5G and Edge Computing revolutionizes data transmission and processing, offering the necessary speed and low latency for real-time, high-fidelity virtual interactions. Artificial Intelligence (AI) brings dynamic responsiveness and personalization, driving

smarter and more adaptive virtual environments. 3D modeling and Digital Twin Technologies facilitate the creation and simulation of intricate virtual replicas of physical entities, enabling robust planning and experimentation within digital spaces. Finally, Spatial Computing bridges the gap between the physical and digital, allowing for natural and intuitive interactions with the virtual world.

Through this exploration, we will uncover how these technologies collectively shape the metaverse, highlighting their synergistic roles in fostering a seamless and expansive digital future. The integration of these technologies not only enhances the metaverse experience but also propels the evolution of digital interactions and economies, positioning the metaverse as a transformative force in both technological innovation and societal evolution.

1. Virtual Reality (VR)

Virtual Reality is a foundational technology for the metaverse, offering immersive experiences by simulating a 3D environment that users can interact with through VR headsets and controllers. These devices track head and hand movements, creating a sense of presence in a virtual space. Provide access to virtual worlds for gaming, social interaction, education, and more. VR's potential in the metaverse includes enhancing remote work, providing virtual tourism, and enabling immersive training and simulations, making it an essential tool for creating interconnected virtual spaces (34), (42). simulated environments. By enabling users to engage with digital spaces as though they were physically present, VR facilitates innovative approaches in various domains such as education, healthcare, and business. In education, VR can provide students with interactive and immersive learning experiences, allowing them to explore complex concepts and environments in a controlled and engaging manner. In healthcare, VR can assist in training medical professionals by simulating surgeries and other medical procedures, thereby increasing precision and reducing risks. In business, VR can revolutionize training and recruitment processes, product prototyping, and virtual meetings by providing realistic simulations of real-world scenarios. Empirical studies underscore the significant impact of VR on enhancing organizational performance, user engagement, and educational outcomes, while also highlighting the necessity for further research to address the ethical, privacy, and technical challenges inherent in its widespread implementation. As VR continues to evolve, its potential to create enriched and interactive experiences in both professional and everyday

contexts becomes increasingly apparent, marking a pivotal advancement in the realm of digital interaction and simulation (14).

2. Augmented Reality (AR)

Augmented Reality overlays digital content onto the real world, enhancing users' perception and interaction with their surroundings. Unlike VR, which creates a completely virtual environment, AR integrates digital elements with the physical world using devices like smartphones, tablets, or AR glasses. Technologies like Apple's ARKit and Google's ARCore enable developers to create AR experiences for various applications, from gaming and entertainment to education and retail. In the metaverse, AR can blend physical and virtual realities, allowing for hybrid experiences where users can interact with both real and digital objects seamlessly (42). Represents a transformative paradigm within contemporary digital interaction, integrating sophisticated computer-generated perceptual information to enhance real-world environments. By overlaying digital content onto the physical world, AR facilitates innovative approaches in various domains such as manufacturing, navigation, healthcare, and interactive marketing. For instance, in education, AR can provide students with interactive and immersive learning experiences, making abstract concepts tangible and engaging. In healthcare, AR can assist in surgeries by overlaying critical information onto the surgeon's view, thereby increasing precision and reducing risks. In business, AR can revolutionize marketing strategies by allowing consumers to visualize products in their real environment before making a purchase. Empirical studies underscore the significant impact of AR on enhancing organizational performance, user engagement, and educational outcomes, while also highlighting the necessity for further research to address the ethical, privacy, and technical challenges inherent in its widespread implementation. As AR continues to evolve, its potential to create enriched and interactive experiences in both professional and everyday contexts becomes increasingly apparent, marking a pivotal advancement in the digital enhancement of the physical world (14).

3. Blockchain and NFTs

Blockchain technology underpins the decentralized nature of the metaverse by providing a secure and transparent method for recording transactions and data. Non-Fungible Tokens (NFTs), unique digital assets verified using blockchain, are integral to the metaverse, enabling true ownership of virtual goods, such as virtual land, avatars, and collectibles.

Platforms like Ethereum and Binance Smart Chain facilitate the creation and exchange of NFTs. These technologies ensure that digital assets in the metaverse are scarce, tradable, and secure, thus enabling a new digital economy where users can own and monetize their creations (40).

4. 5G and Edge Computing

5G and Edge Computing are critical for the metaverse's infrastructure, offering high-speed, low-latency internet connectivity and efficient data processing closer to the user. 5G networks provide the bandwidth necessary for real-time interactions and high-quality streaming in virtual environments, while edge computing processes data at local servers, reducing the time it takes for information to travel to and from the cloud. This combination supports the seamless operation of metaverse applications, ensuring that users experience minimal lag and uninterrupted access to immersive content and services, even on mobile devices (37),(44).

5. Artificial Intelligence (AI)

Artificial Intelligence plays a crucial role in the metaverse by enabling smarter, more responsive virtual environments and characters. AI technologies, including machine learning, natural language processing, and computer vision, are used to create realistic simulations, enhance user interactions, and provide personalized experiences. For example, AI-driven avatars can interact naturally with users, adapt to their preferences, and assist in navigating virtual spaces. Moreover, AI can automate the creation of vast, dynamic virtual worlds, ensuring that the metaverse is rich, diverse, and continuously evolving to meet users' needs and expectations (36), (38), (43). Artificial Intelligence (AI) represents a transformative paradigm within contemporary digital interaction, integrating sophisticated algorithms and machine learning techniques to enhance decision-making processes and automate complex tasks. By enabling systems to learn from data, adapt to new inputs, and perform human-like tasks, AI facilitates innovative approaches in various domains such as healthcare, finance, education, and business. In healthcare, AI can assist in diagnosing diseases, personalizing treatment plans, and predicting patient outcomes, thereby increasing precision and reducing risks. In finance, AI-driven algorithms can analyze market trends, manage risks, and optimize investment strategies, enhancing efficiency and profitability. In education, AI can provide personalized learning experiences, identify student needs, and

automate administrative tasks, making education more accessible and tailored. In business, AI can revolutionize operations by improving customer service through chatbots, optimizing supply chains, and enabling predictive maintenance. Empirical studies underscore the significant impact of AI on enhancing organizational performance, user engagement, and decision-making, while also highlighting the necessity for further research to address the ethical, privacy, and technical challenges inherent in its widespread implementation. As AI continues to evolve, its potential to create enriched and interactive experiences in both professional and everyday contexts becomes increasingly apparent, marking a pivotal advancement in the realm of digital enhancement and automation (14).

6. 3D Modeling and Digital Twin Technologies

3D modeling and digital twin technologies are essential for creating and maintaining the virtual worlds within the metaverse. 3D modeling involves the creation of detailed, lifelike representations of objects, environments, and characters using software like Blender, Maya, or Unity. Digital twins are virtual replicas of physical entities that can simulate and analyze real-world processes. These technologies allow for the accurate depiction of both fictional and real-world scenarios in the metaverse, facilitating activities like virtual construction, product testing, and complex simulations that mirror real-world conditions and behaviors (16), (36), (39), (17). Digital twins in the context of supply chain (SC) management are advanced digital models that represent the SC network in real-time, providing comprehensive end-to-end visibility. These models integrate multiple layers of the SC, including network structure, internal logistics, process control, and external logistics, and are continuously updated through real-time connectivity with external systems and databases. Incorporating optimization and data analytics, digital twins are descriptive, predictive, and prescriptive, offering significant benefits such as enhanced visibility, mitigation of the bullwhip effect, and optimization of the cash conversion cycle. They improve traceability, assist in managing disruption risks, and enhance the resilience of SC networks. Despite being in their early stages, digital twins hold substantial promise for practical applications in SC management, with ongoing research needed to explore their full potential and deployment in real-world scenarios (8). In the context of the provided document, digital twins are virtual representations of physical systems used to enhance the efficiency of food supply chains through real-time planning, monitoring, and control. Specifically, digital twins integrate procurement, production, and distribution strategies

within a medium-scale food processing company, leveraging mixed-integer linear programming (MILP) and agent-based simulation (ABS). These digital models enable accurate estimation of replenishment points and optimized operations with minimal lead time. By implementing digital twins, the study observed significant improvements in key performance indicators (KPIs) such as overall operations effectiveness (OOE), overall equipment effectiveness (OEE), capacity utilization, and reduced data redundancy. For instance, the study noted a 65% utilization of pasteurizers and aging vessels, 97% utilization of freezers, a 6% reduction in backlog, and an overall service level of 94%. Incorporating advanced technologies like IoT, AI, and cloud computing, digital twins provide a seamless integration of procurement, production, and distribution strategies, ultimately enhancing production flexibility and operational efficiency in food supply chains (36).

7. Spatial Computing

Spatial Computing integrates physical and digital objects into a cohesive user experience, enabling interaction with digital content in three-dimensional space. This technology encompasses a range of capabilities, including spatial mapping, tracking, and object recognition. It is crucial for the metaverse as it allows users to interact naturally with virtual objects and environments using gestures, voice commands, and physical movements. Spatial computing technologies, such as Microsoft HoloLens and Magic Leap, enhance the realism and interactivity of the metaverse, creating an intuitive bridge between the digital and physical worlds (18).

Each of these technologies plays a pivotal role in building and sustaining the complex ecosystem of the metaverse, driving innovation, and expanding the possibilities of virtual and augmented experiences.

3. Research Methodology

This section details the methodology employed for conducting our systematic literature review. As illustrated in Figure 1, our review protocol is structured into four steps across three phases: (1) Planning and defining the scope of the review, (2) Conducting a database search, (3) Applying inclusion and exclusion criteria, and (4) Synthesizing and reporting the

survey results. In figure 1 we present the methodological framework adopted for conducting our systematic literature review.

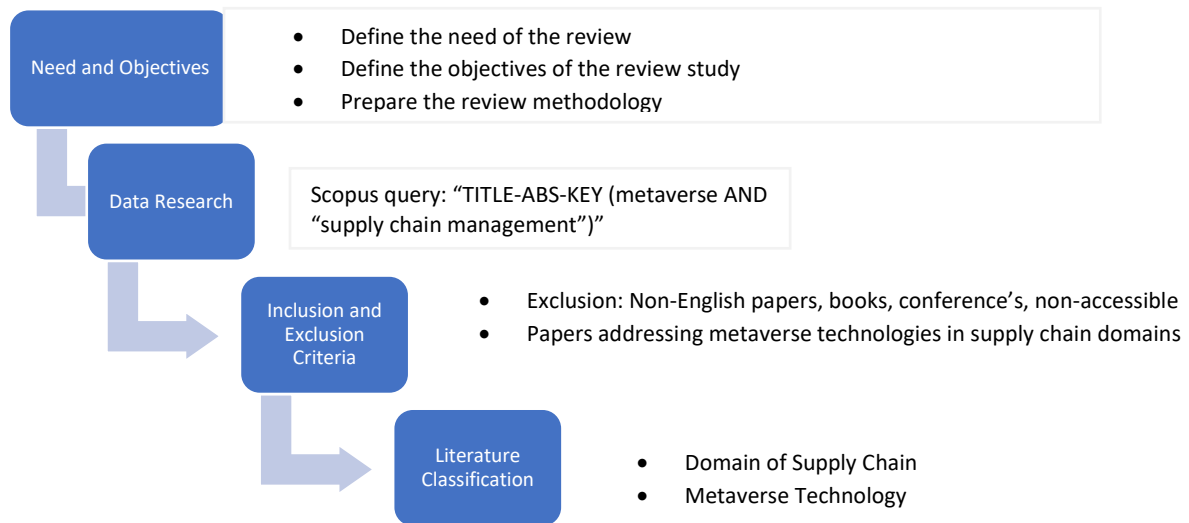


Figure 1 Methodological framework adopted for conducting our systematic literature review.

3.1 Definition of the Scope of the Review

A comprehensive literature review is an essential component of a master thesis, especially when exploring emerging and complex topics such as the integration of metaverses in supply chain management. This review process follows standardized methodologies for searching, screening, analyzing, and synthesizing the existing body of literature within the specified domain. The overarching goal of this systematic review is to compile and analyze the available literature in a methodical, transparent, and reproducible manner, thereby supporting policy formulation and strategic decision-making. Systematic reviews are crucial for academics and practitioners, as they consolidate findings from a wide array of relevant studies, providing a solid foundation of knowledge. This thesis focuses on the investigation of metaverse integration in supply chain management as presented in the current literature.

3.2 Search Strategy

Our overall search strategy relied on the Scopus scientific database for finding relevant papers. We used a predefined set of terms for searching within the titles, abstracts, and keywords of all the available Scopus papers. The terms used included the following: "TITLE-ABS-KEY (metaverse AND "supply chain management")".

3.3 Application of Inclusion and Exclusion criteria

For the master's thesis on the integration of the metaverse in supply chain management, we conducted a thorough literature review to identify and analyze relevant research. The process involved several key stages, starting with the initial collection of 96 papers from Scopus, and we included 55 papers.

3.3.1 Selection Process

- **Language and Database Filtering:** We began by excluding all papers non written in English to ensure accessibility and consistency in the evaluation process. This step also helped to focus on literature available in Scopus, a comprehensive and reputable database.
- **Inclusion Criteria:** The next step involved setting specific criteria for inclusion. We chose to include only peer-reviewed research articles published in scientific journals, thereby excluding papers from conference proceedings, book chapters, editorials, and other non-peer-reviewed sources. This criterion ensured the credibility and academic rigor of the included literature.
- **Title and Abstract Screening:** Then we screened the remaining papers by reading their titles and abstracts to assess their relevance to the topic of metaverse integrations in supply chain management. During this step, many papers were excluded due to a lack of direct relevance, such as those focusing solely on general metaverse applications or supply chain management without the context of the metaverse.
- **Full Text Review:** For the papers that passed the initial screening, we performed a detailed review of their full texts. This comprehensive reading allowed me to evaluate the depth of the research, the methodologies used, and the applicability of the findings to the thesis topic.
- **Exclusion of Non-Implementation Studies:** During the full-text review, we excluded works which were based in conference's, books and on papers which weren't accessible.
- **Inclusion of Implementation-Focused Papers:** Ultimately, we included only those research papers that provided empirical and theoretical evidence of metaverse-related implementations in supply chain management. These included case studies, quantitative analyses, and reports on practical applications of metaverse technologies in real-world supply chain scenarios.

Final Selection

After a rigorous screening and review process, we included 49 papers that provided valuable insights into the integration of the metaverse in supply chain management. These papers form the foundation of my thesis, offering a comprehensive view of the current state

of research and practical applications in this emerging field. In table 1 we present the research questions and objectives of the survey.

Table 1. Research questions and objectives of the survey.

Research Questions	Objectives
RQ1: What are the key Metaverse technologies being utilized in supply chain management, across different supply chain domains?	To identify and analyze the key Metaverse technologies used in supply chain management and their impacts across different domains
RQ2: Which domains within supply chain management are leveraging Metaverse technologies, and how are these technologies transforming processes such as procurement, logistics, inventory management, and customer relations?	To identify which supply chain domains are using Metaverse technologies and assess their impact on procurement, logistics, inventory management, and customer relations
RQ3: What are the key benefits of adopting Metaverse technologies in supply chain management, and how can they enhance operational efficiency, transparency, and resilience across global supply networks?	To explore the key benefits of Metaverse technologies in supply chain management and how they enhance operational efficiency, transparency, and resilience in global supply networks.
RQ4: How are metaverse technologies being applied in the real world?	The objective of studying the application of metaverse technologies in the real world is to understand how virtual and augmented realities are transforming industries, enhancing user experiences, driving economic benefits, and fostering innovation in everyday life.

4. Classification of the Retrieved Literature

In what follows, we present the classification and analysis of the selected literature (55 papers). As already noted, we have identified 2 thematic areas of research interest in metaverse's integration within supply chain management, which they are separated on four subcategories for each one. In figure 2 we present the flow of literature classification.

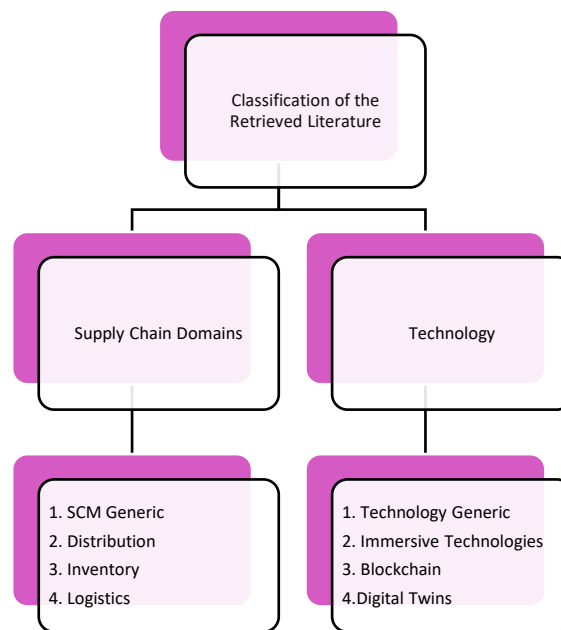


Figure 2 Flow of literature classification

4.1 Taxonomy

4.1.1 Supply Chain Generics

One study reviews the creation and valuation of blockchain tokens and their implications for supply chain management, particularly in enhancing transparency and trust (20). Another examines how metaverse technologies can enhance supply chain resilience and promote green sustainable development (21). Strategies for increasing the willingness of supply chain members to adopt metaverse technologies, focusing on collaboration and trust-building, are explored in a separate study (22). The importance of interoperability in digital technologies, including blockchain and the metaverse, for seamless integration in supply chains is also discussed (23). Further, research explores how metaverse technologies can enhance security and efficiency in the agri-food supply chain. This study discusses the integration of digital technologies such as blockchain, IoT, and AI with metaverse applications to improve traceability, transparency, and overall management in the agri-food supply chain. The authors provide a comprehensive overview of the current scenario and propose future perspectives for leveraging the metaverse to address challenges in this sector (24).

The objective of this study is to design supply chains that are more responsive, secure, and sustainable, with an emphasis on the fashion industry. This will be accomplished through the enhancement of real-time data management, the reduction of waste, and the

implementation of immersive customer experiences, all of which aim to increase customer satisfaction and loyalty (31). This paper explores the use of metaverse technologies in the operations of supply chain management to enhance efficiency and effectiveness within smart cities. The focus is on improving data integration, security, and real-time operational coordination. By incorporating technologies such as AI, VR, and AR, the aim is to create immersive and interactive environments that streamline operations, reduce inefficiencies, and facilitate better decision-making. This integration seeks to transform traditional supply chain functions, making them more resilient, responsive, and better aligned with the dynamic needs of smart urban environments (32).

Also, this study conducts an in-depth analysis of the application of metaverse technologies in supply chain management to enhance visibility, improve collaboration, optimize inventory, and manage risks more effectively. The incorporation of advanced technologies such as digital twins, augmented reality (AR), virtual reality (VR), artificial intelligence (AI), and blockchain aims to establish a transparent and efficient supply chain. This technological integration enables real-time monitoring, predictive analytics, and more effective resource utilization, leading to cost reductions and faster time-to-market for products. These developments are expected to facilitate more informed decision-making, increase sustainability, and significantly enhance the resilience and overall performance of supply chains (33). This paper delves into the domain of product design and development within the context of supply chain management. The authors introduce an innovative method that utilizes a three-dimensional spherical interface to facilitate interactive evolutionary design. This method actively involves users in the customization process, thus enhancing the efficiency of product design and ensuring that the final product aligns more closely with user preferences. The approach integrates advanced metaverse technologies, including virtual reality and 3D modeling, to create an immersive design environment. By streamlining the design process and reducing costs, this method aims to significantly improve supply chain performance. Furthermore, the research provides a robust framework that can serve as a foundation for future explorations in user-centric, virtual product development and its implications for supply chain efficiency (34).

The primary objective of the authors in this study is to formulate a comprehensive framework for integrating metaverse technologies into the healthcare supply chain, with the aim of addressing existing challenges and leveraging opportunities to enhance operational efficiency, traceability, and overall effectiveness. This framework incorporates advanced

technologies such as IoT, AI, blockchain, and digital twins, providing a structured approach to the digital transformation of healthcare supply chains. The authors seek to identify and analyze the technological, organizational, and environmental barriers impeding the adoption of these technologies, offering insights to facilitate smoother implementation and enhance real-time data exchange, product traceability, and supply chain optimization. By promoting further research and practical applications, the study aims to foster continuous innovation and technological advancement, supporting the evolution of resilient and efficient healthcare supply chains capable of meeting future demands (35).

The authors' primary objective within the domain of the healthcare supply chain is to critically evaluate and propose a transformative framework leveraging metaverse technologies to enhance supply chain efficiency, transparency, and resilience. By integrating digital twins, AI, and blockchain into a metaverse environment, they aim to address significant challenges such as the lack of real-time visibility, data accuracy, and supply chain adaptability, which were notably highlighted during the COVID-19 pandemic. This approach seeks to create a more dynamic and secure healthcare supply chain, capable of rapid adaptation to emergent needs and disruptions, thereby ensuring consistent availability and quality of medical supplies and services. The ultimate goal is to provide a forward-thinking solution that aligns with Industry 4.0 principles, fostering innovation and sustainability within the healthcare sector. In table 2 we present the comparison of the different features extracted from the generic supply chain literature (36).

This paper examines how non-fungible tokens (NFTs) can enhance sustainable supply chains by providing transparency and traceability of assets. By leveraging blockchain technology, NFTs ensure that each asset's journey through the supply chain is securely recorded and verifiable. This increased transparency helps in tracking the provenance and authenticity of products, thereby fostering trust and accountability among consumers and stakeholders. Moreover, NFTs can streamline operations, reduce fraud, and promote sustainable practices by offering immutable records of transactions and movements of goods within the supply chain (37). This study focuses on using game-theoretic policy computing and simulation to enhance a blockchain-based buffering system in supply chains. The goal is to optimize logistics and inventory management. By applying game theory, stakeholders can predict and strategically respond to each other's actions, leading to improved decision-making. Blockchain technology ensures transparency and security in these interactions. The combination of these approaches aims to create more efficient and resilient supply chain

operations, reducing costs and improving overall performance (38). This paper aims to reveal the potential of metaverse technologies in enhancing supply chain management. It discusses how immersive virtual environments can improve collaboration, visualization, and real-time data sharing among supply chain stakeholders. Additionally, the discussion includes strategies to address challenges such as technological integration, data security, and user adoption to effectively leverage metaverse technologies for optimized supply chain operations (39).

This study highlights the transformative potential of the metaverse for operations and supply chain management. It outlines the benefits, such as enhanced collaboration, improved visualization, and real-time data sharing. Additionally, it addresses challenges like technological integration, data security, and user adoption. The discussion also identifies future research directions needed to fully leverage the metaverse's capabilities in optimizing supply chain and operational efficiency (40).

The authors explore the potential applications of metaverse technology in operations and supply chain management, highlighting its benefits, challenges, and emerging trends. It examines how metaverse technology can enhance efficiency, collaboration, and data sharing, while also addressing obstacles like integration and security. Future trends in this field are also identified (41). The paper explores how metaverse technologies can improve security and efficiency in the agri-food supply chain. It discusses integrating digital technologies like blockchain, IoT, and AI with metaverse applications to enhance traceability, transparency, and overall management. The authors provide an overview of current practices and propose future strategies for leveraging the metaverse to address challenges in the agri-food supply chain (42). This study focuses on reforming supply chain systems using metaverse technologies, with an emphasis on integrating blockchain and NFTs. The goal is to enhance resilience and efficiency within supply chains. Blockchain ensures secure and transparent transactions, while NFTs provide unique asset traceability, together improving overall supply chain management (43). The study investigates how metaverse technologies can enhance supply chain resilience by focusing on the importance of sensory feedback. It highlights how these technologies can improve collaboration and trust among supply chain partners, leading to more robust and adaptable supply chains. Examines how metaverse technologies can improve supply chain resilience through enhanced sensory feedback, promoting better collaboration and trust (44).

In addition, highlights innovative digital health and blockchain solutions from the ConV2X 2023 Pitch Competition, focusing on their applications in supply chain management (45). Moreover, this paper proposes blockchain frameworks to enhance food traceability in supply chains, aiming for increased transparency and reduced fraud (46).

Furthermore, the authors explore the impact of metaverse technologies on supply chain effectiveness, particularly in collaboration, transparency, and operational performance (47). In this study additionally, provides insights into the development and future of the meta-metaverse, emphasizing its potential impacts on supply chain management (48). Also, assesses the potential benefits and challenges of integrating metaverse technologies across various sectors, including supply chain management (49).

Similarly, examines the role of blockchain technology in the digital economy and Industry 4.0, highlighting its potential to improve supply chain transparency and security (50). Likewise, this study investigates the opportunities and challenges of applying deep learning technologies in the metaverse for optimizing supply chain decisions (51).

Besides, discusses enhancing cyber resilience and societal situational awareness for SMEs through metaverse technologies, improving supply chain security and collaboration (52). In this study explores how Industry 5.0 and emerging technologies, including the metaverse, can promote sustainable development in supply chain management (53). Also, examines the transformative potential of the metaverse in healthcare and its implications for healthcare supply chain management (54). Furthermore, in this paper the authors investigate the role of the metaverse in knowledge sharing and resilience enhancement within supply chains (55).

Focuses on creating responsive, secure, and sustainable supply chains in the fashion industry by enhancing real-time data management and customer experiences (25). In addition, analyzes the use of metaverse technologies in smart cities' supply chains to improve efficiency, security, and real-time operations through immersive and interactive environments (26). Aims to enhance supply chain visibility, collaboration, inventory optimization, and risk management using metaverse technologies, leading to better decision-making and sustainability (27). Moreover, introduces an innovative method using a three-dimensional spherical interface for interactive evolutionary product design, enhancing efficiency and customization in supply chain management (28). Formulates a framework for integrating metaverse technologies into the healthcare supply chain, addressing challenges and leveraging opportunities for operational efficiency and traceability (29).

Finally, proposes a transformative framework for the healthcare supply chain using metaverse technologies to enhance efficiency, transparency, and resilience, especially in response to disruptions like the COVID-19 pandemic (30).

Table 2 Comparison of the different features extracted from the generic supply chain literature

Source	Metaverse Technology	Supply Chain Domain
(20)	Blockchain	To review the creation and valuation of blockchain tokens and their implications for supply chain management, particularly in enhancing transparency and trust.
(21)	AR,VR,XR	To examine how metaverse technologies can enhance supply chain resilience and promote green sustainable development.
(22)	AR,VR,XR	To examine strategies for increasing the willingness of supply chain members to adopt metaverse technologies, focusing on collaboration and trust-building.
(23)	AR,VR,XR	To discuss the importance of interoperability in digital technologies, including blockchain and metaverse, for seamless integration in supply chains.
(24)	Blockchain	To explore how metaverse technologies can enhance security and efficiency in the agri-food supply chain. The document discusses the integration of digital technologies such as blockchain, IoT, and AI with metaverse applications to improve traceability, transparency, and overall management in the agri-food supply chain. The authors aim to provide a comprehensive overview of the current scenario and propose future perspectives for leveraging the metaverse to address challenges in this sector
(31)	Blockchain	To investigate the potential of data and management-driven research in the metaverse, focusing on applications in supply chain management for better decision-making and efficiency.
(32)	Digital Twins	The document explores the integration of cubic picture fuzzy sets (CPFSSs) with blockchain and metaverse technologies to address uncertainties in supply chain management. The authors introduce topological structures on CPFSSs and propose a CRITIC-COPRAS method based on cubic picture fuzzy topological data analysis.
(33)	AR,VR,XR	To investigate the application of metaverse technologies in advanced manufacturing, focusing on enhancing supply chain processes and collaboration.

(34)	Digital Twins	To provide new perspectives on managing disruption risks in supply chains through the integration of metaverse and blockchain technologies.
(35)	Technology Generic	To analyze how metaverse technologies can improve green procurement policies in the semiconductor supply chain, promoting sustainability and efficiency.
(36)	Technology Generic	To explore the use of digital twin technologies for real-time planning and optimization in supply chains, enhancing operational efficiency and responsiveness.
(37)	Blockchain	To explore the role of non-fungible tokens (NFTs) in creating sustainable supply chains by ensuring transparency and traceability of assets.
(38)	Digital Twins	To discuss game-theoretic policy computing and simulation for a blockchain-based buffering system in supply chains, aiming to optimize logistics and inventory management.
(39)	AR,VR,XR	To unveil the potential of metaverse technologies in supply chain management and strategies to overcome associated challenges.
(40)	Digital Twins	To highlight the breakthrough potential of the metaverse for operations and supply chain management, discussing benefits, challenges, and future research directions.
(41)	AR,VR,XR	To analyze the potential applications of metaverse technology in operations and supply chain management, identifying benefits, challenges, and trends
(42)	Digital Twins	The authors provide a comprehensive overview of current scenarios and propose future perspectives for leveraging the metaverse to address challenges in the agri-food supply chain
(43)	Blockchain	To discuss the reform of supply chain systems using metaverse technologies, emphasizing blockchain and NFT integration for enhanced resilience and efficiency
(44)	Blockchain	To explore the relationship between metaverse technologies and supply chain resilience, emphasizing the role of sensory feedback in fostering collaboration and trust among supply chain partners.
(45)	AR,VR,XR	To highlight innovative solutions in digital health and blockchain presented at the ConV2X 2023 Pitch Competition, including applications relevant to supply chain management.
(46)	AR,VR,XR	To propose blockchain-based frameworks for improving food traceability in supply chains, ensuring transparency, and reducing fraud.
(47)	AR,VR,XR	To explore the impact of adopting metaverse technologies on supply chain effectiveness, focusing on collaboration, transparency, and operational performance.

(48)	Blockchain	To provide insights into the ideation and future directions of the meta-metaverse, focusing on its applications and potential impacts on supply chain management.
(49)	Blockchain	To assess the potential integration of metaverse technologies in various sectors, including supply chain management, and the benefits and challenges associated with this integration.
(50)	AR,VR,XR	To examine the integration of blockchain technology within the digital economy and its implications for Industry 4.0, highlighting how it can enhance supply chain transparency and security
(51)	Digital Twins	To explore the challenges and opportunities in using deep learning technologies within the metaverse for supply chain optimization and decision-making.
(52)	Blockchain	To discuss cyber resilience and societal situational awareness for SMEs, including the integration of metaverse technologies for enhancing supply chain security and collaboration
(53)	AR,VR,XR	The purpose of the document is to explore how Industry 5.0 can contribute to sustainable development, particularly in the domain of supply chain management. It outlines the use of emerging technologies, including the metaverse, to enhance supply chain processes.
(54)	AR,VR,XR	To explore the transformative potential of the metaverse in healthcare, including implications for supply chain management in the healthcare sector.
(55)	Blockchain	To explore the role of the metaverse in knowledge sharing and enhancing resilience within supply chains.
(25)	Blockchain	The purpose is to create more responsive, secure, and sustainable supply chains, particularly in the fashion industry, by improving real-time data management, reducing waste, and offering immersive experiences that increase customer satisfaction and loyalty
(26)	AR,VR,XR	The authors' purpose for utilizing metaverse technologies in the specific domain of operations within supply chain management is to leverage these technologies to enhance the efficiency and effectiveness of supply chain processes in smart cities. They aim to improve data integration, security, and real-time operational coordination
(27)	Technology Generic	The authors analyze the use of metaverse technologies in supply chain management with the goal of enhancing visibility, improving collaboration, optimizing inventory, and managing risks more effectively.
(28)	Technology Generic	The authors introduce an innovative method that utilizes a three-dimensional spherical interface to facilitate

		interactive evolutionary design. This method actively involves users in the customization process, thus enhancing the efficiency of product design and ensuring that the final product aligns more closely with user preferences.
(29)	Blockchain	The primary objective of the authors in this study is to formulate a comprehensive framework for integrating metaverse technologies into the healthcare supply chain, with the aim of addressing existing challenges and leveraging opportunities to enhance operational efficiency, traceability, and overall effectiveness.
(30)	AR,VR,XR	The authors' primary objective within the domain of the healthcare supply chain is to critically evaluate and propose a transformative framework leveraging metaverse technologies to enhance supply chain efficiency, transparency, and resilience.

4.1.2 Distribution

In this study, the potential applications of Non-Fungible Tokens (NFTs) in the healthcare sector are explored, particularly regarding their capability to enhance transparency, traceability, and accountability within healthcare supply chain management. The authors specifically examine how NFTs can establish secure and tamper-proof records for the transportation of medical supplies and equipment, aid in the prevention of counterfeiting, and improve distribution efficiency by tracking the conditions under which medical products are stored and transported (1).

Similarly, in their literature review, authors identify critical technologies that support metaverse applications in transportation and logistics, including Artificial Intelligence (AI), blockchain, digital twins, and extended reality (ER) (2). Furthermore, authors discuss the transformative potential of the metaverse for distribution channels and logistics by integrating virtual and physical retail environments, thereby facilitating a seamless omnichannel experience (3).

This study investigates how the metaverse can enable virtual collaboration among supply chain partners, thereby enhancing decision-making processes and coordination. This study underscores the importance of virtual environments in fostering collaborative efforts that can lead to more efficient supply chain operations (4).

Lastly, the study by authors presented contributes to the understanding of the impact of Augmented Reality (AR) technologies on supply chain and distribution. It highlights how AR-supported applications (ARSAPs) can enhance customer satisfaction, thereby influencing e-commerce efficiency and consumer behavior. This impact is particularly significant as it affects the entire supply chain, from product selection to final delivery. In table 3 we present the comparison of the different features extracted from the distribution supply chain literature (5). Also, in this study the authors describe the evolution and impact of digital twins on the supply chain, emphasizing how technologies like sensors, AI, blockchain, and 3D manufacturing contribute to their development (6).

Table 3 Comparison of the different features extracted from the distribution supply chain literature

Source	Metaverse technology	Objective of the Study
(1)	Blockchain	The applications of NFTs in healthcare, focusing on their potential to enhance transparency, traceability, and accountability in supply chain management
(2)	Blockchain	Critical technologies supporting metaverse applications in transportation and logistics, such as AI, blockchain, digital twins, and extended reality (ER)
(3)	AR,VR,XR	Discussed how the metaverse can transform distribution channels and logistics by integrating virtual and physical retail environments
(4)	AR,VR,XR	Investigated how the metaverse can facilitate virtual collaboration among supply chain partners to enhance decision-making and coordination.
(5)	AR,VR,XR	Impact of AR technologies in the context of supply chain and distribution by highlighting how enhanced customer satisfaction with ARSAPs can influence e-commerce efficiency and consumer behavior, potentially impacting the entire supply chain from product selection to final delivery
(6)	AR,VR,XR	Described the evolution and impact of digital twins on the supply chain, emphasizing how technologies like sensors, AI, blockchain, and 3D manufacturing contribute to their development

4.1.3 Inventory

In their study, authors investigate the opportunities and barriers associated with the implementation of augmented reality (AR) in warehouse operations. The research explores how AR can enhance inventory management by improving accuracy, reducing errors, and increasing efficiency in tasks such as order picking, receiving, storing, and shipping. The study employs a comprehensive methodology, including practitioner interviews and experimental trials, to evaluate the practical benefits and challenges of AR adoption in warehouse environments (6).

This research by delves into the utilization of digital twins for enhancing inventory and cash management within supply chains. The focus is on how digital representations of physical assets and processes can enhance decision-making, improve efficiency, and increase responsiveness in managing inventory levels and cash flow. This study underscores the strategic importance of digital twins in optimizing supply chain performance (8).

Furthermore, in this paper seek to advance the understanding of the impact of the metaverse on supply chain and operations management. They propose a comprehensive framework that includes the integration of digital and physical product demand, the enhancement of decision-making through digital twins, and the optimization of inventory management across both metaverse and physical realms. The study emphasizes the socio-technological dimensions and identifies potential new research areas within metaverse-driven supply chain processes (9).

This paper investigates the opportunities and barriers associated with using augmented reality (AR) in warehouse operations. It examines how AR can enhance inventory management by improving accuracy, reducing errors, and increasing efficiency in tasks such as order picking, receiving, storing, and shipping within warehouse environments. The study includes practitioner interviews and experimental trials to evaluate the practical benefits and challenges of AR adoption in warehousing (7). In table 4 we present the comparison of the different features extracted from the inventory supply chain literature.

Table 4 Comparison of the different features extracted from the inventory supply chain literature

Source	Metaverse Technology	Objective of the Study
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(7)	AR,VR,XR	Opportunities and barriers associated with using augmented reality (AR) in warehouse operations. It examines how AR can enhance inventory management. Practitioner interviews and experimental trials to evaluate the practical benefits and challenges of AR adoption in warehousing.
(8)	Digital Twins	The focus is on how digital representations of physical assets and processes can improve decision-making, efficiency, and responsiveness in managing inventory levels and cash flow
(9)	Digital Twins	Understanding of how the metaverse will impact supply chain and operations management.

4.1.4 Logistics

The emerging industry trends related to the metaverse and its impact on various sectors, including logistics and supply chain management, have been explored in several studies. For instance, one study investigates how blockchain-based digital twins in the metaverse can enhance logistics and supply chain management (10). This is further elaborated in another study that focuses on the role of extended reality (XR) technologies in integrating human and cyber-physical systems, thereby enhancing logistics through real-time data visualization, simulation, and interactive decision-making tools (11). Moreover, research has highlighted the intersection of cryptocurrencies and blockchain with sustainable logistics practices, noting that blockchain technology, a key component of the metaverse, can significantly improve transparency, traceability, and efficiency in supply chain logistics (12).

Further, another document discusses the practical applications of metaverse technologies in logistics, aiming to bridge the gap between theoretical research and real-world implementation. It showcases how these technologies can address real-world logistics and supply chain challenges (13). Additionally, the ecological implications of the metaverse are examined, noting its power-consuming infrastructure and the amplification of consumerism through big data and user-targeted algorithms. Although the study does not focus exclusively on logistics, it highlights how the broader ecological impacts of metaverse technology can indirectly influence logistics and supply chain operations by affecting consumer behavior and resource consumption (14).

In another examination, technologies like Digital Twin and Virtual Supply Chain (VSC) systems are discussed for their ability to create digital representations of physical supply chains. These digital twins can mimic real-world operations, providing valuable insights for optimizing logistics, anticipating future events, and identifying potential issues (15). The integration of AIoT (Artificial Intelligence of Things), IIoT (Industrial Internet of Things), and IoT technologies with the metaverse is also explored, emphasizing their role in enabling complex applications such as smart logistics and Industry 4.0, which are crucial for optimizing logistics and supply chain operations (16).

Research into the development of metaverse assets and services highlights their potential for optimizing logistics in a virtual retail environment through the use of computational intelligence tools and immersive technologies. These tools provide enhanced customer traffic analytics, smart environment modeling, and technology-enabled logistics optimization (17). Lastly, an overview of the metaverse's application in engineering management identifies opportunities and challenges, illustrating how immersive and interactive technologies within the metaverse can transform logistics and supply chain management, enhancing efficiency and decision-making processes (18). A study aims to provide an overview of the metaverse's application in engineering management, identifying both opportunities and challenges (19). It highlights the potential for the metaverse to transform various aspects of engineering management, including logistics and supply chain management, by leveraging immersive and interactive technologies. These technologies can enhance efficiency and support decision-making processes, showcasing the metaverse's capability to revolutionize traditional practices within the engineering sector. In table 5 we present the comparison of the different features extracted from the logistics supply chain literature.

Table 5 Comparison of the different features extracted from the logistics supply chain literature

Source	Metaverse Technology	Objective of the Study
(10)	AR,VR,XR	This document investigates the emerging industry trends related to the metaverse and its impact on various sectors, including logistics and supply chain management.
(11)	Blockchain	The use of blockchain-based digital twins in the metaverse to enhance logistics and supply chain management.

(12)	AR,VR,XR	How XR can improve the efficiency and effectiveness of supply chain operations through better human-machine interaction.
(13)	Blockchain	Explore the intersection of cryptocurrencies, blockchain, and sustainable logistics practices.
(14)	AR,VR,XR	The aim is to bridge the gap between theoretical research and practical implementation, showcasing how metaverse technologies can be applied to real-world logistics and supply chain challenges.
(15)	AR,VR,XR	Discusses the broader ecological impact of the technological infrastructure supporting the metaverse, which can indirectly affect logistics and supply chain operations by influencing consumer behavior and resource consumption.
(16)	Digital Twins	Discusses how technologies like Digital Twin and Virtual Supply Chain (VSC) systems can create digital representations of physical supply chains to mimic real-world operations, providing businesses with insights to optimize operations, anticipate future events, and identify potential issues.
(17)	Digital Twins	Challenges and trends in implementing these technologies to optimize logistics and supply chain operations in the metaverse
(18)	Technology Generic	It highlights how computational intelligence tools and captured image data enable technology-enabled logistics optimization in the virtual retail market, emphasizing the role of immersive technologies and context awareness tools in optimizing logistics in a metaverse shopping environment
(19)	Digital Twins	It highlights the potential for the metaverse to transform various aspects of engineering management, including logistics and supply chain management, by leveraging immersive and interactive technologies to enhance efficiency and decision-making processes.

4.1.5 Technology Generic

In recent discussions on securing digital infrastructures within virtual environments and metaverse applications, emphasizes the role of cybersecurity mesh networks and real-time data sharing.

These technologies are crucial for protecting the integrity and security of digital infrastructures, ensuring safe and reliable operations within the metaverse. By enabling robust data protection and real-time monitoring, cybersecurity mesh networks enhance the resilience of digital environments, making them more secure for various applications,

including supply chain management (27). The potential of deep learning, spatial computing, and immersive technologies in optimizing retail and supply chain operations within the metaverse is explored in (18). This paper examines how these advanced technologies can be leveraged to create more efficient and responsive supply chain systems. By utilizing deep learning algorithms and spatial computing, organizations can achieve significant improvements in inventory management, logistics planning, and overall operational efficiency. Immersive technologies, such as augmented and virtual reality, provide enhanced visualization and interaction capabilities, further optimizing supply chain processes and enhancing decision-making. Furthermore, the integration of Industry 5.0 technologies, which focuses on human-centric and sustainable approaches, is critical for advancing sustainable development in various sectors, as discussed in (28).

Authors, explores how these technologies contribute to creating more sustainable and efficient supply chains. Industry 5.0 emphasizes the collaborative interaction between humans and machines, promoting the use of advanced technologies such as artificial intelligence, IoT, and blockchain to achieve environmental and economic sustainability. This integration supports the development of supply chains that are not only efficient but also environmentally responsible, aligning with the broader goals of sustainable development. Collectively, these studies highlight the transformative potential of cybersecurity technologies, deep learning, and Industry 5.0 in enhancing the efficiency, security, and sustainability of supply chain operations within the metaverse and beyond. By leveraging these technologies, organizations can build more resilient, responsive, and sustainable supply chains, driving innovation and progress in various industries. This paper explores the application of metaverse technologies, including digital twins and the Internet of Things (IoT) to enhance inventory accuracy, blockchain for logistics transparency and product traceability, and virtual reality (VR) and augmented reality (AR) for creating engaging customer experiences (31).

Furthermore, the objective is to increase efficiency, sustainability, and customer satisfaction within the supply chain. The authors utilize a range of advanced technologies to propose a transformative framework for integrating metaverse capabilities into the healthcare supply chain. Key technologies include the Internet of Things (IoT) for real-time data collection and monitoring, artificial intelligence (AI) for predictive analytics and

process optimization, blockchain for secure, transparent, and immutable data exchange, and digital twins for simulating and optimizing supply chain processes.

These technologies collectively aim to enhance supply chain efficiency, transparency, and resilience by enabling more accurate demand forecasting, improved product traceability, and seamless data integration. The strategic application of these technologies is intended to support the digital transformation of healthcare supply chains, driving innovation and improving the management of medical products and services (35). The authors aim to explore and advocate for the integration of metaverse technologies in the healthcare supply chain, with a focus on enhancing operational efficiency, security, and adaptability. The technology framework proposed involves the use of advanced tools such as digital twins, AI, blockchain, and extended reality (XR). These technologies are intended to provide comprehensive, real-time data insights, improve predictive analytics, ensure immutable and transparent transaction records, and offer immersive, virtual environments for better decision-making and process management. The goal is to create a sophisticated, interconnected system that not only addresses current inefficiencies and vulnerabilities but also sets a foundation for a resilient and forward-looking healthcare supply chain infrastructure (36). In table 6 we present the comparison of the different features extracted from the technology generic in supply chain literature.

Table 6 Comparison of the different features extracted from the technology generic on supply chain literature

Source	Technology	Integrations
(35)	Virtual Reality (VR) Augmented Reality (AR) Artificial Intelligence (AI) Blockchain Digital Twins (DTs) Internet of Things (IoT) Cloud Computing	<ul style="list-style-type: none"> • Integration of AI and Blockchain • Use of IoT with Cloud Computing • Combination of VR/AR and Digital Twins
(36)	Extended Reality (XR) Artificial Intelligence (AI) Distributed Ledger Technology (DLT) Digital Twins Internet of Medical Things (IoMT) Telecommunications Technologies	<ul style="list-style-type: none"> • IoMT and IoT • Cloud Computing and Edge Nodes • AI • Blockchain • Digital Twins

(27)	deep fakes, ChatGPT, and the Metaverse	<ul style="list-style-type: none"> Machine Learning
(18)	Deep learning-based ambient sound processing ,Visual imagery tools ,Spatial computing ,Immersive technologies ,Context awareness tools ,Path planning algorithms ,Virtual navigation tools ,Augmented reality shopping tools ,Simulation modeling tools ,Computer vision algorithms ,Natural language processing tools	<ul style="list-style-type: none"> Blockchain, Croud Computing, Immersive technologies
(28)	Internet of Everything (IoE) Cognitive Cyber-Physical Systems (CCPS) Augmented Reality (AR) and Virtual Reality (VR) Big Data Analytics Cloud Computing	<ul style="list-style-type: none"> IoE and Cognitive Cyber-Physical Systems (CCPS), Big Data Analytics and Cloud Computing, Augmented Reality (AR) and Virtual Reality (VR)

4.1.6 Immersive Technologies (AR, VR, XR)

The integration of metaverse technologies into supply chain management presents a significant opportunity to enhance resilience and promote green sustainable development through improved knowledge sharing and collaboration (21). Author in this paper analyzes the factors influencing the willingness of supply chain members to adopt metaverse technologies using evolutionary game theory (22).

Furthermore, the interoperability requirements for Web3 and metaverse technologies, focusing on technological, organizational, and regulatory aspects essential for seamless integration within supply chains, are discussed in work presented in (23).

Emerging industries influenced by metaverse technologies, with a particular focus on supply chain innovations and industry trends, are investigated in (10). Additionally, the applications of metaverse technologies in advanced manufacturing, highlighting how virtual reality (VR) and augmented reality (AR) can enhance production processes and operational efficiency, are examined by the authors in (39).

The use of augmented reality in warehouse management, with an emphasis on improving efficiency, accuracy, and worker safety, is explored in (7). The integration of extended reality (XR) technologies in supply chain contexts, particularly in enhancing human and cyber-physical systems, is examined by authors in (12). Furthermore investigates how metaverse technologies can improve green procurement policies within the semiconductor supply chain, aiming for sustainable development and environmental benefits (41).

To bridge the gap between theoretical concepts and practical applications of the metaverse in supply chain management, authors in (14) provides real-world examples and case studies. In the fashion industry, the development, applications, and challenges of using metaverse technologies, with an emphasis on VR and AR for virtual fashion shows and digital try-ons, are examined in (3). The ecological implications of the metaverse from a posthumanist perspective and its impact on supply chains and sustainability are discussed in work (15). The future of marketing within the metaverse, focusing on how brands can interact with consumers in immersive environments to enhance engagement and loyalty, is investigated in (4). Factors influencing customer satisfaction with Augmented Reality Shopping Assistant Applications (ARSAPs) are explored by authors in, utilizing sentiment analysis and topic modeling (5). The potential of the metaverse in supply chain management and the challenges that need to be overcome to realize its full benefits are investigated by authors in (45). The transformative potential of the metaverse for operations and supply chain management, focusing on innovation, collaboration, and process efficiency, is highlighted in work (46).

Various applications of metaverse technologies in operations and supply chain management, including the benefits and challenges of integrating VR and AR, are explored (47). A systematic literature review in (50) explores the application of metaverse technologies in enhancing supply chain resilience through improved collaboration and trust relationships. The impact of adopting metaverse technologies on the effectiveness of supply chains, particularly in terms of efficiency, agility, and transparency, is examined by authors in (53).

Future directions of the metaverse and its potential impact on various industries, including supply chain management and digital commerce, are conceptualized in work (54). The

challenges and opportunities of using deep learning-driven metaverse technologies in fashion design and textiles, with a focus on Generative Adversarial Networks (GANs), are investigated by authors in (38).

The role of digital twins within the metaverse and their impact on business operations, including supply chain management and product lifecycle management, is discussed in (39). Finally, (40) examines how metaverse technologies can enhance supply chain knowledge sharing and resilience, providing empirical evidence from various case studies. This thesis intends to leverage metaverse technologies, including artificial intelligence (AI), virtual reality (VR), and augmented reality (AR), to enhance data management, improve security, and enable real-time, immersive interactions in supply chain operations within smart cities (32). This thesis explores the integration of metaverse technologies in supply chain management, encompassing the use of digital twins for real-time virtual modeling, augmented reality (AR) and virtual reality (VR) for immersive and interactive monitoring, and artificial intelligence (AI) for predictive analytics. These technologies are employed to enhance visibility, improve decision-making, and streamline operations across the supply chain. Blockchain technology ensures secure and transparent transactions. Collectively, these advancements contribute to a more efficient, resilient, and sustainable supply chain by reducing costs, managing risks, and expediting processes from design to delivery (33). Explores advancements in product design technology within the scope of supply chain management. The authors present a cutting-edge approach that employs a three-dimensional spherical interface to facilitate interactive evolutionary design, allowing users to directly engage in the customization and development of products. This method leverages metaverse technologies, such as virtual reality and 3D modeling, to create an immersive and interactive design environment. The integration of these technologies aims to enhance design efficiency, reduce development costs, and ensure that products are closely aligned with user preferences. By optimizing the design process, this approach significantly improves the technological capabilities of the supply chain. The research sets a precedent for future technological advancements in user-centered, virtual product development, demonstrating substantial potential for improving supply chain operations and efficiency (34). In table 7 we present the comparison of the different features extracted from the immersive technologies in supply chain literature.

Table 7 Comparison of the different features extracted from the immersive technologies in supply chain literature

Source	Technology	Integrations
(21)	AR,VR,XR	<ul style="list-style-type: none"> • Information communication technologies (ICTs) • and blockchain
(22)	AR,VR,XR	<ul style="list-style-type: none"> • AI, • IOT, • Big Data
(23)	AR,VR,XR	<ul style="list-style-type: none"> • AR and VR
(10)	AR,VR,XR	<ul style="list-style-type: none"> • IOT,Big Data, • AI
(39)	AR,VR,XR	<ul style="list-style-type: none"> • Digital Twin and Blockchain, • AI and Blockchain
(7)	AR,VR,XR	<ul style="list-style-type: none"> • AR with cyber-physical systems
(12)	AR,VR,XR	<ul style="list-style-type: none"> • IOT,DT,Human-Cyber-Physical Systems
(41)	AR,VR,XR	<ul style="list-style-type: none"> • Blockchain, • AI
(14)	AR,VR,XR	<ul style="list-style-type: none"> • Blockchain,IOT, • Big Data
(3)	AR,VR,XR	<ul style="list-style-type: none"> • Blockchain with NFTs, • Artificial Intelligence (AI), • NFTs
(15)	AR,VR,XR	<ul style="list-style-type: none"> • AI
(4)	AR,VR,XR	<ul style="list-style-type: none"> • Immersive Technologies
(5)	AR,VR,XR	<ul style="list-style-type: none"> • Mobile technologies
(45)	AR,VR,XR	<ul style="list-style-type: none"> • Internet of Things (IoT), • Blockchain, • and artificial intelligence (AI)

(46)	AR,VR,XR	<ul style="list-style-type: none"> • AI and Machine Learning, • Blockchain, • Digital Twin, • AR/VR/XR, • IoT
(47)	AR,VR,XR	<ul style="list-style-type: none"> • Digital transformation initiatives
(50)	AR,VR,XR	<ul style="list-style-type: none"> • AI, • Blockchain, • AR
(53)	AR,VR,XR	<ul style="list-style-type: none"> • AI, • IOT, • Robotics
(54)	AR,VR,XR	<ul style="list-style-type: none"> • Digital twins and multi-layered metaverse platforms
(26)	AR,VR,XR	<ul style="list-style-type: none"> • AI, • AR, • VR
(6)	AR,VR,XR	<ul style="list-style-type: none"> • IoT-Blockchain integration, • AI and Machine Learning,3D/Additive Manufacturing
(30)	AR,VR,XR	<ul style="list-style-type: none"> • Digital twins, • AI for creating digital avatars, • and VR/AR devices

4.1.7 Blockchain

The integration of metaverse technologies into various sectors has become a critical area of study, particularly in enhancing supply chain management. In a comprehensive exploration, into both data-driven and management-focused aspects of metaverse research, discussing the development of intelligent virtual humans and addressing potential risks and challenges. This study provides new insights and research directions for academics and practitioners, highlighting the potential benefits and governance issues associated with metaverse technologies in supply chains (37). Building on these insights, investigates how Non-Fungible Tokens (NFTs) can be integrated into supply chains to enhance transparency and sustainability. NFTs, coupled with blockchain technology, offer

a secure and immutable record of transactions, significantly improving product traceability and authenticity (43). This integration is crucial for maintaining integrity within supply chains and presents a promising approach to enhancing operational transparency. Further examining the role of advanced technologies, explores the application of metaverse technologies, including artificial intelligence, blockchain, digital twins, and extended reality, in transportation and logistics operations. This paper addresses critical technological components and proposes an AI-supported digital framework for the successful implementation of metaverse solutions. Real-world applications, such as MTR's virtual metro system in Hong Kong, are presented to demonstrate the practical benefits in optimizing logistics and supply chain management (2).

In a similar context, explores a game-theoretic approach for computing service policies within a blockchain-enabled buffering system, focusing on dynamic pricing, resource allocation, and federated learning. This approach aims to enhance the efficiency and security of supply chain finance systems, providing a detailed analysis of the methodologies and their impact on financial operations within supply chains (44). Expanding on the potential of metaverse technologies, examines their application in enhancing the security and efficiency of agri-food supply chains (AFSCs). The study highlights how technologies like blockchain, IoT, and augmented reality can improve food safety, traceability, and stakeholder collaboration, leading to more secure and efficient supply chains in the agri-food sector (48). Continuing this exploration, authors analyze the potential of metaverse technologies, particularly blockchain and NFTs, in improving supply chain resilience. Through a case study of the Japanese automotive industry, this paper demonstrates how these technologies can enhance operational efficiency and resilience, offering practical examples of their benefits to supply chain management (49). In a related review, systematically examines blockchain-based frameworks for food traceability. This study discusses how blockchain technology can enhance transparency, accountability, and traceability in the food supply chain from the point of origin to the consumer, highlighting the substantial potential for blockchain to revolutionize food supply chain management (52).

While primarily focused on higher education, evaluates the integration of metaverse technologies, including blockchain, and their potential impact on digital transformation within higher education institutions (HEIs). This analysis indirectly underscores broader implications for supply chain management, suggesting that advancements in educational frameworks and systems can positively affect supply chain operations (55).

Moreover, authors in this paper explore the application of metaverse technologies in the healthcare sector, including blockchain and NFTs, examining how these technologies can improve various aspects of healthcare such as collaborative working, education, clinical care, and wellness. The study also considers the implications for the healthcare supply chain, suggesting potential improvements in medical supply logistics and patient care coordination. Collectively, these studies provide a comprehensive overview of the multifaceted applications of metaverse technologies in supply chain management, highlighting their potential to enhance transparency, security, efficiency, and resilience across various sectors (29). Blockchain technology serves as a foundational component for Non-Fungible Tokens (NFTs), enabling secure and transparent tracking and management of digital assets, which holds significant potential for applications in virtual environments, as discussed in (1). This technology ensures that digital assets can be monitored and managed with high levels of security and transparency, laying the groundwork for various innovative applications. Digital twins are another pivotal technology for real-time simulation and optimization of manufacturing processes.

As highlighted in this study, they enhance efficiency and reduce waste by providing detailed and dynamic representations of physical systems. This allows for improved monitoring, control, and optimization of processes, ultimately leading to more sustainable manufacturing practices. The integration of blockchain with digital twins is further explored in the context of logistics and transportation (24). Authors in focuses on designing a blockchain-based digital twin system specifically for Internet of Things (IoT) deployments. This system aims to enhance the efficiency and reliability of logistics operations by providing a secure and decentralized framework for data management and transaction tracking (11).

Building on these insights, examines the broader role of blockchain in ensuring secure, decentralized transactions and maintaining data integrity within digital ecosystems. This study supports the implementation of digital twins in logistics and supply chain management, emphasizing the potential of blockchain to enhance efficiency and security through decentralized data management and robust verification processes. Together, these studies underscore the critical role of blockchain and digital twin technologies in advancing the efficiency, transparency, and security of supply chain management. They highlight how these technologies can be integrated to create more resilient and efficient logistics systems, thereby paving the way for innovative solutions in various sectors (25). In table 8 we present the comparison of the different features extracted from the blockchain technology in supply chain literature.

Table 8 Comparison of the different features extracted from the blockchain technology in supply chain literature

Source	Technology	Integrations
(37)	Blockchain	<ul style="list-style-type: none"> • AI
(43)	Blockchain	<ul style="list-style-type: none"> • NFT
(2)	Blockchain	<ul style="list-style-type: none"> • AI, Digital Twins
(44)	Blockchain	<ul style="list-style-type: none"> • Use of blockchain for secure, decentralized data storage and smart contracts
(48)	Blockchain	<ul style="list-style-type: none"> • AI and Big Data Analytics, • Edge Computing and 5G, • AR/VR with IoT
(49)	Blockchain	<ul style="list-style-type: none"> • Digital Twins, IoT and AI, • VR/AR and Cloud Computing
(52)	Blockchain	<ul style="list-style-type: none"> • Industry 4.0 and Web 3.0 technologies such as DeFi (Decentralized Finance), • DApps (Decentralized Applications), • NFTs, • Digital Twins, • IoT (Internet of Things), • edge computing,

		<ul style="list-style-type: none"> AI (Artificial Intelligence)
(55)	Blockchain	<ul style="list-style-type: none"> VR, AI
(29)	Blockchain	<ul style="list-style-type: none"> AI, VR
(1)	Blockchain	<ul style="list-style-type: none"> NFTs, BC, IOT
(24)	Blockchain	<ul style="list-style-type: none"> Digital Twins, Cloud Computing
(11)	Blockchain	<ul style="list-style-type: none"> Digital Twins
(25)	Blockchain	<ul style="list-style-type: none"> Blockchain

4.1.8 Digital Twins

The integration of advanced technologies such as topological data analysis and blockchain with digital twins has significant implications for supply chain management.

As discussed in this study, the combination of these technologies can greatly enhance data security, transparency, and operational efficiency. This integration allows for more robust data management within supply chains, leading to improved performance and reliability (38). Exploring the role of digital twins and metaverse technologies in disruption risk management, highlights new perspectives on enhancing supply chain resilience. These technologies are instrumental in predicting and mitigating risks, ensuring smoother and more reliable supply chain operations. The paper underscores how digital twins provide a dynamic representation of supply chain processes, facilitating better risk management and operational continuity (40).

Focusing on inventory and cash flow management, discusses the application of digital twins within supply chains. Paper emphasizes the use of real-time data and predictive

analytics provided by digital twins to optimize inventory levels, reduce costs, and improve financial management. This approach leads to more efficient supply chain operations and better financial oversight (8).

The real-time planning capabilities enabled by digital twin technology in supply chains are examined. Digital twins offer the ability to simulate and optimize various supply chain processes, providing real-time insights and facilitating more informed decision-making. This capability allows for proactive management and adaptation to changing supply chain dynamics (42).

Further advancing the understanding of metaverse impacts on supply chain and operations management (SCOM), proposes a framework for metaverse-driven SCOM. The paper identifies new research areas related to metaverse-enhanced visibility, digital collaboration, and decision-making. It highlights the transformative potential of digital twins in improving coordination between physical and digital supply chain processes, paving the way for more integrated and responsive supply chain management (9).

The integration of the metaverse in marketing and logistics, as explored by the authors, underscores how digital twins and other advanced technologies can revolutionize supply chain management. The document discusses the potential benefits, challenges, and future research directions for incorporating metaverse technologies to enhance supply chain visibility, efficiency, and decision-making. This perspective emphasizes the strategic role of digital twins in modernizing supply chain operations (16).

Innovations presented at the ConV2X Pitch Competition, with a focus on digital health technologies, are highlighted in. The document includes discussions on the application of digital twins in healthcare supply chains, showcasing how metaverse technologies can improve supply chain resilience and efficiency. These innovations are critical for advancing the performance and sustainability of healthcare supply chains (51). Exploring trends and challenges in implementing AIoT (Artificial Intelligence of Things), IIoT (Industrial Internet of Things), and IoT (Internet of Things) in supply chains, discusses the integration of digital twins with these technologies. The paper examines how digital twins enhance supply chain

management by providing comprehensive data analysis and facilitating seamless integration of IoT technologies, addressing key implementation challenges (17).

In, this study provides an overview of the opportunities and challenges associated with integrating the metaverse in engineering management, with a particular focus on logistics within supply chains. It discusses how digital twin technology can enhance real-time interaction, visibility, and operational efficiency. The paper also outlines future research agendas to address the challenges and leverage the opportunities presented by metaverse technologies, highlighting the potential for significant advancements in logistics management. Collectively, these papers underscore the transformative potential of digital twins and metaverse technologies in enhancing the efficiency, transparency, and resilience of supply chain management. They provide valuable insights into how these technologies can be integrated to create more adaptive and responsive supply chains, leading to improved operational performance across various sectors (19). In table 9 we present the comparison of the different features extracted from the digital twin's technology in supply chain literature.

Table 9 Comparison of the different features extracted from the digital twin's technology in supply chain literature

Source	Technology	Integrations
(38)	Digital Twins	<ul style="list-style-type: none"> Blockchain
(40)	Digital Twins	<ul style="list-style-type: none"> Digital twins
(8)	Digital Twins	<ul style="list-style-type: none"> Machine learning
(42)	Digital Twins	<ul style="list-style-type: none"> Digital twin technology and mixed-integer linear programming (MILP) and agent-based simulation (ABS)
(9)	Digital Twins	<ul style="list-style-type: none"> Blockcahin, AI, IOT
(16)	Digital Twins	<ul style="list-style-type: none"> AI,Blockchain, VR, AR

(51)	Digital Twins	<ul style="list-style-type: none"> • Blockchain
(17)	Digital Twins	<ul style="list-style-type: none"> • AIoT/IIoT/IoT Devices, • Edge Computing
(19)	Digital Twins	<ul style="list-style-type: none"> • Blockchain and smart contracts, • IoT (Internet of Things) and AI (Artificial Intelligence), • 5G connectivity

5. Discussion

The integration of metaverse technologies into supply chain management (SCM) represents a transformative shift in operational paradigms, offering enhanced efficiency, transparency, and resilience. From an academic perspective, this integration encompasses the application of advanced technologies such as blockchain, digital twins, augmented reality (AR), virtual reality (VR), and the Internet of Things (IoT). These technologies collectively facilitate real-time data sharing, immersive simulations, and improved collaboration among supply chain stakeholders. The scholarly investigation into this integration aims to address the significant potential and inherent challenges, including technological, economic, and regulatory barriers, as well as data security and user acceptance issues. By systematically exploring these dimensions, this research seeks to provide a comprehensive analysis of the implications, benefits, and challenges associated with metaverse technologies in SCM. It also aims to offer practical recommendations to enhance operational efficiency and resilience, contributing to the evolving academic discourse on digital transformation in supply chain management.

5.1 Open Issues and Challenges

The integration of Metaverse technologies in various domains presents a myriad of open issues and challenges that must be addressed to realize their full potential. The rapid evolution of technology has led to the emergence of advanced systems such as the metaverse and blockchain, which promise to revolutionize various sectors. However, their successful implementation is hindered by several challenges that span across technological, data security, market adoption, and regulatory dimensions. Understanding these challenges from

a professional perspective is crucial for developing effective strategies that ensure sustainable and responsible integration of these technologies. This thesis categorizes the key limitations into four primary areas: Technological and Integration Challenges, Data Security and Privacy Concerns, Market and Adoption Dynamics, and Regulatory and Ethical Considerations, providing insights into the professional perspectives necessary for overcoming these obstacles.

5.1.1 Technological Challenges

Integrating metaverse technologies into supply chain management presents significant technological challenges that necessitate a nuanced academic investigation. The complexity arises from the need for seamless interoperability among diverse technologies and platforms, which requires establishing standardized protocols and frameworks. The academic discourse emphasizes the critical role of interoperability in preventing data silos and ensuring smooth communication across different systems. Additionally, the immaturity of emerging technologies such as virtual reality (VR), augmented reality (AR), and blockchain poses substantial hurdles. These technologies are still in their developmental stages and require further refinement to meet the rigorous demands of global supply chains. The need for robust network infrastructure that can support high-speed, real-time data exchanges is also paramount, as is the necessity for advanced cybersecurity measures to safeguard sensitive data against breaches and unauthorized access. Academic research should therefore focus on developing scalable solutions that address these technological impediments, ensuring that the metaverse can be effectively integrated into supply chains to enhance efficiency and operational capacity.

5.1.2 Economic and Operational Challenges

Economic and operational challenges are pervasive in the adoption of metaverse technologies within supply chain frameworks. From an academic perspective, these challenges highlight the significant financial barriers and operational complexities that organizations face. The substantial initial investments required for hardware, software, and training, along with ongoing maintenance costs, present a formidable obstacle. Academic inquiry into cost-effective financial models that justify these expenditures is crucial. Furthermore, the disparities in technology accessibility across different regions and organizations underscore the need for equitable solutions that bridge this digital divide.

The operational transition to metaverse-integrated systems is fraught with risks, including potential disruptions to existing processes. Continuous maintenance and upgrades are essential to keep pace with technological advancements without compromising operational continuity. Academically, this necessitates a comprehensive analysis of the economic viability and operational resilience required to support the widespread implementation of metaverse technologies in supply chains.

5.1.3 Social and Ethical Challenges

The integration of metaverse technologies raises profound social and ethical challenges that warrant thorough academic exploration. The virtual nature of the metaverse blurs the boundaries between digital and physical realms, creating complex ethical dilemmas related to user privacy, data protection, and digital identity management. Ensuring the ethical use of personal and business data within these environments is critical. Academic research must develop robust data protection policies and ethical guidelines to govern these new digital spaces. Furthermore, the issue of digital inclusion is paramount; there is a need to ensure equitable access to metaverse technologies to avoid exacerbating existing socio-economic disparities. This includes creating inclusive frameworks that facilitate participation for all, regardless of their digital literacy or access to technology. The academic community must also address the societal impact of digital addiction and the psychological effects of prolonged virtual interaction, advocating for responsible usage and the promotion of mental well-being within these immersive environments. In figure 3 we present the classification of open issues and challenges.

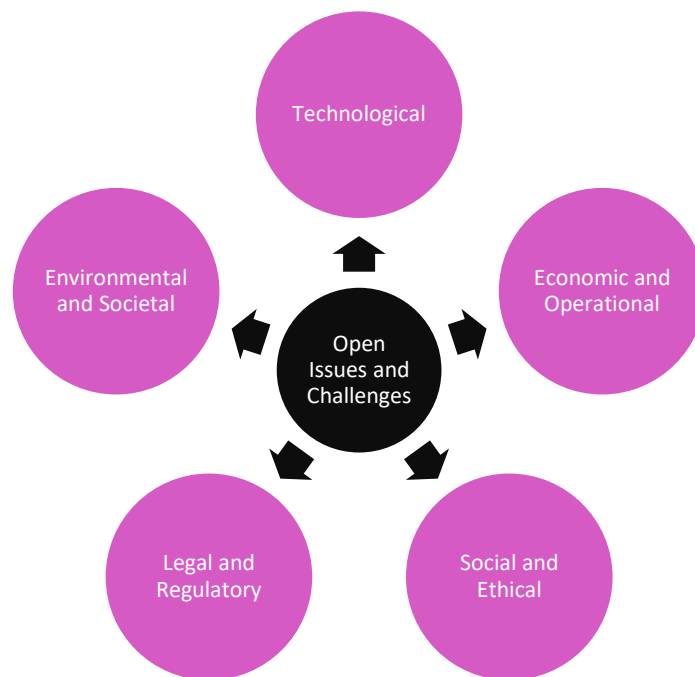


Figure 3 Classification of Open issues and Challenges

5.1.4 Legal and Regulatory Challenges

The legal and regulatory landscape of metaverse technologies is a complex and evolving field that poses significant challenges. Academically, this area requires a deep dive into the development of comprehensive legal frameworks that can navigate the multifaceted issues of data security, privacy, and intellectual property rights in virtual environments. The decentralized nature of the metaverse complicates matters of legal jurisdiction and accountability, particularly in cross-border contexts. Research must explore how existing legal principles can be adapted to accommodate the unique characteristics of digital spaces and transactions. Moreover, the protection of intellectual property in the metaverse, where digital content and assets can be easily replicated and distributed, is a critical area of concern. Establishing clear, enforceable regulations that protect creators' rights while fostering innovation is essential. Academically, this entails an in-depth analysis of how legal norms and regulations can evolve to support the ethical and secure development of metaverse technologies in a way that upholds the principles of justice and accountability.

5.1.5 Environmental and Societal Challenges

The integration of metaverse technologies into supply chains brings with it significant environmental and societal challenges that demand academic scrutiny. The extensive computing power required for these technologies contributes to increased energy consumption and greenhouse gas emissions, raising concerns about their environmental impact. Academically, there is a pressing need to explore sustainable practices and technologies that can mitigate these adverse effects. This includes investigating energy-efficient data centers and the potential for renewable energy sources to power these systems. Additionally, the societal implications of the metaverse, such as digital addiction and its impact on mental health, require careful examination. Ensuring that users can adapt to and responsibly engage with these technologies is critical to their successful implementation. Academically, this involves studying the behavioral and cultural shifts necessary to support a digital transformation in supply chains while promoting mental well-being and preventing social isolation. Addressing these environmental and societal issues is essential for fostering a sustainable and inclusive future in which metaverse technologies contribute positively to both economic growth and social welfare.

5.2 Key Findings

RQ1: Metaverse technologies, encompassing blockchain, digital twins, augmented reality (AR), virtual reality (VR), artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT), are profoundly transforming supply chain management across diverse sectors. Blockchain technology is extensively utilized for its capacity to secure, authenticate, and streamline transactions via immutable ledgers, thereby enhancing transparency and traceability within procurement and logistics processes. Digital twins enable real-time monitoring and simulation, supporting predictive maintenance, optimized route planning, and dynamic inventory management through the creation of virtual replicas of physical assets and systems. AR and VR technologies are redefining training, remote inspections, and operational visualization, particularly within warehouse management and supplier evaluations, leading to improved efficiency and reduced error rates. AI and ML are pivotal for data-driven decision-making, offering advanced analytics for demand forecasting, risk assessment, and the automation of complex tasks, which are

essential for optimizing logistics and procurement operations. Concurrently, IoT integrates physical assets into digital networks, facilitating real-time tracking and condition monitoring, thereby enhancing inventory control and logistics management through continuous data flow and insights. Collectively, these technologies constitute the foundation of the evolving digital supply chain, driving improved operational efficiency and responsiveness throughout the entire supply network.

RQ2: In the ever-evolving landscape of supply chain management, Metaverse technologies are playing a pivotal role in revolutionizing key processes across multiple domains. This transformative shift is marked by the integration of advanced digital tools that enhance efficiency, transparency, and customer engagement, fundamentally reshaping how supply chains operate. In procurement, blockchain technology is employed to establish immutable records and execute smart contracts, thereby streamlining supplier transactions and enhancing transparency and trust. This approach results in more secure and efficient procurement processes by reducing fraud and verifying the authenticity of goods and services. The logistics sector is undergoing significant transformation through the application of digital twins and IoT, which facilitate real-time asset tracking, predictive maintenance, and the optimization of transportation routes. These technologies contribute to reduced operational downtime and improved logistics efficiency by providing accurate and timely data for decision-making.

Inventory management is enhanced through the integration of AI and IoT, which allow for continuous monitoring of inventory levels and the implementation of automated replenishment systems. This integration improves the accuracy of inventory forecasts, reduces excess stock, and minimizes waste, thereby refining overall inventory control. Customer relations are being advanced through the use of AR and VR technologies, which create immersive experiences that enable customers to interact with products virtually. This leads to increased engagement and satisfaction, as customers can better understand and visualize products before making a purchase. Furthermore, these technologies facilitate improved customer service through virtual consultations and personalized interactions, fostering stronger customer relationships and loyalty.

The adoption of these Metaverse technologies is reshaping supply chain processes by enhancing operational efficiency, transparency, and customer engagement across various domains.

RQ3: Adopting Metaverse technologies in supply chain management yields a multitude of significant benefits, enhancing operational efficiency, transparency, and resilience across global supply networks. A primary advantage is the enhanced visibility and traceability of products and transactions facilitated by blockchain technology, which establishes secure and immutable records. This transparency not only aids in the detection and prevention of fraud but also guarantees the authenticity of goods, thereby fostering trust among supply chain stakeholders.

The integration of digital twins and IoT enables real-time monitoring and management of assets, allowing for predictive maintenance and the optimization of logistics operations. This results in reduced downtime, decreased operational costs, and more efficient resource utilization, consequently improving overall operational efficiency.

Additionally, Metaverse technologies such as AI and machine learning provide advanced data analytics and predictive capabilities, which are crucial for accurate demand forecasting, inventory management, and risk mitigation. These technologies empower supply chain managers to anticipate disruptions and proactively adjust operations, thereby enhancing the resilience and agility of supply chains.

In the realm of customer relations, AR and VR offer immersive and interactive experiences that elevate customer engagement and satisfaction by providing virtual product trials and personalized services. This not only enriches the customer experience but also supports stronger customer loyalty.

Overall, the adoption of Metaverse technologies equips supply chain networks with the tools to operate more transparently and efficiently, while also enhancing their capacity to withstand and recover from disruptions. This technological integration fosters the

development of a more robust and reliable global supply network, capable of adapting to evolving market demands and challenges.

RQ4: The integration of metaverse technologies into supply chain management represents a paradigm shift, employing a sophisticated array of tools that significantly enhance transparency, operational efficiency, and resilience across industries. Metaverse technologies, including digital twins, blockchain, virtual and augmented reality (VR/AR), and Internet of Things (IoT) integrations, offer a dynamic platform for real-time simulation and optimization of supply chain operations. For example, BMW's collaboration with NVIDIA's Omniverse has enabled the creation of comprehensive digital twins for their global production facilities. These digital replicas facilitate real-time data analysis, allowing BMW to simulate production processes, optimize factory layouts, and predict maintenance needs without the constraints of physical prototypes, thereby reducing downtime and operational costs. Similarly, Renault's industrial digital twin system integrates over 8500 pieces of equipment, providing continuous monitoring of 90% of supply flows. This integration has significantly improved predictive maintenance, operational efficiency, and cost-effectiveness.

Blockchain technology complements digital twins by ensuring the integrity, traceability, and transparency of transactions across the supply chain. The Blockchain-based Digital Twin for IoT deployments, developed using Ethereum and FIWARE Canis Major, exemplifies this integration. It enables detailed tracking and secure management of logistics operations, addressing common issues such as delays and fraud by providing an immutable ledger of all transactions. This approach enhances stakeholder trust and operational reliability.

The metaverse also fosters enhanced collaboration and training through immersive virtual environments. Accenture's virtual collaboration rooms, for instance, provide a platform for supply chain stakeholders to meet, simulate scenarios, and coordinate activities efficiently. These rooms utilize VR to create a realistic and interactive space for discussing supply chain disruptions, inventory management, and logistics planning, leading to more effective decision-making. DHL's VR training programs are another example, where VR is used to

simulate warehouse operations like order picking in a controlled, risk-free environment. This training approach not only enhances the skill set of employees but also reduces the need for extensive physical setups and associated costs.

In terms of resilience, metaverse technologies enable real-time monitoring and predictive maintenance, ensuring that supply chains remain robust against disruptions. Maersk employs digital twins to monitor the condition of its logistics infrastructure, predicting maintenance needs and optimizing logistics processes. This capability helps in reducing downtime and maintaining the continuity of supply chain operations. Hypertrack's last-mile delivery metaverse system simulates delivery scenarios to identify and mitigate potential disruptions, enhancing the reliability of order fulfillment processes.

The metaverse also plays a critical role in promoting sustainability within supply chains. For example, in the semiconductor industry, metaverse technologies are used to enforce green procurement policies and ensure compliance with environmental standards. This integration allows for virtual inspections and digital auditing, which help in reducing environmental impacts and promoting sustainable practices. JD.com's metaverse initiatives, including their Supply Chain Emission Management Platform, illustrate how metaverse technologies can track and manage the carbon footprint of logistics operations, aligning with eco-friendly goals and regulatory compliance.

Real-world applications of metaverse technologies in supply chain management demonstrate their practical benefits and transformative potential. DHL's use of augmented reality for order picking in their Netherlands storage facility, employing smart glasses like Google Glass, has led to a 25% reduction in picking time by providing real-time visual instructions to workers. This example highlights the efficiency gains that metaverse technologies can bring to logistics operations. Similarly, Google Glass's implementation in warehousing has improved order sorting and operational accuracy. JD.com's significant investments in metaverse technologies underscore the potential for these tools to enhance supply chain resilience and transparency, with initiatives focused on AI integration and carbon footprint management.

In the realm of luxury goods, Nike's Cryptokicks iRL project leverages NFTs and NFC technology to ensure the authenticity of physical products, seamlessly integrating digital and physical supply chains. This innovative approach not only secures product quality but also enhances inventory management. BMW's collaboration with NVIDIA to create a digital twin of their Regensburg factory exemplifies the use of metaverse technologies in optimizing production processes and enhancing worker productivity through AI-driven simulations.

Overall, the metaverse offers a transformative platform for supply chain management, integrating advanced technologies to foster a more efficient, transparent, and resilient supply chain ecosystem. By leveraging these technologies, companies can achieve significant improvements in operational workflows, sustainability, and stakeholder collaboration, setting a new standard for supply chain management in the digital era.

5.3 Limitations

We adopted a systematic approach throughout this survey for assessing the retrieved literature. However, our overall approach presents some limitations worth noting. For instance, we may not have achieved content saturation during our search process, especially because we included in our analysis mainly papers published in peer-reviewed journals. Excluding papers published in book chapters or peer-reviewed international conferences may have lessened our survey's comprehensive and interdisciplinary nature. Additionally, during the full-text review, we excluded works based in conferences, books, and papers that were not accessible, which may have further impacted the breadth of our analysis.

6. Conclusion

This thesis comprehensively investigates the transformative implications of digitalization and the integration of metaverse technologies within supply chain management (SCM). The study underscores the pivotal role of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), blockchain, and the metaverse in revolutionizing SCM processes by enhancing operational visibility, efficiency, and resilience. The

metaverse, defined as an amalgamated virtual space facilitated by Virtual Reality (VR), Augmented Reality (AR), and blockchain, emerges as a significant technological advancement. It enables real-time interaction and the secure management of digital assets, thereby optimizing supply chain functions through improved transparency and traceability.

This review identifies a prominent focus on applications within sectors such as agriculture and food supply chains, where there is a critical need for enhanced traceability and transparency. Despite these advancements, the literature reveals substantial gaps, particularly in the explicit assessment of economic, environmental, and social impacts of these technologies. This highlights the need for more comprehensive research to elucidate the broader implications of metaverse integration in SCM. Several challenges impede the full realization of these technologies in SCM, including technological integration, data security, market adoption, and regulatory compliance. Addressing these challenges necessitates the development of scalable, standardized solutions and ensuring seamless integration with existing systems.

Moreover, there is an urgent need to address the legal and ethical considerations associated with these technologies to support their sustainable and responsible deployment. The practical applications of metaverse technologies within SCM are diverse and impactful. VR and AR technologies significantly enhance inventory visualization and remote training capabilities, while blockchain and digital twins facilitate superior transparency and decision-making in logistics and distribution. These technologies are instrumental in transforming traditional SCM paradigms into more agile, resilient, and efficient systems. Future research must focus on the practical implementation of metaverse technologies, demonstrating tangible benefits such as cost reduction and enhanced sustainability. Establishing standardized benchmarks will be critical for evaluating the efficacy of these technologies. Additionally, there is a necessity for more detailed sustainability assessments to provide a comprehensive understanding of the long-term value of metaverse technologies in SCM.

In conclusion, the integration of metaverse technologies into SCM holds substantial promise for enhancing efficiency, transparency, and resilience within supply chains. By addressing the existing challenges and focusing on real-world applications, these

technologies can significantly contribute to the development of more robust and adaptive supply chains, capable of meeting the demands of an increasingly dynamic global market.

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