Internet of Things 23 (2023) 100884

Contents lists available at ScienceDirect

Internet of Things

journal homepage: www.elsevier.com/locate/iot

Review article

Metaverse applications in smart cities: Enabling technologies, opportunities, challenges, and future directions

Ibrar Yaqoob [a,*], Khaled Salah [a], Raja Jayaraman [b], Mohammed Omar [b]

[a] Department of Electrical Engineering and Computer Science, Khalifa University, Abu Dhabi, 127788, United Arab Emirates
[b] Department of Industrial & Systems Engineering, Khalifa University, Abu Dhabi, 127788, United Arab Emirates

ARTICLE INFO

Keywords:
Metaverse
Internet of Things
Smart cities
Extended reality
Digital twins
Avatars
Virtual world

ABSTRACT

Recent years have witnessed a global trend toward the metaverse. The metaverse is a collection of immersive and interconnected digital spaces in which users can interact through computer-generated environments. As smart cities aim to enhance the experiences of their citizens by improving infrastructure, modernizing government services, increasing accessibility, accelerating economic growth, and promoting sustainability, the metaverse has the potential to significantly revolutionize, reshape, and transform smart cities. In this paper, we discuss how leveraging the metaverse for smart cities can stimulate innovations and bring about major improvements. We discuss the key enabling technologies for the metaverse, along with the premier benefits of adopting this technology and the opportunities it presents for smart city applications. We present ongoing projects and case studies to showcase the practicality of metaverse technology across various industries. Furthermore, we identify and discuss critical research challenges that currently impede the realization of the full potential of the metaverse. Finally, we outline future research directions that can be pursued to further the development of the metaverse and its integration with smart cities.

1. Introduction

The popularity of the metaverse has been continuously growing worldwide since Facebook rebranded itself as ‘Meta’ in October 2021. A metaverse is an immersive and 3D virtual world in which people can interact through avatars to carry out their daily interactions, unlocking the potential to communicate, transact, and experience new opportunities on a global scale [1–4]. The metaverse involves the convergence of several cutting-edge technologies, such as artificial intelligence (AI), digital twins, augmented reality (AR), virtual reality (VR), blockchain, non-fungible tokens (NFTs), 3D modeling and simulation, cloud computing, and edge computing, to name a few [5–8]. A Gartner report predicts that approximately 25% of people will spend at least an hour daily in the metaverse by 2026 [9]. A McKinsey report identifies that more than $120 billion have already flowed into the metaverse in 2022, and it is expected to generate up to $5 trillion in value by 2030 [10]. According to the European Parliament report, economic studies predict that the global metaverse market will reach €597.3 billion by 2030 [11]. The metaverse activities are growing rapidly at major tech companies. Tech giants, including Meta (formerly Facebook), Microsoft, and Qualcomm, have invested in the creation of the metaverse [11]. There is an emerging metaverse trend in China as well. The European Parliament report reveals that the parent company of TikTok, ByteDance, has invested €1.2 billion in Pico, a maker of virtual reality headsets. Furthermore, Alibaba has also invested €52.8 million in Nreal, which makes augmented reality glasses. Investments in the metaverse are not only made by companies but also by individual users. For example, the biggest individual purchase in the metaverse has been made by one

* Corresponding author.
E-mail address: ibraryaqoob@ieee.org (I. Yaqoob).

https://doi.org/10.1016/j.iot.2023.100884
Received 10 April 2023; Received in revised form 10 July 2023; Accepted 18 July 2023
Available online 29 July 2023

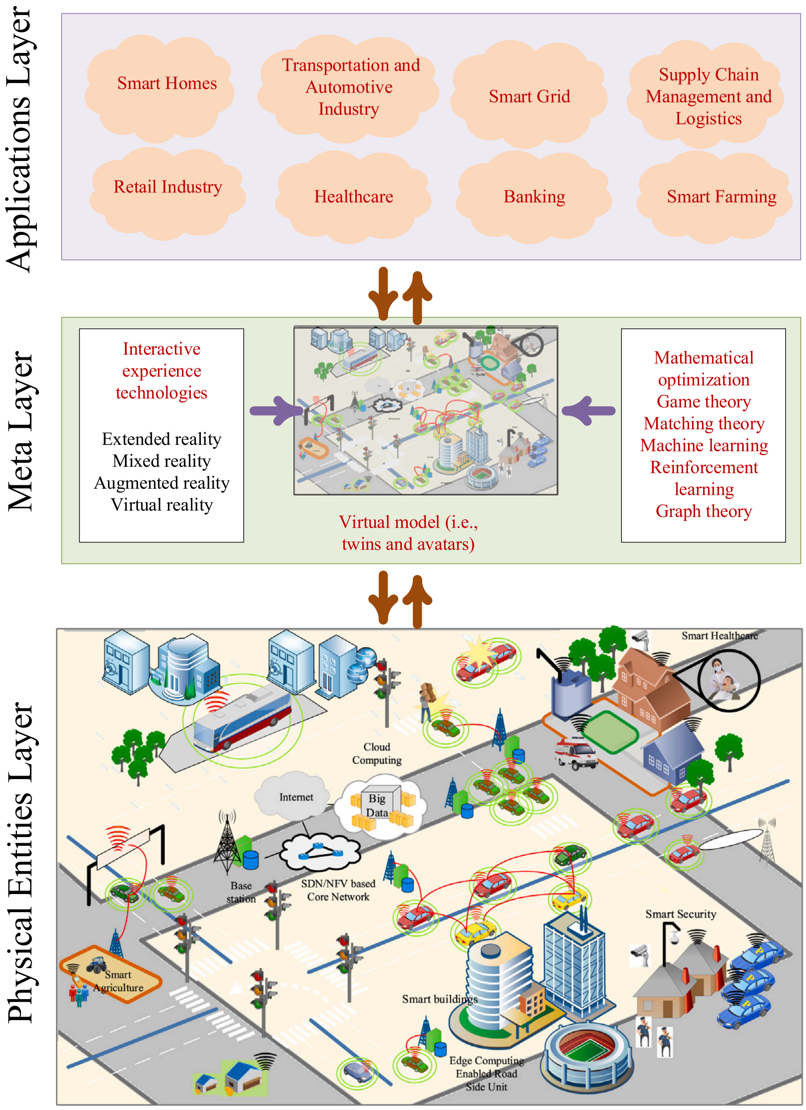

Fig. 1. Overview of the metaverse-based smart city architecture.

user in the virtual world Sandbox, worth around €3.7 million [11]. Another user has invested $450,000 just to become Snoop Dogg's virtual neighbor [12]. The evolution of smart cities is about to take another turn, as Seoul announced its plans to spend $3.3 billion to become a metaverse city [13]. Besides, the UAE also announced its plans to create a virtual city in the metaverse [13]. Undoubtedly, the metaverse is emerging as a fast-developing technology sector.

Smart cities are urban areas that utilize digital technologies and cutting-edge solutions to provide better infrastructure, modernize government services, improve accessibility, accelerate economic growth, and improve sustainability [14]. The metaverse has the potential to revolutionize many areas in smart cities, including healthcare, energy management, transportation, smart homes, supply chain and logistics, tourism, retail and marketing, smart farming, and banking, among others, as illustrated in Fig. 1. Mathematical optimization, game theory, matching theory, machine learning, reinforcement learning, and graph theory can play integral roles in virtual worlds, such as digital twins and avatars, as shown in Fig. 1. These techniques and methods can assist in optimizing resource allocation, analyzing strategic interactions, extracting patterns from data, and modeling network structures in metaverse-based smart cities. In addition, their application can enhance the functionality and realism of virtual environments, resulting in more immersive and efficient experiences in metaverse-based smart cities. More specifically, the metaverse can enhance urban planning and construction, economic development, daily life, education, and emergency events in smart cities [15]. It can provide a virtual experiment site for planning and construction and can allow for the creation of a metaverse economy that can mitigate pollution and carbon emissions [15,16]. It can also improve transportation, predict resource usage, and provide a new way of life and experiences. The metaverse can simulate city operations and emergency events, and improve emergency response capabilities and

Table 1
Comparison between our and the existing survey/review articles on the metaverse topic.

Ref.	Survey/review title	Key focus
[1]	A full dive into realizing the edge-enabled metaverse: Visions, enabling technologies, and challenges	Edge computing, Metaverse, Enabling Technologies, and Challenges
[3]	A survey on metaverse: Fundamentals, security, and privacy	Metaverse, Security, and Privacy
[24]	Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy	Metaverse, Research, Policy, and Practice
[25]	A new technology perspective of the metaverse: Its essence, framework and challenges	Metaverse, Framework, and Challenges
[26]	A review of QoE research progress in metaverse	Metaverse, QoE, and User Experience
[27]	Artificial intelligence for the metaverse: A survey	Metaverse, AI, Distance Learning, and Education
[28]	Physical and digital worlds: implications and opportunities of the metaverse	Metaverse, Physical World, and Digital World
[29]	The digital metaverse: Applications in artificial intelligence, medical education, and integrative health	Metaverse, AI, Medical Education, and Health
[30]	A review of metaverse's definitions, architecture, applications, challenges, issues, solutions, and future trends	Metaverse, Definitions, Architecture, and Applications
[31]	Fusing blockchain and AI with metaverse: A survey	Metaverse, Blockchain, and AI
[32]	Financial crimes in web3-empowered metaverse: Taxonomy, countermeasures, and opportunities	Metaverse, Web3, and Financial Crimes
[33]	A metaverse: taxonomy, components, applications, and open challenges	Metaverse, Taxonomy, Components, and Applications
[34]	A survey of blockchain and intelligent networking for the metaverse	Blockchain and Networking Technologies
[35]	Fusion of building information modeling and blockchain for metaverse: a survey	Building Information Modeling (BIM) and Blockchain Integration
[36]	Security and privacy in metaverse: A comprehensive survey	Security and Privacy in Metaverse
[37]	All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystem, and research agenda	Technological Singularity, Virtual Ecosystem, and Research Agenda in Metaverse
[38]	Metaverse	General Overview of Metaverse
[39]	Educational applications of metaverse: possibilities and limitations	Educational Applications of Metaverse
[40]	Metaverse for Healthcare: A Survey on Potential Applications, Challenges and Future Directions	Metaverse Applications in Healthcare, Challenges, and Future Directions in terms of Healthcare
[41]	Metaverse in healthcare: Applications, Challenges, and Future directions	Applications of Metaverse in Healthcare along with challenges and Future Directions
[42]	The Metaverse as a Virtual Form of Smart Cities: Opportunities and Challenges for Environmental, Economic, and Social Sustainability in Urban Futures	Reviews the Metaverse's products and services and their impact on smart cities, emphasizing sustainability and assisting policymakers.
	Our Survey	Smart City Applications of Metaverse, Metaverse-Enabling Technologies, Key Components and Benefits of Metaverse in Smart Cities, Case Studies, and Challenges

urban resilience. Besides, using the metaverse in smart cities can improve accessibility and humanity for users since they can interact as virtual images and avoid real-world problems [17]. With a stable monetary and cultural system, immersive user participation, and virtual-real interactions that are powered by the metaverse, residents of smart cities can discover changes in advance, simulate problem disposal, and provide feasible pre-treatment schemes for the real world.

The metaverse can profoundly enhance the development of smart cities. However, to fully realize the potential of the metaverse, further technological development is needed, along with the complementary integration of multiple technologies. Also, some key challenges posed by the metaverse need to be solved before it can be used as a practical solution for smart city problems. In this paper, we aim to explore the role of the metaverse in smart cities. In general, smart cities [18–23] and metaverse [1,3,24–42] topics have been individually investigated. Our survey is distinctively different from the existing surveys and reviews conducted on the metaverse topic in terms of focus and content, as can be seen in Table 1. Besides, several other important aspects of the metaverse technology with respect to intrinsic features, emerging opportunities, and potential challenges, which are presented in the current survey, have not been previously reported. Our key contributions are listed below:

- We provide insightful discussions on the key enabling technologies for the metaverse and outline its components, as well as present notable benefits of the metaverse in smart cities.
- We explore and discuss in detail the important opportunities brought about by the metaverse for smart city applications.
- We present several reported case studies to showcase the practicality of metaverse-based solutions.

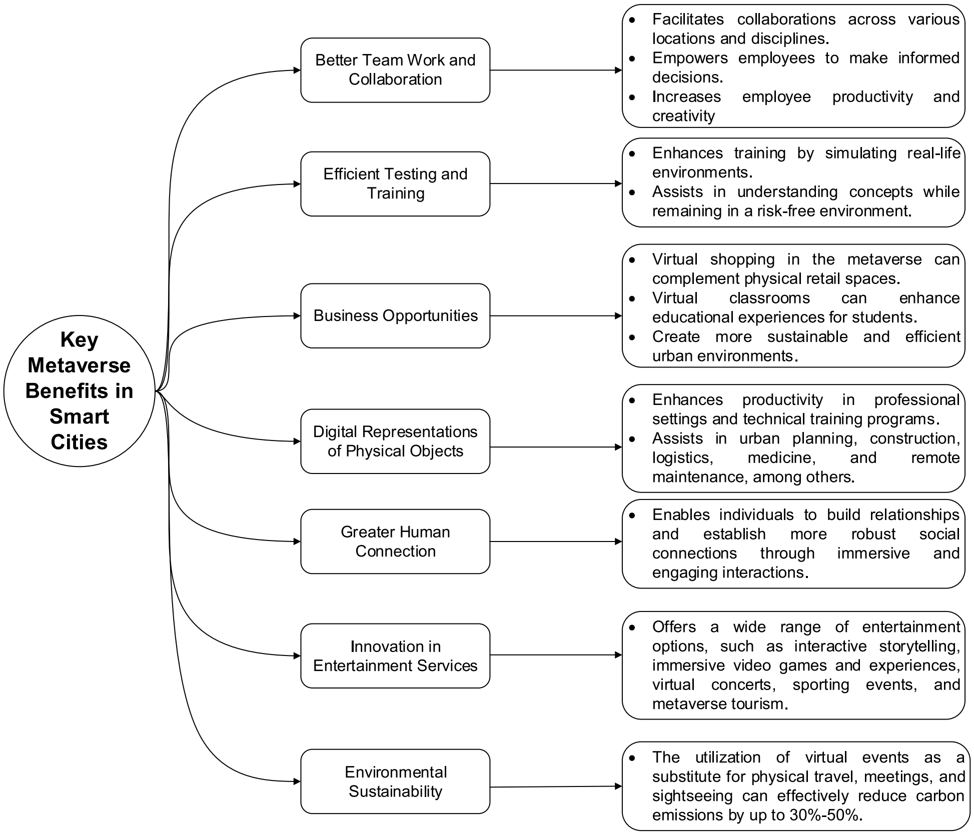

Fig. 2. Key metaverse benefits in smart city applications.

- We identify and discuss important research challenges of the metaverse, along with their underlying key causes, and outline several future recommendations.

The paper is organized as follows: Section 2 introduces the metaverse and its key components, followed by a discussion of the benefits of the metaverse in smart cities. Section 3 presents the enabling technologies for the metaverse. In Section 4, potential opportunities brought about by the metaverse for smart city applications are discussed. Section 5 highlights recent projects and case studies related to the metaverse. Section 6 outlines open research challenges that need to be addressed in order to fully realize the potential of the metaverse. Section 7 summarizes the key findings and provides future recommendations for the implementation and development of the metaverse in smart cities.

2. Components and benefits of the metaverse in smart cities

2.1. Components

The metaverse consists of four key components: space, interface, monetary infrastructure, and compute [43]. The space component is a virtual world accessed through the Internet, requiring high-speed networks and real-time connections. The interface includes VR/AR headsets, mobile devices, and smart glasses. The monetary infrastructure supports digital transactions for buying and selling digital assets in the metaverse. The compute component provides the necessary computational power for users to interact with 3D objects. Through the integration of various technologies, the metaverse creates a tangible digital layer over reality. Additionally, the metaverse can adopt different organizational models, such as centralized, decentralized, or hybrid structures.

2.2. Key benefits of the metaverse in smart cities

Fig. 2 outlines the key benefits of leveraging the metaverse for smart city applications, as discussed below.

2.2.1. Better team work and collaboration

The metaverse has the potential to revolutionize workspaces in smart cities. It achieves this by enabling improved team communication, rapid skill acquisition, and AI-driven insights. These advancements lead to increased employee productivity and creativity [44]. The impact is particularly significant for smart city workspaces that involve collaborations across different locations and disciplines. Real-time collaboration, irrespective of distance, plays a vital role in fostering innovation and effective teamwork, which are critical factors for smart city projects [44]. Moreover, the flexibility, customization, and personalization options offered by the metaverse optimize employee focus, resulting in more efficient work outcomes. Augmented metaverses further enhance the experience by overlaying real-time information onto the physical world. This empowers employees to make informed decisions, an essential aspect of smart city development and management [44].

2.2.2. Efficient testing and training

Extended reality (XR) technology has immense potential in smart cities. It primarily enhances training through realistic simulations and valuable feedback [45]. This application is particularly relevant in the medical field. XR can assess treatment responses, surgical outcomes, and product issues using digital twin technology [45]. Personalized XR content provides convenient access, while live streaming enables real-time communication with instructors. XR also enables the safe exploration of risky or costly procedures, aiding in the comprehension of complex concepts. Invasive surgeries can be transformed through XR, as it allows doctors to record and visualize patient anatomy using AR and VR-based models. Additionally, in the smart city context, the metaverse plays a role by accumulating substantial data. This data supports decision-making processes and alleviates cognitive load.

2.2.3. Business opportunities

The metaverse and its underlying technologies have implications for smart city development, offering businesses virtual space opportunities [16,46]. It is considered the next iteration of the Internet, providing engagement and innovation prospects within smart cities. Additionally, it complements physical retail spaces through virtual shopping and enhances educational experiences with virtual classrooms [47]. The metaverse's decentralized, interoperable, and collaborative nature fosters the creation of sustainable and efficient urban environments. In smart cities, users have the ability to own metaverse assets and engage in trading [48]. Exploring the possibilities of the metaverse enables smart city planners and businesses to expand their digital capabilities and enhance the quality of life for citizens [47].

2.2.4. Digital representations of physical objects

Digital twins are a crucial component of the metaverse. They enable the precise replication of reality and enhance smart city areas, such as urban planning, construction, logistics, and medicine [6,49]. These digital replicas can be continuously updated with real-time data from various smart city sources. In smart cities, digital twins have the potential to improve productivity in professional settings and technical training programs. They facilitate the operation of complex systems in a 3D environment. Additionally, the metaverse can establish a complete maintenance workshop that is connected to a real workshop, enabling remote maintenance capabilities. The potential applications of digital twins in the metaverse are still being explored across diverse smart city environments.

2.2.5. Greater human connection

The metaverse connects geographically separated individuals in smart cities and those with disabilities, fostering social connections [50,51]. Immersive interactions in the metaverse build relationships and strengthen social ties. Shared experiences, like games or events, create community and purpose [52,53]. Avatar customization allows for personal expression and individuality within smart city communities. Virtual reality chat rooms, forums, and groups facilitate social connections among individuals with shared interests. The virtual reality experiences in the metaverse enhance communication and collaboration in smart cities, with particular benefits for those with physical or cognitive differences. Overall, the development of the metaverse has significant potential to promote and enhance human connection in smart cities through technological advancements.

2.2.6. Innovation in entertainment services

The metaverse can reshape the entertainment industry in smart cities by offering interactive storytelling, immersive video games, virtual concerts, sporting events, and metaverse tourism [54,55]. It combines traditional media and video games for interactive storytelling and can become a VR gaming hub for immersive experiences [54]. Additionally, the metaverse enables hosting virtual music performances, album releases, and exclusive content. Sporting events provide a realistic stadium experience, and metaverse tourism allows affordable exploration of famous landmarks [56]. Overall, the metaverse can revolutionize the entertainment industry in smart cities.

2.2.7. Environmental sustainability

There is debate over the environmental effects of the metaverse. One perspective is that virtual activities can reduce energy consumption. According to [57], creating a digital twin in the metaverse with AI and machine learning (ML) can lead to up to 50% energy and cost savings during a building's life cycle, thereby revolutionizing environmental sustainability in smart cities. By replacing physical travel, meetings, and sightseeing with virtual events, smart cities can effectively reduce carbon emissions while enhancing work productivity [58]. Hence, the metaverse offers a promising platform to address global environmental issues and foster a sustainable future.

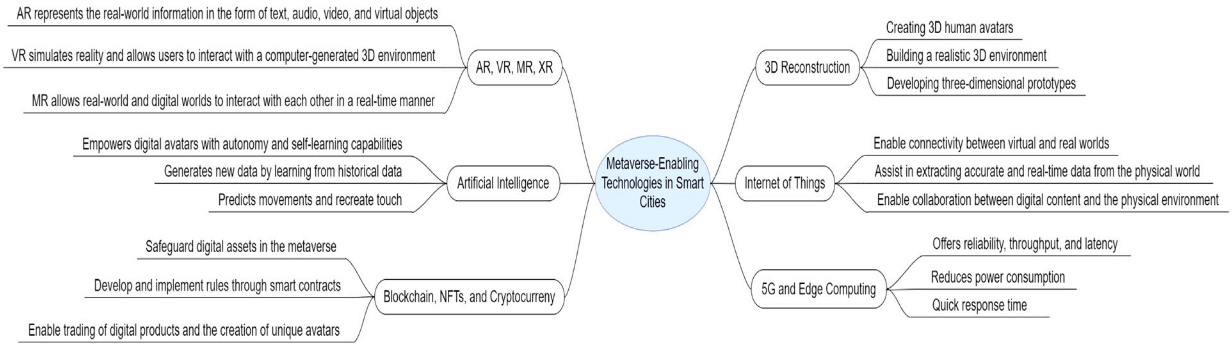

Fig. 3. Metaverse-enabling technologies.

3. Enabling technologies for the metaverse

In this section, we present the main metaverse-enabling technologies, as summarized in Fig. 3. Further details are provided in the following subsections.

3.1. AR, VR, MR, and XR

AR, VR, mixed reality (MR), and XR are the driving metaverse technologies that offer immersive experiences. AR represents real-world information in real-time using text, audio, video, and virtual objects [59]. It has two types: marker-based and markerless. Marker-based AR identifies objects and determines camera position and orientation through image recognition. On the other hand, markerless AR uses recognition algorithms and data from accelerometers, GPS, and compass to overlay AR images onto real-time identified objects. There are five components of AR: AI, AR software, processing power, lenses, and sensors. AI is used for voice prompts and information processing, while AR software can be custom-built. Processing power is required for AR to work, and lenses are needed to view content. Sensors help align the real and digital worlds by processing data from the camera. VR [60] is a computer-generated 3D environment that simulates reality and allows users to interact with it. VR headsets or helmets are used to perceive the VR environment. There are mainly three types of VR systems [61]: non-immersive, semi-immersive, and fully immersive. The first category involves accessing a 3D simulated environment through a computer screen; whereas, the second type emphasizes visual 3D effects and lacks physical movement. However, fully immersive VR provides a complete experience by simulating a 3D world with visual, auditory, and tactile sensations. MR combines VR and AR, allowing real-world and digital objects to interact with each other in real-time [62]. It requires more processing power than VR or AR. Microsoft's HoloLens is an example of this technology. Through built-in cameras, Microsoft HoloLens offer unique gaming experiences. These games allow characters to interact with the physical world. To create genuine MR experiences, three key components are required: cloud-based computer processing, enhanced input methods, and environmental recognition. Immersive technologies, including VR, AR, and MR, are collectively referred to as XR [63].

3.2. Artificial intelligence

AI powers the metaverse using a combination of natural language processing (NLP) and computer vision techniques [27,64]. NLP and computer vision play a vital role in enhancing the comprehension and processing of both natural language and visual information. ML algorithms automate decision-making in NLP and computer vision, empowering systems to autonomously analyze data, extract patterns, and make well-informed predictions. NLP primarily focuses on language processing, while computer vision specializes in image and video analysis, extracting valuable insights from unstructured data. The metaverse relies on AI to generate most of its 3D images, animations, and speech, as well as to generate smart contracts and conduct virtual transactions [65]. In addition, AI enhances the metaverse by improving rendering, object detection, and cybersickness control [65]. Through AI advancements, digital avatars are empowered with autonomy and self-learning capabilities. With their own motivations, stories, and objectives, these avatars can interact with users and other AI beings. Integrating AI with game engines enables immersive experiences as well as the creation of hyper-realistic avatars. The creation of virtual assets can also be streamlined using AI. Digital humans can be created using AI that can act in response to user actions as 3D versions of chatbots [66]. AI can process natural language inputs like English in a fraction of a second by converting them into a machine-readable format, analyzing them, and converting the results back into English for the user, replicating a real conversation [67]. In the metaverse, AI can also generate new data by learning from historical data. The newly generated data stimulates innovation by introducing novel scenarios and objects, resulting in increased diversity, accuracy, adaptability, and innovative stimulation. In virtual reality, AI can predict movements and recreate touch. Data misuse can also be prevented by AI. Overall, AI in the metaverse facilitates user interaction, data processing, and protection, enables avatar and chatbot creation, and offers various other features for an authentic experience.

3.3. Blockchain, NFTs, and cryptocurrencies

Blockchain is a decentralized, transparent, traceable, auditable, secure, and trustworthy digital ledger of transactions that can safeguard digital assets in the metaverse [5,68,69]. The metaverse must function as a synchronized virtual world, which can be achieved using a blockchain-based decentralized ecosystem that allows independent nodes to synchronize [70]. Smart contracts allow participants in an ecosystem to regulate their economic, legal, and social relationships effectively. Also, they allow the metaverse to develop and implement basic rules. In the metaverse, users can socialize, entertain themselves, and trade in a real-time manner. Crypto assets are used to facilitate exchanges between these activities in the metaverse since these activities require a common currency. Metaverse users use blockchain-based cryptocurrency for both real and virtual purchases, making it a versatile payment option [71]. Incorporating NFTs, which are blockchain-based crypto tokens, into the metaverse can ease the trading of digital products and the creation of unique avatars since they offer immutable proof of ownership recorded on the blockchain [72–75]. Additionally, NFTs can contribute to the growth and development of the metaverse by creating a digital economy within it. Thus, NFTs are essential to the evolution of the metaverse, ensuring a transparent and secure environment for users [76]. Overall, blockchain has the potential to protect against hacks and malware, as well as eliminate centralized decision-making processes regarding the functioning of the metaverse. Blockchain can help build a secure, stable, reliable, and trustworthy virtual ecosystem.

3.4. 3D reconstruction

The existence of the metaverse greatly relies on a 3D environment. 3D reconstruction technology is used to create 3D objects in virtual spaces. Land-related matters have increasingly been handled using this technology, mostly to facilitate access to land by those who are not able to visit it in-person [77]. A 3D representation of the land can be viewed by potential buyers through 3D reconstruction, which has become a useful tool [77]. For the metaverse to become a fully realized virtual space, this technology is essential for creating 3D human avatars. Building a realistic 3D environment for the metaverse is one of the core requirements. 3D cameras and reconstruction technologies capture real-world data that is analyzed by computers to create simulations for the metaverse. In summary, to make the metaverse more realistic, 3D reconstruction technology is essential. Real objects can be transformed into 3D models that capture their shape and appearance, allowing the metaverse to become a reality. 3D modeling and reconstruction methods are used to develop 3D prototypes for specific processes or products in the metaverse. A SkyQuest Technology Consulting report estimates that the global market for 3D reconstruction technology will double to $2 billion in 2028 [78].

3.5. Internet of Things, 5G technology, and edge computing

The Internet of Things (IoT) enables virtual worlds to interact with the real world [79]. In contrast, metaverse technology offers 3D user interfaces for IoT device clusters [80]. In this way, user-centric IoT and metaverse experiences are created [80]. Combining these technologies enables minimal training and effort for data-driven decision-making. Besides, the IoT plays an essential role in extracting and incorporating accurate, secure, and real-time data from the physical world into the metaverse. The success of the metaverse depends on its ability to extract and present meaningful patterns from real data while ensuring user safety and accessibility. Since IoT establishes links between the physical and digital worlds, a sophisticated IoT infrastructure is required to support the growing complexity of the digital environment. IoT-powered digital avatars are a key component of the next-generation internet [80]. Some examples of IoT devices that can be used in the metaverse include HMDs, AR glasses, haptic devices, and motion sensors, which can enable users to engage with virtual environments through gestures and touch. Besides, in the metaverse of smart cities, a variety of other IoT devices are used for seamless integration. For example, environmental sensors for real-time monitoring, smart infrastructure devices for efficient management, intelligent transportation systems for traffic control, wearable devices for personalized interactions, and building automation systems for optimized operations. These IoT devices enable data collection, monitoring, and enhanced urban experiences.

5G technology plays a key role in enabling the metaverse and its applications. The 5G network can provide reliability, throughput, and latency, which are the essential requirements of the metaverse. 5G technology dramatically reduces power consumption and increases data rates over most wired broadband connections by almost 90% [81]. In addition, the system reduces latency by almost 20X, and it improves reliability by about 95% [81]. The metaverse benefits from all of these factors and meets special needs for applications within the metaverse. On the other hand, edge computing is also one of the enabling technologies of the metaverse. With edge computing, users can experience a quick response time, which gives users a sense of immersion and keep them in the metaverse [1,78].

4. Opportunities

In this section, we briefly discuss how metaverse technology can assist in enhancing smart city applications by bringing major improvements, as summarized and shown in Fig. 4.

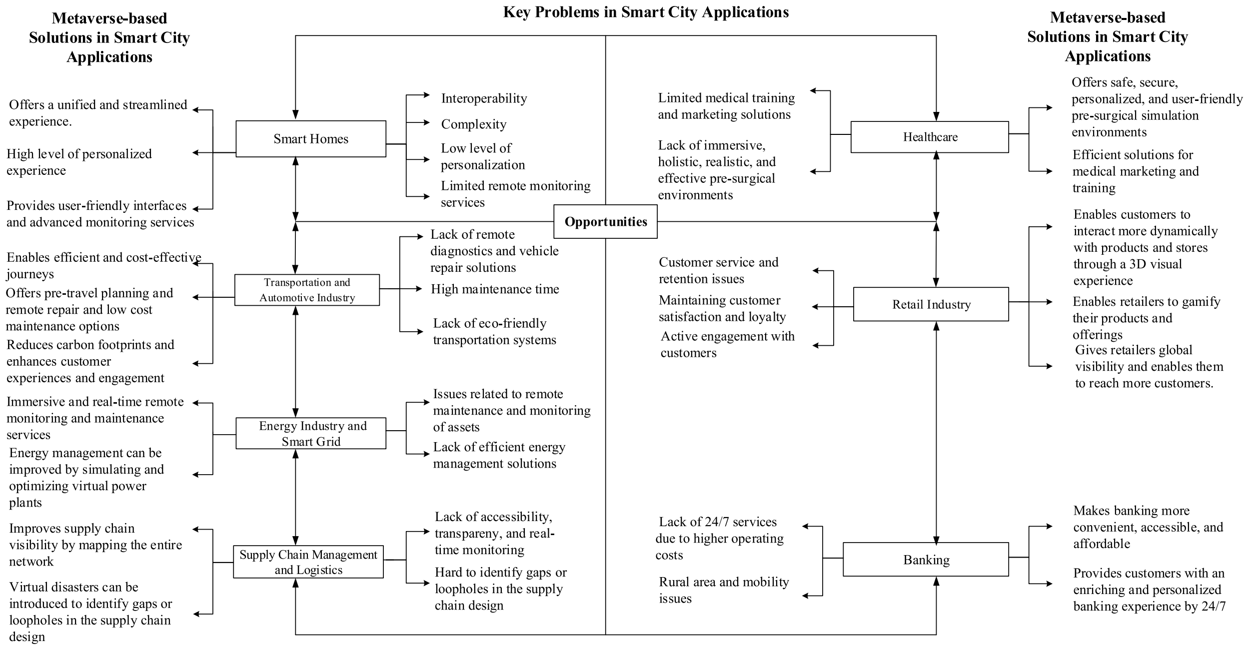

Fig. 4. Metaverse opportunities in smart city applications.

4.1. Smart homes

In recent years, there has been a notable increase in the adoption of smart home devices, ranging from smart speakers and displays to cameras, thermostats, and vacuum cleaners [82]. Besides, Alexa, Google Assistant, and Siri have also emerged as popular voice-activated assistants that can help perform different tasks and provide entertainment in smart homes [82]. Using VR and AR technologies, Alexa and Google Assistant are modeled as interactive avatars. Smart speakers and displays can be used in the early stages of metaverse assistants and smart hubs as gateways to visual assistance. Smart home products also allow online shopping and social interaction. Smart home devices offer various ways to connect with people without leaving the house. With Amazon's Drop-in and video calling features, smart home device owners can have virtual chats with family members through interactive displays. The next wave of VR technology can lead to a revolutionary virtual experience, combining reality with augmented elements. Smart home devices can serve as gateways for avatar versions of ourselves to interact with real-world environments. This can be especially helpful for elderly device owners using Alexa and Google Assistant's Ask My Buddy skill in case of emergencies [82].

The metaverse widgets can allow smart home devices to be mapped and controlled [82]. This can assist in managing smart home devices in virtual reality. For example, metaverse widgets linked to the actual smart thermostat can be used to raise the temperature in a smart home with a few hand gestures [82]. A similar experience can be offered by the metaverse, where one can interact with a robot vacuum through an on-screen inventory, controlling various settings and commands [82]. Despite its exciting opportunities for improving smart homes, the metaverse also poses challenges, such as privacy and security. To maximize benefits and minimize adverse impacts, stakeholders must prepare for these changes as technology advances and smart homes become more integrated with the metaverse. Overall, the metaverse has the potential to substantially enhance smart homes by making lives more convenient and advanced.

4.2. Transportation and automotive industry

The transportation sector can benefit significantly from meta-mobility technologies, including autonomous cars and remote-control robots. By leveraging these technologies to bridge the digital and physical worlds, one can discover more efficient and eco-friendly routes [83,84]. Digital replication of physical infrastructure, such as airports and transit systems, can enable the seamless movement of people and goods, resulting in more efficient and cost-effective journeys [83]. Furthermore, the metaverse has significant potential to enhance customer experiences and engagement. For example, three-dimensional virtual tours can be utilized by the hospitality industry to improve pre-travel planning information, booking experiences, guest satisfaction, and booking volume [83].

On the other hand, the metaverse holds the potential to enhance customer experiences in the automotive industry by enabling manufacturing companies to engage customers through entertainment, gaming, and productivity features in vehicles [83,85]. Besides, the metaverse technology offers efficient remote diagnostics and touchless vehicle repair, increasing customer satisfaction and retention [86]. It also enhances automotive technicians' skills, improving customer satisfaction. Virtual reality in the metaverse showcases vehicle features, further contributing to customer satisfaction. The metaverse has the potential to revolutionize transportation by developing an eco-friendly system with meta-mobility technologies and digital replicas. Leveraging the metaverse provides unique automotive experiences, thereby boosting satisfaction and retention.

4.3. Energy industry and smart grid

The metaverse holds great promise for the energy sector, especially in the adoption of renewable energy sources. According to [87], it can offer three advantages for the industry. Firstly, it can act as a robust communication channel. This can enable customer interaction and supplier support while enhancing brand image through immersive virtual activities. Secondly, it can provide a secure and engaging platform for training and skill development by utilizing digital twins to simulate realistic scenarios. Lastly, it can facilitate the creation of industrial replicas for testing energy infrastructure changes, thereby leading to cost reductions, decreased errors, and improved emissions measurements.

The integration of IoT devices and AI with virtual reality objects presents an opportunity to gain a more precise understanding of energy consumption and efficiency. Several technologies, including AR, VR, MR, IoT, AI, 3D reconstruction, and blockchain, can be used to enable the power and utility sector in the metaverse. These advanced technologies can facilitate remote maintenance and monitoring of assets, virtual site visits, field staff training, real-time asset monitoring, and transparent and efficient energy accounting. Furthermore, the implementation of these technologies can enable energy companies to expand their services to consumers and support smarter communities as distribution service operators. Besides, by leveraging virtual simulations in the metaverse, workers can be trained to manage turbines and wind power plants, thus reducing risks, saving time, and increasing efficiency.

Efficient energy usage can be achieved by utilizing the metaverse within the smart grid, as discussed in [88]. The metaverse offers the possibility to create virtual power plants composed of distributed energy resources, including wind turbines, solar panels, and battery storage systems, all managed by software platforms. Through simulation and optimization within the metaverse, energy management can be significantly improved. By visualizing energy consumption in a real-time manner, consumers and energy providers can make better-informed decisions. For example, visualization of energy usage patterns through virtual reality interfaces can lead to reducing energy consumption during peak hours. In summary, the metaverse holds tremendous potential to enhance energy management by enabling the creation of virtual power plants and real-time monitoring of energy usage.

4.4. Supply chain management and logistics

The metaverse can improve supply chain visibility by mapping the entire network. This leads to providing real-time data on product lead times, transit time, logistics costs, and delays [89]. The entire supply chain can be monitored through a virtual environment, and potential issues like weather events, component shortages, and transport disruptions can be simulated to identify weak links [89]. As a result, the supply chain's performance can be improved through trial and error testing. Furthermore, the metaverse solutions can optimize peak load planning by testing different scenarios, from order management to distribution and fulfillment, and identifying areas where the supply chain may need reinforcement during times of high demand. When historical data is unavailable or irrelevant, artificial intelligence can be used to provide accurate forecasts and decisions. Ultimately, metaverse solutions can strengthen and improve the resilience of real-world supply chains.

The metaverse can facilitate mass customization, which fosters creativity and facilitates the fast-tracking of personalized items. The ability to digitally replicate products can also improve resource allocation across numerous locations in the supply chain, allowing alternative production scenarios to be implemented [90]. Physical manufacturing facilities can be less disrupted, downtime can be reduced, and alternative production methods can be adopted more often. In addition to meeting consumer demands for personalized items, the metaverse can enable conventional factories designed for mass production to produce at a cost-efficient rate.

Using the metaverse, virtual disasters can be set up to assist in identifying gaps or loopholes in the supply chain design [91]. As a result, a more resilient and robust supply chain can be designed. Black Friday and Cyber Monday are two of the busiest times of the year for the supply chain in the E-commerce and retail sectors [91]. However, ensuring that the physical and resource capacity for handling the peak period and scaling it down for the remainder of the year is available is challenging. Using a virtual world as a simulation of peak conditions and identifying weak points in the supply chain can improve the real-world supply chain's performance.

In logistics, the metaverse can enable brands to interact with customers through virtual products [92]. One can create virtual versions of homes, try furniture models on virtual websites, and even try on clothes before making a purchase using avatars [92]. Brands can expedite marketing to their target markets and allow Bitcoin payments by providing customized products and testing new products on the virtual market. The logistics system is also expected to change with concentrated warehouse points for customization and improving the preparation and delivery of specific orders. This adds another channel to customer relations.

4.5. Healthcare

The Coronavirus 2019 (COVID-19) pandemic has exposed significant limitations of the current digital healthcare systems and raised major challenges. For example, telemedicine and e-health services relied on suboptimal solutions, such as online interviews, in-home medical tests, online pharmacies, and the exchange of simple biodata and photos collected from mobile applications [93]. Digital health in general has fallen short of providing immersive, holistic, realistic, real-time, accurate remote and intelligent diagnostics, patient monitoring, and effective treatment [40]. Furthermore, existing digital health systems have failed to provide data management solutions capable of handling and accessing the massive amounts of data generated in healthcare while maintaining privacy, security, patient-centric control, transparency, traceability, auditability, and compliance with regulations, such as GDPR and HIPAA. Hence, there is a pressing need to transform digital healthcare using novel technologies. The metaverse is one of the emerging technologies that can bring ground-breaking innovations, digital transformations, and massive improvements in the smart healthcare sector [40,94].

The metaverse can bring significant improvements and innovations to the current healthcare systems by providing superior healthcare services; offering safe, secure, personalized, and user-friendly pre-surgical simulation environments (e.g., to perform pre-surgical mapping in patients with cardiovascular diseases and brain tumors), as well as efficient solutions for the mental health of frontline medical workers and for medical marketing and training [58,95,96]. With the metaverse, cardiovascular interventional procedures can be performed with superior efficiency and precision, as well as with lower complications. Using the metaverse, cardiac cavities, coronary anatomy, and the vascular system can be more clearly visualized, ensuring enhanced operability through real-time guidance combined with surgical navigation systems. Through the metaverse, cardiac surgeons can operate across the world and train the next generation of physicians, which can drastically transform the smart healthcare sector. In dental surgery, the metaverse can be used to manage pain through distraction therapy. A consultation can be provided to patients using the VR headset to elaborate on their case by virtually simulating the surgery. Overall, the metaverse has the potential to significantly improve the healthcare sector.

4.6. Retail industry

Customer service, active engagement with customers, customer retention, and building and maintaining customer loyalty are all areas where the retail industry faces challenges and intense competition [97]. The metaverse has the potential to address these challenges. With the metaverse, shoppers have the opportunity to interact dynamically with products and stores, leading to higher levels of satisfaction and loyalty. Retailers can tailor their offerings and enhance customer satisfaction by leveraging personalized digital avatars. Small retailers with limited resources can benefit from metaverse stores' global visibility. Using the metaverse, retailers can effectively target and segment marketing efforts [98]. New product launches in the metaverse can be gamified to appeal to younger audiences. Ultimately, retailers can improve customer engagement, gain insights, increase visibility, and attract a broader customer base through the metaverse.

4.7. Banking

Businesses are increasingly utilizing the metaverse to create virtual digital branches for banks, offering personalized service and convenience [99]. Virtual bank branches provide customers with the ability to chat with bank personnel for financial advice, transactions, and account opening, catering to those unable to visit physical branches or desiring a personalized experience [99]. These virtual branches also help banks lower costs, enhance customer service, and reduce their environmental impact. The key advantage lies in the comprehensive view of customers' financial situations, enabling access to account details, investments, transactions, upcoming offerings, and request statuses [99]. This empowers customers to make informed decisions and gain a better understanding of their financial status.

In the metaverse context, an initial pilot project involving 400 people has already been scaled up by Bank of America [99]. To train employees working with clients, the bank is expected to deploy a virtual platform that will require thousands of VR headsets. A number of other banks are likely to follow suit since virtual banking has already become a reality. A UBS banker recently equipped his London traders with Microsoft HoloLens smart glasses to recreate the experience of being on a trading floor during the pandemic, which has also been accelerating the use of virtual banking. By providing a more engaging and personalized experience for customers, virtual banking can revolutionize the banking industry.

In summary, metaverse developers can build a virtual digital bank branch to provide customers with an enriching and personalized banking experience. By using virtual banking, physical branch costs can be reduced, sustainable banking models can be created, and customer financial information can be viewed in a 360-degree manner. The growing adoption of VR technologies is expected to drive an increase in virtual banking usage in the future. As a result, the banking industry will become increasingly reliant on virtual banking services.

5. Recent ongoing projects and case studies

This section discusses recent case studies and ongoing projects toward the deployment of the metaverse technology. The purpose is to show how metaverse technology has been leveraged to bring innovations and advancements in various industries.

5.1. Nikeland

Nike has effectively utilized technologies, such as NFTs, Web3, and the metaverse to create personalized and unique customer experiences through Nikeland on Roblox [100]. The Nikeland platform [100] enables fan interaction, brand experiences, and promotional opportunities, attracting over 7 million visitors since its launch in November 2021. In response to the growing trend of NFTs, Nike acquired RTFKT Studios to develop exclusive digital assets, including the notable CryoKicks Dunk Genesis sneakers. By strategically leveraging emerging technologies, Nike caters to millennials (people born between 1981 and 1996) and Generation Z (people born between 1996 and 2010) with customized and distinctive products. Additionally, AI, e-commerce, and in-store experiential technology have long played essential roles in Nike's brand strategy. Introducing new concepts, such as the metaverse, NFTs, and Web3 has helped Nike give its customers a more personalized and unique experience. In addition to creating Nikeland and acquiring RTFKT Studios, Nike continues to demonstrate its commitment to staying at the forefront of emerging technology and providing consumers with personalized experiences.

5.2. Microsoft mesh

The Microsoft Metaverse, also known as Mesh, is a virtual space where users can interact with each other and digital objects. Microsoft Mesh [101] allows users to participate in shared holographic experiences from different locations. People can collaborate more effectively and creatively using Microsoft Teams' productivity tools. Using avatars and immersive environments, Mesh enhances teamwork and reduces meeting fatigue, similar to other post-lockdown offerings. Rather than relying on static profile images for communication, three-dimensional avatars enable users to make eye contact, interpret facial expressions, and recognize body language. Additionally, users can customize their avatars. HP Reverb G2 and Microsoft HoloLens are two examples of headgear and glasses compatible with Microsoft Mesh. Microsoft Company entered the metaverse market in 2022 and is now one of the largest investors in the space. Microsoft's pioneering products, such as HoloLens and HP Reverb G2, have made a significant contribution to the development of the metaverse. Microsoft has also incorporated other popular products like Xbox, Office 365, and Teams into the metaverse and emerged as the top player despite high competition. Additionally, Microsoft's partnership with Meta is driving innovation and offering users advanced features in virtual offices and conference rooms. Businesses and individuals benefit from seamless, interactive virtual environments. Security, transparency, and interoperability of the metaverse are currently being improved by Microsoft, which indicates a promising future for virtual space. In making the metaverse more accessible and enjoyable, Microsoft aims to pave the way for future developments.

5.3. Amazon AR view, Walmart Land, and Walmart's Universe of Play

Amazon has integrated metaverse technology into its e-commerce platform. By utilizing augmented reality, customers are now able to view products within their personal space before making a purchase. Amazon utilizes AR View [102] to ensure accurate perception of product size through appropriate proportioning of elements. Their Showroom tool enables customers to preview furniture in customized rooms with different wall and floor colors. Furthermore, Amazon is heavily investing in AR/VR technology to enhance the overall consumer experience. On the other hand, Walmart has introduced two immersive platforms: Walmart Land and Walmart's Universe of Play [103]. Walmart Land offers avatar-based shopping, a Ferris wheel, and rewards in the form of badges and tokens. Within Walmart Land, Electric Island, House of Style, and Electric Fest are the primary immersive experiences. Electric Island offers music festival-inspired activities and popular artist performances. House of Style includes a virtual dressing room, cosmetic obstacle course, and roller skating rink featuring diverse brands. Electric Fest presents a motion-capture concert experience. Additionally, Walmart's Universe of Play on Roblox provides users with virtual toys and games, enabling them to earn coins and rewards. Users can explore various toy worlds, collect virtual toys, and interact with e-mobility items like hoverboards. The platform offers a diverse range of immersive games, desirable rewards, and online activities.

5.4. Decentraland

With a $1 billion value, the Decentraland metaverse has become one of the most popular metaverses in 2022 [104,105]. It was launched in 2020. It is based on the Ethereum blockchain. The Decentraland metaverse enables users to explore, perform activities, and shop in this digital universe. Within the Decentraland metaverse, users can trade goods and services using the MANA cryptocurrency. Besides, NFTs can also be used. The land plots of Decentraland metaverse are in high demand and have sold for up to $2.4 million. Businesses and brands have also begun buying land in this virtual world to interact with their customers. Samsung has established a store in the Decentraland metaverse where customers can enjoy live performances and product launches. The Decentraland metaverse also hosted the launch of the Samsung S22. Development in the Decentraland metaverse has some notable advantages. For example, purchasing land and building commercial properties in the Decentraland metaverse can generate substantial profits. Rental income from commercial properties is significant, and maintenance costs are low. Landowners are not required to follow tenant regulations or pay set rent, allowing them more control over their properties in the Decentraland metaverse. Decentraland enables users to create their own 3D objects and scenes that can be listed on the in-game market for MANA, combining creativity with cryptocurrency earnings. Moreover, it fosters community participation in platform development and facilitates the creation of novel experiences. Crypto exchanges like Binance and CoinBase allow converting MANA to other cryptocurrencies or local currencies. The Decentraland metaverse continues to push the limits of the virtual world space with its cutting-edge technology and growing community.

Table 2
Summary of the metaverse challenges along with their causes and guidelines.

Challenges	Causes	Potential guidelines
Interoperability	(a) Variations in hardware, software, and network protocols (b) Competing rights, intellectual property, and governance (c) Variations in user behavior and preferences across platforms	(a) Providing meaningful and timely standards/regulations (b) Promoting digital literacy
Security and Privacy	(a) Lack of privacy regulations (b) Intrusive and extensive data collection (c) Lack of users' data rights and ownership (d) Interpreting current regulations in the metaverse world	(a) Create a viable metaverse privacy policy (b) Enforce user-to-user privacy (c) Decentralized identity management mechanisms (d) Employ enhanced multi-factor authentication methods
Network Capabilities	(a) High responsiveness and high-bandwidth connectivity requirements	(a) Investing in network infrastructure and upgrading existing networks
Data Management	(a) Various data formats (b) Heterogeneous storage needs (c) Massive amounts of data (d) Lack of data integration solutions	(a) Designing novel operators, context-aware algorithms, and new forms of approximation operators (b) Novel indexing methods and data structures
Digital Addiction and Mental Health	(a) Overusing digital devices (b) Obsessively thinking about digital use (c) Replacing face-to-face communication	(a) Develop applications for mental wellness (b) Promote outdoor sports activities (c) Constantly monitoring the underage children
Law and Jurisdiction	(a) Virtual nature of the realm (b) Anonymity of avatars (c) No traditional institutions with physical premises to fix complaints (d) Difficulty in determining which laws apply to disputes involving intangible assets in the virtual space (e) Anonymous and encrypted virtual transactions	(a) Transparent and decentralized conflict resolution solutions (b) Flexible jurisdictional policies and regulations (c) Develop decentralized governance systems for virtual worlds
Environmental Pollution	(a) High computing power and bandwidth (b) Requirement for high-quality images (c) The growing use of cloud computing in virtual reality, online gaming, and high-resolution image processing (d) Advancements in VR technology lead to a rise in e-waste	(a) Novel calculation methods (b) Mathematical solutions, such as selective scanning (c) Develop lightweight solutions (d) Promote recycling methods

5.5. Roblox studio

Roblox Studio [106,107] enables developers to build virtual worlds and games. These developers are allowed to sell their game items. Roblox Studio is easy to use, as evidenced by the fact that a majority of the 20 million games produced were created by minors. On Roblox, some of the most popular games include Adopt Me!, Blox Fruits, Brookhaven RP, and Shindo Life. Besides, Pet Simulator X, Sonic Speed Simulator, King Legacy, Gacha Online, and Livetopia, are other popular games that have attracted millions of players. Clothing and avatar accessories are available for purchase in the Roblox metaverse. The items can be purchased with Robux, Roblox's cryptocurrency, or real-world money. The Roblox metaverse has hosted some celebrities and rappers, including Lil Nas X and David Guetta. Popular brands, including luxury ones like Gucci, Nike, and Lego, have collaborated with the Roblox metaverse for advertising purposes, along with Spotify, the BBC, and Netflix. The Roblox studio has all the basic features people expect from a metaverse, including virtual worlds and a cryptocurrency-based economy. Users do not have to buy headsets or other expensive gear to use the Roblox metaverse, as it only uses a small amount of AR and VR technologies. Platform versatility and easily accessible requirements have led Roblox to gain immense popularity in recent times.

6. Open research challenges

This section presents key challenges hindering the metaverse to become a reality. We outline the underlying causes of these challenges and provide guidelines to new researchers working in the domain. Table 2 summarizes such causes along with their guidelines.

6.1. Interoperability

The emergence of the metaverse has created significant interoperability challenges that must be addressed to enable the seamless integration of virtual worlds created by different developers using different hardware and software tools. Challenges related to metaverse interoperability can be classified into three categories: technical, usage, and jurisdictional challenges [108]. The technical challenges include addressing network limitations, asset ownership, intellectual property protection, payments, identity verification, data privacy, and security concerns, both in hardware and software. Usage interoperability challenges relate to ensuring a user-centered design that makes the metaverse accessible globally, inclusively, and across all demographics to ensure fairness in experiences. Finally, jurisdictional interoperability challenges involve covering best practices and standards across various industries, locations, and countries.

Technical issues are among the primary challenges, arising from variations in hardware, software, and network protocols that can hinder communication between different virtual worlds and platforms. Ownership and control challenges are also emerging due to competing rights to data, intellectual property, and governance. Jurisdictional differences across regions and countries pose additional challenges to interoperability, such as variations in user behavior and preferences across platforms, which can limit usage interoperability. Stakeholders involved in the metaverse development must take into account all of these challenges. Another crucial challenge is balancing interoperability with privacy, security, safety, and identity requirements [108]. The key to addressing these challenges is developing human-centric interoperability standards and best practices through collaboration among stakeholders [108]. This requires prioritizing well-being through human-centric design, promoting digital literacy, providing meaningful and timely standards and regulations to solve established concerns, and respecting social contracts and expectations when making decisions [108,109].

6.2. Security and privacy

VR and AR are the two most popular technologies driving the metaverse, but they pose security risks, especially to user privacy [110,111]. To address these risks, it is required to answer questions, such as how compromised AR devices affect privacy, how AR firms use and protect user data, and whether they share it with third parties [110]. All these questions point out security concerns in the metaverse, including social engineering attacks, credential theft, and denial of service [112,113]. In the metaverse, users use voice, video, and facial recognition features to verify their identities. Through AR and VR devices, users can communicate and interact within the metaverse, making them vulnerable to identity theft and social engineering attacks. Metaverse identity theft poses a major challenge, as hackers can gain access to network credentials through wearables. This can result in the compromise of the users' personal and financial information. VR technologies within the metaverse can be manipulated by machine learning algorithms to appear authentic, which makes them vulnerable to identity theft. Through motion-tracking data from VR headsets, hackers can create copies of another person's VR experience and perform social engineering attacks on them. Ransomware is also a security risk associated with the metaverse. A ransomware attack can be initiated by deceiving users into disclosing their personal information through VR platforms. Reduced perception of physical space is another security-related challenge posed by the metaverse. Although VR creates immersive experiences, it disconnects users from the audio-visual world. When users are separated from reality, they can be at risk of physical security risks. Polarization and radicalization are also severe security risks associated with the metaverse [110]. These security risks are not technology-driven but emerge from the users' behavior in the metaverse. Such risks are crucial and stem from the concept of a shared universe. The metaverse relies on serving as a centralized access point for all resources; however, bringing together opposing user groups can cause significant problems. Cyberbullying, trolling, and harassing are privacy and security risks that emerge from polarization and radical behavior in the metaverse [110]. Substantial attention needs to be paid to address all the aforementioned security and privacy concerns to enable the widespread adoption of the metaverse.

6.3. Network capabilities

The network capabilities required for the metaverse can be measured through bandwidth and latency. Real-time virtual reality experiences require high responsiveness and high-bandwidth connectivity [114]. Especially in the metaverse, the vast amount of data generated by users requires a high-speed and symmetrical broadband connection with high bandwidth. Low latency is another essential factor for a smooth experience in the metaverse. According to a WBA industry report, extreme VR aims for 1–2.35 Gb/s bandwidth with 10 ms latency [115]. Scalable broadband and home networks are essential to meet these requirements. Communication service providers are deploying 10G PON/25G-PON networks and 5G fixed wireless access to provide multi-gigabit broadband services. To meet latency requirements, active queue management techniques like PI2/L4S and other QoS policies are necessary [115]. On the other hand, achieving low latency with 5G technology can be challenging, making it difficult to support immersive environments in the metaverse. Furthermore, 4K video resolution is insufficient to express the pixels necessary for creating realistic and immersive environments, leading to large data files [114]. Developing real-time video compression technology is required for compressing and decompressing files without signal delay. For the metaverse to function effectively for fiber customers, it must be adaptable to their unique network conditions. Internet service providers must provide fast two-way traffic to enable the metaverse to function in smart homes. Although wireless networks have made significant improvements over the years, more improvements are required to satisfy the requirements of the metaverse. This is because existing access and content delivery networks lack the capacity to handle a large spike in consumer usage all at once [114]. If the network is overloaded, it can slow down the metaverse and result in an unrealistic experience. Metaverse bandwidth requirements require next-generation networks. Investing in network infrastructure and upgrading existing networks is essential to ensure that the metaverse provides an immersive experience.

6.4. Data management

Managing data in the metaverse poses multiple challenges. These challenges stem from managing various data formats, such as structured data, multimedia data, and location information, which necessitate different storage and management methods [116]. In current approaches, 3D objects and multimodal data in entertainment and the metaverse are managed through various techniques, including data compression, streaming, and cloud storage. However, these techniques pose limitations in terms of data size, processing power, network bandwidth, and interoperability. To fully unlock the potential of the metaverse, it is essential to address certain new requirements, including the need for scalable infrastructure, efficient data management, improved compression algorithms, and seamless integration of diverse data types. Additionally, there are technical challenges that must be addressed, such as real-time rendering, data synchronization, and optimizing the user experience. Furthermore, determining whether to treat physical and virtual data separately or collectively and optimizing data organization for a unified metaverse view and enhanced performance is a crucial decision. Integrating data from various sources and making complex inferences from them, as well as developing innovative solutions for data integration beyond conventional heterogeneous databases, is equally essential [116]. To handle context-aware scenarios, designing novel operators, context-aware algorithms, and new forms of approximation operators is required [116]. Integrating findings from onsite and online visitors, adapting and applying effective measures from one space to another, managing onsite and online users simultaneously, and developing flexible schemes to cater to frequent updates of information for update-intensive applications are other important challenges [116]. In addition, to enable efficient similarity search of 3D objects composed of tens of thousands of polygons in the metaverse, novel indexing methods, and data structures that support a hierarchy of coarse- and fine-grained resolutions while minimizing computation overhead are required [116]. Finally, to capture models at all levels in high resolution, transform the model into an appropriate resolution for transmission in real-time, and handle frequently changing scenes, a more dynamic and robust structure needs to be developed [116].

6.5. Digital addiction and mental health

Metaverse device and service addiction can result from excessive usage, loss of control over usage, and obsessive thinking about digital use when not using the devices [117]. Individuals can also become addicted to metaverse devices when they use them, even though they negatively impact work, school, hygiene, sleep, and relationships. Furthermore, digital addiction is associated with losing interest in leisure and social activities, using digital devices in risky situations, using digital devices more frequently and extended to experience the same level of satisfaction, and concealing them [117]. Addiction to the metaverse can have harmful effects on one's mental, physical, emotional, financial, and social well-being, which can in turn impact daily functioning and relationships in devastating ways. Also, the excessive use of the metaverse can exacerbate and develop depression and anxiety. The overuse of metaverse devices, combined with social media dependency, can intensify feelings of isolation. Additionally, replacing physical communication with virtual interactions can negatively affect mental health. Besides, dependence on virtual communication can lead to a reduction in interpersonal skills and decreased job performance. Concerns have been raised about the potential risks of the metaverse, which may induce symptoms of psychosis, such as hallucinations and delusions, as users become disconnected from reality [117]. It is important to be aware of these potential hazards and seek assistance if struggling with technology overuse or digital addiction. Although digital addiction and mental health problems share similarities across various platforms, such as PCs, smartphones, and social networking [118], some researchers believe that the metaverse for smart cities presents its own set of distinctive challenges. These challenges encompass aspects, such as the potential for excessive reliance on virtual interactions, the blurring of boundaries between the virtual and physical realms, potential impacts on social relationships, and the possibility of addiction to immersive virtual experiences within the metaverse. Some possible treatments are therapy, medication, and support groups [117]. Mental disorders can also benefit from VR therapy. Technology advancements are enabling VR companies to develop mental wellness applications. Additional research is needed to uncover how the metaverse affects human mood and behavior.

6.6. Law and jurisdiction

The metaverse involves a computer-simulated reality where people can engage in various activities, such as buying avatar wearables, purchasing property, and setting up businesses. However, the metaverse poses several legal challenges. One major issue is the difficulty in enforcing laws across international borders due to the virtual nature of the realm where payments are made in cryptocurrencies [119]. Virtual transactions in the form of cryptocurrencies are often anonymous and encrypted in the metaverse, making it difficult to punish parties for data theft. Businesses in the metaverse lack regulation and consumer protection, as traditional institutions with physical premises do not exist to handle complaints. The anonymity of avatars also poses a risk of dealing with unverified parties. Governments must address these challenges by implementing regulations, audits, and controls for commercial activities in the metaverse. Virtual crimes are another significant legal issue, requiring proper legislation to address them. However, establishing jurisdiction and enforcing laws is challenging due to the intangible nature of virtual assets. Conflict of law issues further complicate the determination of the appropriate forum for dispute resolution [119]. Although cybercrime and virtual currency are general concerns, some researchers believe the metaverse for smart cities introduces specific challenges. These include the potential for unauthorized access to virtual infrastructure, privacy breaches within virtual environments, manipulation of virtual data and services, and the need for robust security measures to protect both the physical and virtual components of smart cities within the metaverse. Navigating these challenges is crucial to ensure user safety in the metaverse.

6.7. Environmental pollution

Emerging metaverse technologies, such as AR, blockchains, NFTs, AI models, and advanced communication require high computing power and bandwidth, contributing to greenhouse gas emissions and environmental pollution [120]. The requirement for high-quality images also increases energy demand. In a recent study, the University of Massachusetts estimated that training just one AI model can generate 284 tons of carbon dioxide, which is very high [121]. The growing use of cloud computing in virtual reality, online gaming, and high-resolution image processing can greatly increase carbon emissions [121]. In short, the metaverse and its related technologies consume significant energy. Innovative solutions, such as novel calculation methods, need to be developed to reduce the energy consumption of metaverse technologies. It has been reported in [121] that mathematics can reduce the metaverse energy consumption, as Nanyang Technology University researchers used selective scanning to transmit only objects of interest instead of entire images to service providers. Another issue to consider is that as VR technology advances, there is a potential for an increase in electronic waste (e-waste) that can contaminate soil, groundwater, and landfills, ultimately contributing to environmental pollution. Researchers and industrialists must collaborate to study the metaverse's environmental impact and take it into account while developing any metaverse-based solution in the future.

7. Conclusions and future recommendations

In this paper, we discussed how leveraging the metaverse for smart cities can enhance their infrastructure, government services, accessibility, economic growth, and sustainability. The metaverse can revolutionize various aspects of smart cities, including healthcare, energy management, transportation, smart homes, supply chain and logistics, tourism, retail, and banking. We discussed the enabling technologies and advantages of the metaverse technology to show how it can unlock its full potential for smart cities. We explored the key opportunities offered by the metaverse for smart cities and presented several case studies to show how various industries have been facilitated and complemented by metaverse technology. We identified and discussed the imperative open research challenges hindering the widespread adoption of the metaverse. Finally, we conclude that the metaverse has the potential to reshape and transform smart cities by bringing significant improvements in terms of the quality of services. Although the metaverse still needs time to take off meaningfully, it has already proven to be a significant concept in various domains. However, for the metaverse to become a reality, several challenges need to be addressed, including but not limited to interoperability, security and privacy, network capabilities, data management, digital addiction and mental health, law and jurisdiction, and environmental pollution. These challenges are summarized below in the form of future recommendations:

- The development of the metaverse is facing significant challenges related to interoperability, particularly in the areas of technical, usage, and jurisdictional challenges. To address these challenges, stakeholders involved in the development of the metaverse must collaborate to develop human-centric interoperability standards and best practices that prioritize user well-being, promote digital literacy, and respect social contracts and expectations. Future research needs to be focused on balancing interoperability with privacy, security, safety, and identity requirements to ensure fairness in experiences and accessibility globally.
- VR and AR, the two most popular technologies driving the metaverse, pose various security risks, including social engineering attacks, identity theft, and ransomware. These risks are due to the use of voice, video, and facial recognition features to verify identities and interact within the metaverse. Additionally, reduced perception of physical space and user behavior in the metaverse, such as polarization and radicalization, can also pose security risks like cyberbullying, trolling, and harassment. To enable widespread adoption of the metaverse, it is necessary to address these security and privacy concerns by developing appropriate technologies and practices that safeguard user privacy, prevent unauthorized access, and promote safe and inclusive interactions within the metaverse. This requires substantial attention and investment in cybersecurity, privacy protection, and user education.
- The metaverse requires high-speed, symmetrical broadband connectivity, low latency, and high responsiveness for real-time virtual reality experiences. The vast amount of user-generated data requires next-generation networks with high bandwidth. Achieving low latency with 5G technology is challenging, and video compression technology is required to handle large data files in real time. Network infrastructure investment and upgrades are necessary to meet the metaverse's requirements and ensure an immersive experience.
- Managing data in the metaverse poses challenges related to various data formats, physical and virtual data integration, context-aware scenarios, and efficient similarity search. To address these challenges, new storage and management methods, data integration solutions, context-aware algorithms, and novel indexing methods are required. Additionally, effective measures to manage onsite and online users, frequent updates, and high-resolution models are required. A dynamic and robust structure needs to be developed to handle changing scenes in real time.
- The metaverse addiction can result from overusing devices, obsessively thinking about digital use, and experiencing negative effects on daily functioning and relationships. It can lead to mental, physical, emotional, financial, and social harm, exacerbating depression and anxiety. It can induce symptoms of psychosis and reduce interpersonal skills and job performance. Further research is needed to uncover how the metaverse affects human mood and behavior. Awareness of digital addiction is crucial as the metaverse continues to rise.

- The metaverse presents legal challenges related to enforcing laws across borders, lack of regulation and consumer protection for businesses, and potential virtual crimes. Governments need to address these issues to regulate commercial activities and establish jurisdiction for disputes involving intangible assets in the virtual space. These challenges require careful consideration from all stakeholders in the future.
- The metaverse technologies require high energy consumption and emit greenhouse gases. Also, the use of cloud computing and high-resolution images further increases carbon emissions. Besides, advancements in VR technology can contribute to an increase in e-waste. In the future, it is required to study the metaverse's environmental impact and develop sustainable solutions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article

Funding details and acknowledgment

This publication is based upon work supported by the Khalifa University of Science and Technology under Award No. RCII-2019-002-Research Center for Digital Supply Chain and Operations Management. The authors would like to thank ChatGPT for providing proofreading assistance.

References

[1] M. Xu, W.C. Ng, W.Y.B. Lim, J. Kang, Z. Xiong, D. Niyato, Q. Yang, X.S. Shen, C. Miao, A full dive into realizing the edge-enabled metaverse: Visions, enabling technologies, and challenges, IEEE Commun. Surv. Tutor. (2022).
[2] The next economy: Creating new ways to shop, work, and play, 2022, https://www.fastcompany.com/90771640/the-next-economy-creating-new-ways-to-shop-work-and-play. (Accessed on: 01 November 2022).
[3] Y. Wang, Z. Su, N. Zhang, R. Xing, D. Liu, T.H. Luan, X. Shen, A survey on metaverse: Fundamentals, security, and privacy, IEEE Commun. Surv. Tutor. 25 (1) (2023) 319–352, http://dx.doi.org/10.1109/COMST.2022.3202047.
[4] M. Sparkes, What is a metaverse, Elsevier, 2021.
[5] T. Huynh-The, T.R. Gadekallu, W. Wang, G. Yenduri, P. Ranaweera, Q.-V. Pham, D.B. da Costa, M. Liyanage, Blockchain for the metaverse: A review, Future Gener. Comput. Syst. 143 (2023) 401–419, http://dx.doi.org/10.1016/j.future.2023.02.008, https://www.sciencedirect.com/science/article/pii/S0167739X23000493.
[6] Z. Lv, S. Xie, Y. Li, M. Shamim Hossain, A. El Saddik, Building the metaverse by digital twins at all scales, state, relation, Virt. Real. Intell. Hardw. 4 (6) (2022) 459–470, http://dx.doi.org/10.1016/j.vrih.2022.06.005, https://www.sciencedirect.com/science/article/pii/S2096579622000602.
[7] Y. Liu, Y. Shen, C. Guo, Y. Tian, X. Wang, Y. Zhu, F.-Y. Wang, MetaSensing in metaverses: See there, be there, and know there, IEEE Intell. Syst. 37 (6) (2022) 7–12.
[8] X. Wang, J. Yang, J. Han, W. Wang, F.-Y. Wang, Metaverses and demetaverses: From digital twins in CPS to parallel intelligence in CPSS, IEEE Intell. Syst. 37 (4) (2022) 97–102, http://dx.doi.org/10.1109/MIS.2022.3196592.
[9] Gartner: 25% of people to spend 1 hour daily in the metaverse by 2026, 2022, https://futureiot.tech/gartner-25-of-people-to-spend-1-hour-daily-in-the-Metaverse-by-2026/. (Accessed on: 01 November 2022).
[10] Value creation in the metaverse, the metaverse does actually impact the environment, 2022, https://www.mckinsey.com/capabilities/growth-marketing-and-sales/our-insights/value-creation-in-the-Metaverse. (Accessed on: 01 November 2022).
[11] C. Polona, M.T. André, N. Maria, Metaverse: Opportunities, risks and policy implications, EPRS: European Parliamentary Research Service, 2022.
[12] NFT collector spends $450,000 to live as snoop doggś virtual neighbor, 2022, https://www.nme.com/news/music/nft-collector-spends-450000-to-live-as-snoop-doggs-virtual-neighbour-3114160. (Accessed on: 02 November 2022).
[13] Virtual smart cities using metaverse, digital twins, 2023, https://www.biznesstransform.com/virtual-smart-cities-using-metaverse-digital-twins/. (Accessed on: 13 March 2023).
[14] Smart cities: The cities of the future, 2023, https://www.microsoft.com/en-us/industry/government/resources/smart-cities#:~:text=A%20smart%20city%20is%20an,the%20cities%20of%20the%20future. (Accessed on: 02 March 2023).
[15] J. Wang, G. Medvegy, Exploration the future of the metaverse and smart cities, 2022.
[16] D. Vidal-Tomás, The illusion of the metaverse and meta-economy, Int. Rev. Financ. Anal. 86 (2023) 102560, http://dx.doi.org/10.1016/j.irfa.2023.102560, https://www.sciencedirect.com/science/article/pii/S1057521923000765.
[17] M. Zallio, P.J. Clarkson, Designing the metaverse: A study on inclusion, diversity, equity, accessibility and safety for digital immersive environments, Telemat. Inform. 75 (2022) 101909, http://dx.doi.org/10.1016/j.tele.2022.101909, https://www.sciencedirect.com/science/article/pii/S0736585322001423.
[18] H. Chourabi, T. Nam, S. Walker, J.R. Gil-Garcia, S. Mellouli, K. Nahon, T.A. Pardo, H.J. Scholl, Understanding smart cities: An integrative framework, in: 2012 45th Hawaii International Conference on System Sciences, IEEE, 2012, pp. 2289–2297.
[19] M. Angelidou, Smart cities: A conjuncture of four forces, Cities 47 (2015) 95–106.
[20] C. Harrison, I.A. Donnelly, A theory of smart cities, in: Proceedings of the 55th Annual Meeting of the ISSS-2011, Hull, UK, 2011.
[21] E. Al Nuaimi, H. Al Neyadi, N. Mohamed, J. Al-Jaroodi, Applications of big data to smart cities, J. Internet Serv. Appl. 6 (1) (2015) 1–15.
[22] M. Batty, K.W. Axhausen, F. Giannotti, A. Pozdnoukhov, A. Bazzani, M. Wachowicz, G. Ouzounis, Y. Portugali, Smart cities of the future, Eur. Phys. J. Spec. Top. 214 (2012) 481–518.
[23] B.N. Silva, M. Khan, K. Han, Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities, Sustain. Cities Soc. 38 (2018) 697–713.

[24] Y.K. Dwivedi, L. Hughes, A.M. Baabdullah, S. Ribeiro-Navarrete, M. Giannakis, M.M. Al-Debei, D. Dennehy, B. Metri, D. Buhalis, C.M. Cheung, K. Conboy, R. Doyle, R. Dubey, V. Dutot, R. Felix, D. Goyal, A. Gustafsson, C. Hinsch, I. Jebabli, M. Janssen, Y.-G. Kim, J. Kim, S. Koos, D. Kreps, N. Kshetri, V. Kumar, K.-B. Ooi, S. Papagiannidis, I.O. Pappas, A. Polyviou, S.-M. Park, N. Pandey, M.M. Queiroz, R. Raman, P.A. Rauschnabel, A. Shirish, M. Sigala, K. Spanaki, G. Wei-Han Tan, M.K. Tiwari, G. Viglia, S.F. Wamba, Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy, Int. J. Inf. Manage. 66 (2022) 102542, http://dx.doi.org/10.1016/j.ijinfomgt.2022.102542, https://www.sciencedirect.com/science/article/pii/S0268401222000767.

[25] F. Shi, H. Ning, X. Zhang, R. Li, Q. Tian, S. Zhang, Y. Zheng, Y. Guo, M. Daneshmand, A new technology perspective of the metaverse: Its essence, framework and challenges, Digit. Commun. Netw. (2023) http://dx.doi.org/10.1016/j.dcan.2023.02.017, https://www.sciencedirect.com/science/article/pii/S2352864823000524.

[26] G. Zheng, L. Yuan, A review of QoE research progress in metaverse, Displays 77 (2023) 102389, http://dx.doi.org/10.1016/j.displa.2023.102389, https://www.sciencedirect.com/science/article/pii/S0141938223000227.

[27] T. Huynh-The, Q.-V. Pham, X.-Q. Pham, T.T. Nguyen, Z. Han, D.-S. Kim, Artificial intelligence for the metaverse: A survey, Eng. Appl. Artif. Intell. 117 (2023) 105581, http://dx.doi.org/10.1016/j.engappai.2022.105581, https://www.sciencedirect.com/science/article/pii/S0952197622005711.

[28] F. De Felice, C. De Luca, S.D. Chiara, A. Petrillo, Physical and digital worlds: Implications and opportunities of the metaverse, Procedia Comput. Sci. 217 (2023) 1744–1754, http://dx.doi.org/10.1016/j.procs.2022.12.374, 4th International Conference on Industry 4.0 and Smart Manufacturing, https://www.sciencedirect.com/science/article/pii/S1877050922024590.

[29] A.S. Ahuja, B.W. Polascik, D. Doddapaneni, E.S. Byrnes, J. Sridhar, The digital metaverse: Applications in artificial intelligence, medical education, and integrative health, Integrat. Med. Res. 12 (1) (2023) 100917, http://dx.doi.org/10.1016/j.imr.2022.100917, https://www.sciencedirect.com/science/article/pii/S2213422022000841.

[30] A.M. Al-Ghaili, H. Kasim, N.M. Al-Hada, Z. Hassan, M. Othman, T.J. Hussain, R.M. Kasmani, I. Shayea, A review of metaverse's definitions, architecture, applications, challenges, issues, solutions, and future trends, IEEE Access (2022).

[31] Q. Yang, Y. Zhao, H. Huang, Z. Xiong, J. Kang, Z. Zheng, Fusing blockchain and AI with metaverse: A survey, IEEE Open J. Comput. Soc. 3 (2022) 122–136.

[32] J. Wu, K. Lin, D. Lin, Z. Zheng, H. Huang, Z. Zheng, Financial crimes in Web3-empowered metaverse: Taxonomy, countermeasures, and opportunities, IEEE Open J. Comput. Soc. 4 (2023) 37–49, http://dx.doi.org/10.1109/OJCS.2023.3245801.

[33] S.-M. Park, Y.-G. Kim, A metaverse: Taxonomy, components, applications, and open challenges, IEEE Access 10 (2022) 4209–4251.

[34] Y. Fu, C. Li, F.R. Yu, T.H. Luan, P. Zhao, S. Liu, A survey of blockchain and intelligent networking for the metaverse, IEEE Internet Things J. (2022).

[35] H. Huang, X. Zeng, L. Zhao, C. Qiu, H. Wu, L. Fan, Fusion of building information modeling and blockchain for metaverse: A survey, IEEE Open J. Comput. Soc. 3 (2022) 195–207.

[36] Y. Huang, Y.J. Li, Z. Cai, Security and privacy in metaverse: A comprehensive survey, Big Data Min. Anal. 6 (2) (2023) 234–247, http://dx.doi.org/10.26599/BDMA.2022.9020047.

[37] L.-H. Lee, T. Braud, P. Zhou, L. Wang, D. Xu, Z. Lin, A. Kumar, C. Bermejo, P. Hui, All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystem, and research agenda, 2021, arXiv preprint arXiv:2110.05352.

[38] S. Mystakidis, Metaverse, Encyclopedia 2 (1) (2022) 486–497.

[39] B. Kye, N. Han, E. Kim, Y. Park, S. Jo, Educational applications of metaverse: Possibilities and limitations, J. Educ. Eval. Health Profess. 18 (2021).

[40] R. Chengoden, N. Victor, T. Huynh-The, G. Yenduri, R.H. Jhaveri, M. Alazab, S. Bhattacharya, P. Hegde, P.K.R. Maddikunta, T.R. Gadekallu, Metaverse for healthcare: A survey on potential applications, challenges and future directions, IEEE Access (2023).

[41] A. Musamih, I. Yaqoob, K. Salah, R. Jayaraman, Y. Al-Hammadi, M. Omar, S. Ellahham, Metaverse in healthcare: Applications, challenges, and future directions, IEEE Consum. Electron. Mag. (In Press, 2022).

[42] Z. Allam, A. Sharifi, S.E. Bibri, D.S. Jones, J. Krogstie, The metaverse as a virtual form of smart cities: Opportunities and challenges for environmental, economic, and social sustainability in urban futures, Smart Cities 5 (3) (2022) 771–801, https://www.mdpi.com/2624-6511/5/3/40.

[43] Characteristics of the metaverse: A new dimension to the Internet of Today, 2023, https://medium.com/rising-capital/issue-5-6-characteristics-of-the-metaverse-a-new-dimension-to-the-internet-of-today-6f92880a897. (Accessed on: 05 April 2023).

[44] Metaverse pros and cons: Top benefits and challenges, 2023, https://www.techtarget.com/searchcio/tip/Metaverse-pros-and-cons-Top-benefits-and-challenges. (Accessed on: 07 March 2023).

[45] Medical training in metaverse is the new route to immersive learning medical training in metaverse is the new route to immersive learning, 2023, https://www.educationtimes.com/article/careers-offbeat/96085858/medical-training-in-metaverse-is-the-new-route-to-immersive-learning. (Accessed on: 09 March 2023).

[46] N. Kshetri, Metaverse and developing economies, IT Prof. 24 (4) (2022) 66–69.

[47] 5 profitable business opportunities in metaverse, 2023, https://101blockchains.com/business-opportunities-in-metaverse/. (Accessed on: 11 March 2023).

[48] J. Weking, K.C. Desouza, E. Fielt, M. Kowalkiewicz, Metaverse-enabled entrepreneurship, J. Bus. Ventur. Insights 19 (2023) e00375, http://dx.doi.org/10.1016/j.jbvi.2023.e00375, https://www.sciencedirect.com/science/article/pii/S2352673423000045.

[49] Journey through the metaverse: Digital twins are synchronizing the physical and virtua, 2023, https://hellofuture.orange.com/en/journey-through-the-metaverse-digital-twins-are-synchronizing-the-physical-and-virtual/. (Accessed on: 10 March 2023).

[50] H.J. Oh, J. Kim, J.J. Chang, N. Park, S. Lee, Social benefits of living in the metaverse: The relationships among social presence, supportive interaction, social self-efficacy, and feelings of loneliness, Comput. Hum. Behav. 139 (2023) 107498, http://dx.doi.org/10.1016/j.chb.2022.107498, https://www.sciencedirect.com/science/article/pii/S0747563222003181.

[51] H. Liang, J. Li, Y. Wang, J. Pan, Y. Zhang, X. Dong, Metaverse virtual social center for the elderly communication during the social distancing, Virt. Real. Intell. Hardw. 5 (1) (2023) 68–80, http://dx.doi.org/10.1016/j.vrih.2022.07.007, https://www.sciencedirect.com/science/article/pii/S2096579622000699.

[52] The metaverse and the future of human connection, 2023, https://www.programsbuzz.com/article/metaverse-and-future-human-connection. (Accessed on: 14 March 2023).

[53] P.A. Kara, R.R. Tamboli, V.K. Adhikarla, T. Balogh, M. Guindy, A. Simon, Connected without disconnection: Overview of light field metaverse applications and their quality of experience, Displays 78 (2023) 102430, http://dx.doi.org/10.1016/j.displa.2023.102430, https://www.sciencedirect.com/science/article/pii/S014193822300063X.

[54] Metavertainment: A vision into the world of the metaverse and entertainment, 2023, https://hackernoon.com/metavertainment-a-vision-into-the-world-of-the-metaverse-and-entertainment. (Accessed on: 08 March 2023).

[55] S. Yang, Storytelling and user experience in the cultural metaverse, Heliyon 9 (4) (2023) e14759, http://dx.doi.org/10.1016/j.heliyon.2023.e14759, https://www.sciencedirect.com/science/article/pii/S2405844023019667.

[56] D. Buhalis, D. Leung, M. Lin, Metaverse as a disruptive technology revolutionising tourism management and marketing, Tour. Manag. 97 (2023) 104724, http://dx.doi.org/10.1016/j.tourman.2023.104724, https://www.sciencedirect.com/science/article/pii/S0261517723000067.

[57] N. Kshetri, Y.K. Dwivedi, Pollution-reducing and pollution-generating effects of the metaverse, Int. J. Inf. Manage. 69 (2023) 102620.

[58] Y.K. Dwivedi, L. Hughes, A.M. Baabdullah, S. Ribeiro-Navarrete, M. Giannakis, M.M. Al-Debei, D. Dennehy, B. Metri, D. Buhalis, C.M. Cheung, et al., Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy, Int. J. Inf. Manage. 66 (2022) 102542.

[59] What is augmented reality or AR? 2023, https://dynamics.microsoft.com/en-us/mixed-reality/guides/what-is-augmented-reality-ar/. (Accessed on: 16 February 2023).
[60] What is virtual reality? 2023, https://www.techtarget.com/whatis/definition/virtual-reality. (Accessed on: 15 February 2023).
[61] M. Ma, H. Zheng, Virtual reality and serious games in healthcare, Adv. Comput. Intell. Paradigms Healthcare 6. Virt. Real. Psychother. Rehabil. Assess. (2011) 169–192.
[62] What is extended reality technology? A simple explanation for anyone, 2023, https://www.forbes.com/sites/bernardmarr/2019/08/12/what-is-extended-reality-technology-a-simple-explanation-for-anyone/?sh=3c2b76a67249. (Accessed on: 20 February 2023).
[63] What is extended reality? 2023, https://blogs.nvidia.com/blog/2022/05/20/what-is-extended-reality/. (Accessed on: 23 February 2023).
[64] The role of AI in shaping the metaverse, 2023, https://www.neilsahota.com/the-role-of-ai-in-shaping-the-metaverse/. (Accessed on: 27 February 2023).
[65] AI: The driving force behind the metaverse? 2023, https://www.itu.int/hub/2022/06/ai-driving-force-metaverse/. (Accessed on: 25 February 2023).
[66] What role does artificial intelligence play in the metaverse? 2023, https://evergine.com/artificial-intelligence-metaverse/. (Accessed on: 17 February 2023).
[67] Artificial intelligence in the metaverse: Bridging the virtual and real, 2023, https://www.xrtoday.com/virtual-reality/artificial-intelligence-in-the-metaverse-bridging-the-virtual-and-real/. (Accessed on: 26 February 2023).
[68] J. Ryu, S. Son, J. Lee, Y. Park, Y. Park, Design of secure mutual authentication scheme for metaverse environments using blockchain, IEEE Access 10 (2022) 98944–98958.
[69] J. Chen, H. Xiao, M. Hu, C.-M. Chen, A blockchain-based signature exchange protocol for metaverse, Future Gener. Comput. Syst. 142 (2023) 237–247, http://dx.doi.org/10.1016/j.future.2022.12.031, https://www.sciencedirect.com/science/article/pii/S0167739X22004356.
[70] M. Xu, Y. Guo, Q. Hu, Z. Xiong, D. Yu, X. Cheng, A trustless architecture of blockchain-enabled metaverse, High-Conf. Comput. 3 (1) (2023) 100088, http://dx.doi.org/10.1016/j.hcc.2022.100088, https://www.sciencedirect.com/science/article/pii/S266729522200040X.
[71] T. Maksymyuk, J. Gazda, G. Bugár, V. Gazda, M. Liyanage, M. Dohler, Blockchain-empowered service management for the decentralized metaverse of things, IEEE Access 10 (2022) 99025–99037.
[72] R. Belk, M. Humayun, M. Brouard, Money, possessions, and ownership in the metaverse: NFTs, cryptocurrencies, Web3 and wild markets, J. Bus. Res. 153 (2022) 198–205, http://dx.doi.org/10.1016/j.jbusres.2022.08.031, https://www.sciencedirect.com/science/article/pii/S0148296322007147.
[73] J. Thomason, Metaverse, token economies, and non-communicable diseases, Glob. Health J. 6 (3) (2022) 164–167, http://dx.doi.org/10.1016/j.glohj.2022.07.001, Special Issue on Prevention and Control of Obesity and Related Non-communicable Diseases, https://www.sciencedirect.com/science/article/pii/S2414644722000458.
[74] Y. Hwang, When makers meet the metaverse: Effects of creating NFT metaverse exhibition in maker education, Comput. Educ. 194 (2023) 104693, http://dx.doi.org/10.1016/j.compedu.2022.104693, https://www.sciencedirect.com/science/article/pii/S0360131522002640.
[75] C.T. Lee, T.-Y. Ho, H.-H. Xie, Building brand engagement in metaverse commerce: The role of branded non-fungible tokens (BNFTs), Electron. Commer. Res. Appl. 58 (2023) 101248, http://dx.doi.org/10.1016/j.elerap.2023.101248, https://www.sciencedirect.com/science/article/pii/S1567422323000133.
[76] D. Vidal-Tomás, The new crypto niche: NFTs, play-to-earn, and metaverse tokens, Finance Res. Lett. 47 (2022) 102742, http://dx.doi.org/10.1016/j.frl.2022.102742, https://www.sciencedirect.com/science/article/pii/S1544612322000630.
[77] 5 key technologies for the development of the metaverse, 2023, https://aristeksystems.com/blog/5-key-metaverse-technologies/. (Accessed on: 22 February 2023).
[78] 7 top technologies for metaverse development, 2023, https://www.techtarget.com/searchcio/tip/7-top-technologies-for-metaverse-development#:~:text=3D%20reconstruction%20captures%20the%20shape,a%20specific%20process%20or%20product. (Accessed on: 16 February 2023).
[79] K. Li, Y. Cui, W. Li, T. Lv, X. Yuan, S. Li, W. Ni, M. Simsek, F. Dressler, When Internet of Things meets metaverse: Convergence of physical and cyber worlds, IEEE Internet Things J. 10 (5) (2023) 4148–4173, http://dx.doi.org/10.1109/JIOT.2022.3232845.
[80] The role of IoT in metaverse, 2023, https://www.indiumsoftware.com/blog/the-role-of-iot-in-metaverse/#:~:text\=by%20cloud%20services.-,Digital%20replicas%20and%20simulations%20to%20create%20real%2Dworld%20experiences,of%20these%20digital%20human%20counterparts. (Accessed on: 24 February 2023).
[81] 5 key technologies that power the metaverse, 2023, https://www.excellarate.com/blogs/5-key-technologies-that-power-the-metaverse/. (Accessed on: 27 February 2023).
[82] What does the metaverse mean for smart homes? 2023, https://www.digitaltrends.com/home/will-the-metaverse-affect-smart-home/. (Accessed on: 04 February 2023).
[83] The metaverse: An evolution in transportation, travel, and hospitality, 2023, https://www.microsoft.com/en-us/industry/blog/automotive/2022/11/29/the-metaverse-an-evolution-in-transportation-travel-and-hospitality/#:~:text\=Metaverse%20in%20transportation&text=By%20leveraging%20digital%20twins%20of,and%20goods%20will%20improve%20dramatically. (Accessed on: 27 February 2023).
[84] D. Pamucar, M. Deveci, I. Gokasar, D. Delen, M. Köppen, W. Pedrycz, Evaluation of metaverse integration alternatives of sharing economy in transportation using fuzzy schweizer-sklar based ordinal priority approach, Decis. Support Syst. (2023) 113944, http://dx.doi.org/10.1016/j.dss.2023.113944, https://www.sciencedirect.com/science/article/pii/S0167923623000192.
[85] D. Mourtzis, N. Panopoulos, J. Angelopoulos, B. Wang, L. Wang, Human centric platforms for personalized value creation in metaverse, J. Manuf. Syst. 65 (2022) 653–659, http://dx.doi.org/10.1016/j.jmsy.2022.11.004, https://www.sciencedirect.com/science/article/pii/S0278612522001959.
[86] J. Lee, P. Kundu, Integrated cyber-physical systems and industrial metaverse for remote manufacturing, Manuf. Lett. 34 (2022) 12–15, http://dx.doi.org/10.1016/j.mfglet.2022.08.012, https://www.sciencedirect.com/science/article/pii/S2213846322001833.
[87] What role does the metaverse play in the future of energy? 2023, https://goodnewenergy.enagas.es/en/innovative/what-paper-does-the-metaverse-occupy-in-the-future-of-the-energy/. (Accessed on: 27 February 2023).
[88] Virtual power plants: Metaverse for the power sector, 2023, https://www.financialexpress.com/opinion/virtual-power-plants-metaverse-for-the-power-sector/2511907/. (Accessed on: 27 February 2023).
[89] 3 ways the metaverse will transform your supply chain, 2023, https://www.maersk.com/insights/digitalisation/how-the-metaverse-will-transform-supply-chain-management. (Accessed on: 27 February 2023).
[90] The impact of the metaverse on the supply chain, 2023, https://blog.board.com/metaverse-supply-chain/. (Accessed on: 27 February 2023).
[91] The metaverse and the digital supply chain!, 2023, https://supplychaingamechanger.com/the-metaverse-and-the-digital-supply-chain/. (Accessed on: 22 February 2023).
[92] Digital logistics: The future of logistics in the metaverse, 2023, https://www.saloodo.com/blog/digital-logistics-the-future-of-logistics-in-the-metaverse/. (Accessed on: 22 February 2023).
[93] R.W. Ahmad, K. Salah, R. Jayaraman, I. Yaqoob, S. Ellahham, M. Omar, The role of blockchain technology in telehealth and telemedicine, Int. J. Med. Inform. 148 (2021) 104399.
[94] T.-C. Wu, C.-T.B. Ho, A scoping review of metaverse in emergency medicine, Australas. Emerg. Care (2022).
[95] I. Skalidis, O. Muller, S. Fournier, CardioVerse: The cardiovascular medicine in the era of metaverse, Trends Cardiovasc. Med. (2022).
[96] Y. Zeng, L. Zeng, C. Zhang, A.S. Cheng, The metaverse in cancer care: Applications and challenges, Asia-Pacific J. Oncol. Nurs. (2022) 100111.
[97] The future of the retail industry in the metaverse, 2023, https://www.pwc.in/assets/pdfs/emerging-tech/metaverse/the-future-of-the-retail-industry-in-the-metaverse.pdf. (Accessed on: 22 February 2023).

[98] K. Giang Barrera, D. Shah, Marketing in the metaverse: Conceptual understanding, framework, and research agenda, J. Bus. Res. 155 (2023) 113420, http://dx.doi.org/10.1016/j.jbusres.2022.113420, https://www.sciencedirect.com/science/article/pii/S0148296322008852.
[99] The impact of the metaverse in banking and finance, 2023, https://skywell.software/blog/the-impact-of-the-metaverse-in-banking-and-finance/. (Accessed on: 22 February 2023).
[100] The amazing ways nike is using the metaverse, Web3 and NFTs, 2023, https://www.forbes.com/sites/bernardmarr/2022/06/01/the-amazing-ways-nike-is-using-the-metaverse-web3-and-nfts/sh=1827462c56e9. (Accessed on: 22 February 2023).
[101] Microsoft metaverse: Products, services, tech, and much more, 2023, https://metaverseinsider.tech/2022/11/29/microsoft-metaverse/. (Accessed on: 22 February 2023).
[102] How the metaverse is reshaping amazon and walmart, 2023, https://datahawk.co/blog/amazon-and-walmart-metaverse. (Accessed on: 22 February 2023).
[103] Walmart jumps into roblox with launch of walmart land and walmart's universe of play, 2023, https://corporate.walmart.com/newsroom/2022/09/26/walmart-jumps-into-roblox-with-launch-of-walmart-land-and-walmarts-universe-of-play#:~\protect\leavevmode@ifvmode\kern+.2222em\relaxtext\=Today%2C%20Walmart%20is%20announcing%20the,isles'%20in%20a%20virtual%20world. (Accessed on: 22 February 2023).
[104] What is decentraland? 2023, https://www.investopedia.com/what-is-decentraland-6827259. (Accessed on: 22 February 2023).
[105] What is the decentraland metaverse? How it works, and much more!, 2023, https://metaverseinsider.tech/2022/11/17/decentraland-metaverse/. (Accessed on: 22 February 2023).
[106] The roblox metaverse: What is it, and why is it so popular amongst gen z, 2023, https://fanbytes.co.uk/the-roblox-metaverse. (Accessed on: 22 February 2023).
[107] Everything you need to know about roblox metaverse, 2023, https://www.cashify.in/roblox-metaverse-things-you-need-to-know. (Accessed on: 22 February 2023).
[108] Interoperability in the metaverse, 2023, https://www3.weforum.org/docs/WEF_Interoperability_in_the_Metaverse.pdf. (Accessed on: 22 February 2023).
[109] U. Jaimini, T. Zhang, G.O. Brikis, A. Sheth, iMetaverseKG: Industrial metaverse knowledge graph to promote interoperability in design and engineering applications, IEEE Internet Comput. 26 (6) (2022) 59–67.
[110] Metaverse security threats in the future of internet, 2023, https://www.juegostudio.com/blog/metaverse-security-threats-in-the-future-of-internet#:~:text=Among%20all%20the%20metaverse%20security,manipulate%20the%20environment%20around%20them. (Accessed on: 22 February 2023).
[111] S. Qamar, Z. Anwar, M. Afzal, A systematic threat analysis and defense strategies for the metaverse and extended reality systems, Comput. Secur. 128 (2023) 103127, http://dx.doi.org/10.1016/j.cose.2023.103127, https://www.sciencedirect.com/science/article/pii/S0167404823000378.
[112] T. Oleksy, A. Wnuk, M. Piskorska, Migration to the metaverse and its predictors: Attachment to virtual places and metaverse-related threat, Comput. Hum. Behav. 141 (2023) 107642, http://dx.doi.org/10.1016/j.chb.2022.107642, https://www.sciencedirect.com/science/article/pii/S0747563222004629.
[113] S.-Y. Kuo, F.-H. Tseng, Y.-H. Chou, Metaverse intrusion detection of wormhole attacks based on a novel statistical mechanism, Future Gener. Comput. Syst. 143 (2023) 179–190, http://dx.doi.org/10.1016/j.future.2023.01.017, https://www.sciencedirect.com/science/article/pii/S0167739X23000249.
[114] Network requirements for the metaverse, are we ready, 2023, https://www.iceconnect.com/blog/it-support/metaverse-network-requirements/. (Accessed on: 22 February 2023).
[115] The metaverse and communication service providers, 2023, https://www.nokia.com/blog/the-metaverse-and-communication-service-providers/. (Accessed on: 05 June 2023).
[116] Data management for the metaverse, 2023, https://wp.sigmod.org/p\=3481. (Accessed on: 22 February 2023).
[117] What the metaverse means for mental health and digital addiction 2023, https://www.familyaddictionspecialist.com/blog/a-new-age-of-digital-addiction-what-the-metaverse-means-for-mental-health-and-digital-addiction#:~:text=The%20Metaverse%20and%20Mental%20Health,%2C%20and%20psychoses%2C%20among%20others. (Accessed on: 22 February 2023).
[118] J.Y. Lebni, R. Toghroli, J. Abbas, N. NeJhaddadgar, M.R. Salahshoor, M. Mansourian, H.D. Gilan, N. Kianipour, F. Chaboksavar, S.A. Azizi, et al., A study of internet addiction and its effects on mental health: A study based on Iranian university students, J. Educ. Health Promot. 9 (2020).
[119] No country has jurisdiction over the metaverse (yet), 2023, https://bsabh.com/knowledge-hub/news/no-country-has-jurisdiction-over-the-metaverse-yet. (Accessed on: 22 February 2023).
[120] Even though itś virtual, the metaverse does actually impact the environment, 2023, https://www.weforum.org/agenda/2022/02/how-metaverse-actually-impacts-the-environment/. (Accessed on: 15 March 2023).
[121] The carbon footprint of the metaverse can be reduced, 2023, https://courier.unesco.org/en/articles/liu-jianya-and-guo-liang-carbon-footprint-metaverse-can-be-reduced. (Accessed on: 22 February 2023).