Review

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Review

Artificial Intelligence-Enabled Metaverse for Sustainable Smart Cities: Technologies, Applications, Challenges and Future Directions

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Abstract: In recent years, rapid urbanisation has intensified the need for sustainable solutions to address growing demands on urban infrastructure, climate change, and resource constraints. As smart cities strive to enhance citizen experiences by improving infrastructure, increasing accessibility, and accelerating economic growth, artificial intelligence (AI) and the Metaverse offer transformative potential for developing sustainable urban environments. However, integrating AI with the Metaverse for sustainable smart city development remains underexplored amid data management and processing challenges, privacy, security, and technological integration. This study addresses this gap by reviewing advancements in AI and its role within the Metaverse's architecture in smart cities. It explores how AI enables data analysis, enhances user experiences through computer vision and natural language processing, optimises connectivity with 6G and Edge AI, strengthens security through blockchain, and manages the creation of digital twins. Through a comprehensive analysis of peer-reviewed publications and research projects, the review investigates how AI is integrated into key technologies to realise the Metaverse for sustainable smart cities. Specific applications in smart environments, mobility, energy, health, governance, and the economy are highlighted through AI-enabled use cases, offering a practical roadmap for implementing solutions to enhance citizens' quality of life, promote economic growth, and achieve sustainability. Lastly, future directions are discussed, addressing potential challenges by emphasising interoperability and scalability and underscoring the need for robust data governance frameworks and AI ethics guidelines to address privacy, security, and ethical concerns. This approach aims to unlock the full potential of AI in enhancing the sustainability of smart cities within the Metaverse.

Keywords: artificial intelligence; digital twins; Metaverse; smart cities; sustainable cities; technologies; urban transformation; urban planning

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1. Introduction

Urbanisation, characterised by the growth and expansion of cities, is a significant global trend involving population migration from rural towns or villages to cities. Cities possess complex systems interconnected with their residents and infrastructure, such as transportation, communication networks, advanced services, businesses, and utilities supporting a high living standard. Technological advancements, economic opportunities, and social innovations drive cities' emergence and growth, which attracts people seeking improved living conditions and employment prospects [1,2]. In recent years, many people have relocated to urban areas, and forecasts suggest that by 2030,

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approximately 60% of the global population will live in cities. Furthermore, according to the United Nations, projections indicate that this trend will continue, with around 68% of the world's population expected to reside in urban areas by 2050 [3]. Rapid urbanisation and an increasing city population bring numerous challenges, including technical, socio-economic, and organisational issues, threatening urban environmental and economic sustainability [2,4]. For instance, in developing countries and modern cities, it has resulted in problems such as increased pollution and depletion of natural resources [5], overcrowding, and socioeconomic inequality [6–8]. Additionally, unplanned urbanisation can increase the burden on public services, including transportation and waste management [9,10]. This has further intensified the need for sustainable solutions to address the growing demands on urban infrastructure, climate change, and resource constraints [11], which necessitates innovative technological approaches to urban planning and management to create resilient, efficient and sustainable urban environments.

As the urban population grows, various applications have been introduced to provide solutions, contributing significantly to the development of smart urban ecosystem through smart cities [12,13]. A smart city is one where traditional networks and services are enhanced using digital and telecommunication technologies to improve the efficiency and quality of life for its inhabitants and businesses [14]. Additionally, smart cities not only help mitigate urbanisation effects but also drive entrepreneurship and economic development [15], as evidenced by the 2008 financial crisis, in which several countries pioneered smart city initiatives to boost economic growth. These cities offer a futuristic, adaptable approach that promotes environmental conservation and transformation across social, economic, and environmental domains while ensuring residents' well-being [16]. The development of smart cities is heavily influenced by advanced information and communication technologies (ICTs), such as cloud and fog computing [17,18], machine learning (ML) [19], Internet of Things (IoT) [20], blockchain [21], and artificial intelligence (AI) [13,22], to create a smart ecosystem [23].

In recent years, the Metaverse has emerged as an innovative virtual environment where digital and physical worlds converge, offering a new layer of technological integration for smart cities with the potential to enhance urban sustainability. It has evolved to represent an immersive, interactive space where users engage through digital avatars and digital twins (DTs), which are digital replicas of physical objects or systems [24]. The Metaverse integrates extended reality (XR), including virtual reality (VR), mixed reality (MR), and augmented reality (AR), to varying degrees [25], enabling users to experience alternate lives through their avatars [26]. High-quality 3D models, advanced communication technologies like 5G/6G, and AI create intelligent environments in the Metaverse. The combination of Metaverse and smart city technologies enhances city management and development. Smart cities utilise real-time monitoring and data collection through sensors, which collect information about various aspects of the city, including the environment, transportation, and energy sectors. This information improves resource management, emergency response, and public safety and optimises energy use. Integrating the Metaverse introduces immersive and interactive virtual environments, allowing residents to engage with city services in new ways, enhancing city planning and overall user experience. Therefore, the Metaverse enables smarter decision-making, resource allocation, and citizen engagement through real-time data analysis and virtual simulations [27], creating a more interconnected urban ecosystem.

Notably, AI is integral to the Metaverse’s foundation and development [28] and has numerous applications for Metaverse in smart cities. For instance, AI plays a crucial role in enhancing automation and connectivity [29], allowing the Metaverse to support smart city applications in intelligent transportation systems [30] and other urban sectors. This enables smart cities to address the needs of citizens and municipalities more effectively [13,31]. For instance, AI-driven deep learning (DL) models have demonstrated the ability to detect early air pollution [32] and support sustainable agriculture within smart cities, aiding in yield prediction, quality evaluation, and pest detection [33]. Implementing and designing the urban ecosystem for administrative services like transportation, energy, environment, and culture in smart cities while ensuring ethics and security poses challenges but could offer potential improvements through AI-enabled data analytics [28] and

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Metaverse technologies. Furthermore, using AI-based technologies [34], cities can efficiently analyse the vast amounts of data generated by stakeholders and sources, such as IoT devices, video cameras, and Metaverse-based interactions, helping city officials manage these data quickly and effectively [35]. However, while AI offers significant benefits, it also presents challenges that must be addressed to ensure the seamless coexistence of humans and machines, both in physical smart cities and their digital counterparts within the Metaverse.

Nevertheless, key technologies such as AI, XR, digital twins, blockchain, 5G/6G and IoT will fully enable Metaverse applications in smart cities to aid users in interacting and collaborating within virtual environments. However, even though AI is crucial in the foundation and development of the Metaverse, it is less prominently discussed how it can or is integrated into the Metaverse, with other key technologies, to actualise a sustainable smart city. For instance, to provide animated 3D building models, state-of-the-art computer vision can be utilised, enabled by AI/ML/DL models. However, utilising the 3D content for the Metaverse is challenging due to the scalability of the current infrastructure. Therefore, it is essential to develop tools and infrastructure that allow developers to create more scalable 3D/AR/VR experiences across various platforms and purposes [36]. Furthermore, as the Metaverse is massive and creates interpretability challenges, developing explainable smart city applications is essential [37]. The AI-enabled Metaverse will rely on explainable AI to ensure transparency and explainability in integrating and functioning various key technologies, enabling efficient, trustworthy, and immersive experiences across smart city applications. Motivated by the evolving technologies and foreseen challenges, we survey the state-of-the-art AI-enabled technologies and how they are integrated with other key technologies in the context of Metaverse for a sustainable smart city to answer the following question: How can AI-enabled technologies, integrated with key technologies like XR, digital twins, blockchain, 5G/6G and IoT, drive the development of a sustainable smart city within the Metaverse? In the following subsections, we review the related surveys and outline the contribution and structure of this review.

1.1. Related Surveys

In this subsection, we examine the latest surveys on various technologies related to smart cities. Numerous studies have recently been conducted to explore the potential of smart city technologies, their implementation, applications, and future research directions [2,22,27,28,30,38–45].

For instance, Wang et al. [38] present a comprehensive framework for integrating Artificial General Intelligence (AGI) and parallel intelligence into Metaverse-based smart cities, emphasising human ethics, social responsibility, and ecological sustainability. Similarly, the authors in [39] examine the ethical implications of the Metaverse as a virtual form of data-driven smart cities, focusing on privacy, surveillance capitalism, data surveillance, geo-surveillance, human health and wellness, and collective cognitive echo chambers. The researchers in [42] also provide an extensive overview of potential and already implemented Metaverse applications in smart cities, discussing various benefits and challenges associated with these applications. Similarly, [41] highlights the Metaverse's potential to enhance environmental, economic, and social sustainability in smart cities, focusing on integrating digital twins and AI technologies. Bibri et al. [40] provide a comprehensive overview of the potential applications, opportunities, and challenges associated with deploying XR technologies in IoT applications within the broader framework of IoCT, emphasising the synergy between XR and AIoT technologies. Furthermore, the integration of Metaverse technologies into intelligent transportation systems is studied, highlighting their potential to enhance transportation safety, reliability, and efficiency through secure communication, virtual simulations, and real-time analytics [30]. The role of AI, including machine learning algorithms and deep learning architectures, in the foundation and development of the Metaverse is explored, providing a comprehensive investigation of AI-based methods concerning several technical aspects and AI-aided applications, such as healthcare, manufacturing, smart cities, and gaming, in virtual worlds in [28]. Similarly, Chen et al. [27] provide a detailed review of smart cities based on Metaverse technologies. Alahi et al. [2] discuss the role of IoT and AI in developing smart cities, focusing on recent advancements, potential applications, and future trends, emphasising integrating these technologies to enhance urban

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sustainability and productivity. Yaqoob et al. [45] reviewed the enabling technologies, opportunities, challenges, and future directions of the Metaverse for smart cities, highlighting its potential to enhance infrastructure, services, and sustainability. Arora et al. [22] examine the role of multi-agent systems in smart city applications, providing a detailed description of AI paradigms, critical application areas, and future research directions, while the researchers in [43] study the integration of advanced technologies for sustainable smart cities, focusing on the role of IoT, AI, blockchain, and other technologies in enhancing various smart city domains and addressing sustainability challenges. A summary of these studies compared to our study is presented in Table 1.

Table 1. Comparison of our work to other current studies concerning smart cities, AI and the Metaverse.

Paper	Short Description	Key Technologies covered	Applications Covered
[46] 2023	Integration of IoT-enabled technologies and AI for smart city development	IoT, AI	Mobility, governance, education, economy, healthcare, environment, living
[22] 2023	Multi-agent-driven smart city applications	Multi-agent systems, distributed AI	Home, governance, environment, mobility
[28] 2023	Artificial intelligence for the Metaverse	AI, NLP, blockchain, machine vision, networking, neural interface	Healthcare, manufacturing, smart cities, gaming
[30] 2024	Metaverse for intelligent transportation systems	XR, blockchain, AI, digital twin, IoT, 5G/6G, distributed computing	Transportation systems
[38] 2024	AGI in the Metaverse for smart cities and societies	AGI, parallel intelligence	Smart cities, societal management, urban infrastructure
[39] 2023	The Metaverse as a virtual model of platform urbanism	AIoT, XR, neurotechnology, nanobiotechnology	Urbanism, platform urbanism, smart cities
[40] 2023	The potential of the Metaverse and artificial intelligence for the Internet of City Things	AIoT, XR, IoT, 5G, digital twins, cloud computing	Smart city infrastructure, urban mobility, energy, healthcare, education
[41] 2022	The Metaverse as a virtual form of smart cities	AI, IoT, digital twins, XR, big data	Urban planning, smart cities
[42] 2024	Applications, benefits, and challenges of Metaverse in smart city	AI, IoT, digital twins, XR, blockchain	Urban planning, citizen services, transportation systems
[43] 2021	Amalgamation of advanced technologies for smart city environment	IoT, AI, blockchain, big data, cloud computing, wireless sensor networks (WSN)	Smart cities, healthcare, transportation, energy management
[45] 2023	Metaverse applications in smart cities	IoT, AI, blockchain, XR, digital twins, cloud computing	Healthcare, energy management, transportation, smart homes, supply chain, and logistics
[27] 2024	Metaverse for smart cities	IoT, AI, cyber-physical systems (CPS), digital twins, blockchain	Urban monitoring, governance, emergency management, simulation
Our study	Integration of AI-enabled technologies and Metaverse for sustainable smart city	AI, big data, NLP, computer vision, digital twin, IoT, blockchain, 5G/6G, edge/cloud Computing	Environment, mobility, energy, health, governance, economy

1.2. Method

Studies were identified by searching databases, including IEEE Xplore, ACM Digital Library, Springer, MDPI and Science Direct. The additional literature was collected from Google Scholar, archive databases and other sources, with a publication date range limited to the past six years. We present details in Table 2. The selected articles comprised early-access materials and published peer-reviewed research from technical conferences and journals. For screening, we focused on the core elements of each paper relevant to our research topic. To ensure the inclusion of unique and relevant studies, we implemented a rigorous screening process to remove redundant references. Duplicate entries across multiple databases were identified and removed.

Table 2. Search criteria method for selecting studies for review.

Search Criteria	**Content and Evaluation**
Period	Past six years
Databases	IEEE Xplore (115), ACM Digital Library (16), MDPI (24), Springer (15), Science Direct (35), and other sources (48); Total (253)
Article Type	Early-access, Peer-reviewed conference and journal papers.
Screening Process	Each paper's relevance to the research topic is determined by the Title, Abstract, Introduction and Conclusion
Search String	" AI for Metaverse", "digital twins", "blockchain for Metaverse", "explainable AI", "IoT enabled Metaverse", "6G powered for the Metaverse", "edge and cloud computing for the Metaverse"," smart city", "sustainable smart city"
Search strategy	Boolean (AND, OR, and NOT) combination

The searching keywords comprised key technologies supporting the smart city applications in the Metaverse: this included AI for Metaverse, digital twins, Metaverse, explainable AI, IoT enabled Metaverse, 6G powered for the Metaverse, communication, edge and cloud computing for the Metaverse, smart city, sustainable smart city etc. Based on these keywords, we use boolean (AND, OR, and NOT) combination searching to broaden or narrow the searches. After searching all related studies, we screened titles, abstracts, conclusions and introductions. We examined them by the inclusion criteria, which should apply the key technologies supporting the AI applications in the Metaverse. This was followed by assessing the quality of all the screened studies, sorting, and summarising the key technology related to Metaverse for smart cities.

1.3. Contributions

It is clear from the above discussion that some of the existing surveys have focused on very narrow perspectives of AI and relevant technologies, while others have investigated the role of the Metaverse in terms of societal, economic, and digital value, as well as covering limited applications in the context of smart cities. The exploration of how AI enables the key technologies in the Metaverse to attain sustainable smart cities is still unexplored. In contrast, our review specifically focuses on the AI-enabled Metaverse, where AI is leveraged to map the physical world into a digital reality in the virtual world. As such, the review's key contributions are:

1) It provides a comprehensive review of advancements in AI and examines its role within the Metaverse's layered architecture for smart cities. By exploring how AI as the core intelligence enables data analysis and decision-making, enhances user experiences through Computer Vision (CV) and Natural Language Processing (NLP), optimises connectivity with 6G and Edge AI, strengthens security through blockchain applications, and manages the creation of digital twins, the study explains the technical integration of AI into key Metaverse-enabling technologies to deepen the understanding of AI's capabilities in improving user engagement,

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connectivity, efficiency, and services, laying the foundation for developing advanced Metaverse applications that address challenges in smart cities.

2) Building upon the technical insights, it reviews the integrated role of AI and key technologies in realising the Metaverse for sustainable smart cities. By presenting potential AI-enabled applications and use cases in smart environments, mobility, energy, health, governance, and the economy, it offers a practical roadmap for implementing sustainable solutions to enhance citizens' quality of life, promote economic growth, and achieve sustainability.
3) It identifies and analyses the challenges and future research directions in integrating AI and key technologies within the Metaverse for sustainable smart cities by highlighting existing gaps, guiding future research and development efforts to overcome these challenges, and informing policymakers to facilitate the implementation of solutions that enhance the quality of life for citizens and promote economic growth and sustainability.

The rest of the article is organised as follows: Section 2 includes the background and technical aspects of the smart city and the Metaverse. Section 3 presents the state-of-the-art AI and its role in realising the Metaverse and enabling key supporting technologies. Section 4 highlights the integrated role of AI and key technologies in realising the Metaverse for sustainable smart cities, along with potential applications and use cases. Section 5 summarises the analysis of the findings, while Section 6 discusses the future research directions. Section 7 concludes the paper.

2. Background on Smart City and the Metaverse

This section explores the intersection of smart cities and the Metaverse, focusing on key components and architecture. We begin by outlining a brief background of smart cities and then discuss the architecture of the Metaverse for a smart city. Lastly, we highlight the key challenges for the Metaverse in smart cities.

2.1. Smart City

Developing a smart city relies on key elements such as infrastructure, data-driven decision-making, citizen-centric approaches, innovation, entrepreneurship, collaboration, and resilience. Smart cities are advanced urban ecosystems that use ICT infrastructure to gather and apply real-time data from widespread sensors and devices [47]. This infrastructure includes cutting-edge technologies like IoT, cloud computing, and big data analysis, which enable real-time monitoring and efficient management of city systems and enhance urban management, crisis mitigation, and coordinated planning, contributing to achieving the UN Sustainable Development Goal[1], which promotes inclusive, safe, resilient, and sustainable cities. The convergence of technologies such as AI, IoT, big data analytics, and 5G/6G drives the digitisation and sustainability of smart cities. As a result, smart city applications are expanding across various domains, including transportation, environment, energy, healthcare, and public safety. Integrating these technologies supports sustainable urban development and facilitates new business opportunities, ultimately sustaining the city's economy within the Metaverse. For instance, the Metaverse can enhance virtual urban planning, provide immersive platforms for citizen engagement, and simulate smart city operations in a digital environment, enabling innovative solutions for urban challenges. Smart cities also depend on institutional and social infrastructure. Institutional infrastructure involves governance and coordination between public, private, and civil organisations to deliver transparent and efficient services. In contrast, social infrastructure plays a key role by engaging citizens and improving their living standards through innovative solutions [47]. Data-driven decision-making is essential for real-time urban management, utilising vast datasets from IoT devices and sensors to extract actionable insights for urban planning, transportation, and environmental management [48,49]. Additionally, smart cities utilise integrated platforms such as intelligent transportation systems, energy management, logistics, and building services. Furthermore, the government's public service platform offers residents easy access to essential services, improving overall efficiency and convenience [27].

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[1] https://www.un.org/sustainabledevelopment/cities/

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The generic architecture for a smart city consists of four primary layers [47]:

1) *Sensing Layer*: This layer is at the bottom of the architecture and collects data from physical devices, such as sensors and IoT devices distributed throughout the city.
2) *Transmission Layer*: This layer facilitates communication between the sensing and upper layers, using various communication technologies to transmit collected data.
3) *Data Management Layer*: Once data is transmitted, it processes and stores valuable information, ensuring it is ready for analysis and service provision.
4) *Application Layer*: At the top, this layer provides various services and applications that utilise the processed data to deliver smart city functionalities, such as transportation, healthcare, and energy management.

Additionally, security modules are integrated into each layer to protect sensitive data, addressing one of the key concerns in smart city deployments. Figure 1 presents a Metaverse architecture for a smart city, with the corresponding smart city generic architecture layers highlighted in bold red square brackets. The following section provides a detailed explanation of this architecture.

2.2. Metaverse Architecture for a Smart City

As smart cities evolve, the Metaverse offers new possibilities for enhancing urban living. The Metaverse is a transformative 3D virtual environment that seamlessly integrates various aspects of our physical and digital lives. In other words, it represents a virtual space that merges computer-generated elements, virtual environments, digital assets, and user-controlled avatars, allowing individuals to engage, socialise, and collaborate through various smart devices. This concept has evolved to include various interpretations, such as an omniverse [50], a mirror world [51], hyper-spatio-temporality [52], and an embodied Internet or spatial Internet [53].It is characterised by key features such as immersive, where users experience a realistic and emotionally engaging virtual environment [54], and heterogeneity, which encompasses diverse modes of communication, data types, and interfaces [55]. Scalability is another key attribute, allowing the Metaverse to accommodate numerous concurrent users and complex interactions [55]. Interoperability ensures that users can seamlessly transition between different virtual worlds, while sustainability is maintained through a decentralised framework that supports a persistent and independent economic system [24]. Lastly, hyper-spatiotemporality allows users to transcend the limitations of physical space and time, enabling them to explore various virtual worlds with different spatiotemporal dimensions [52].

The Metaverse in smart cities is powered by key technologies, which include AI, XR, IoT, 5G/6G, edge/cloud computing and blockchain [27,30,44]. AI facilitates intelligent decision-making and automation, while XR allows citizens to engage with virtual city infrastructure. IoT integrates real-world data, supported by 5G/6G communication and edge and cloud computing for low-latency, real-time interactions. Blockchain secures digital assets and transactions. These technologies form the foundation for immersive, secure, scalable smart city services. As these technologies advance, the Metaverse's implementation becomes more feasible, attracting interest from high-tech companies like NVIDIA, Meta, and Tencent [56]. In essence, Metaverse is anticipated to integrate all essential aspects of cyberspace, such as AI/ML)/DL platforms and applications, 5G/6G, cloud and edge computing, social media, online gaming, XR, blockchain, and IoT, to allow users to interact virtually [36,57,58]. Metaverse will also proliferate the trend of data-centric intelligent systems that are central in smart cities. This trend poses some constraints on existing 5G communication systems, making them less efficient and unreliable [59,60].

The architecture of the Metaverse is multi-layered, with each layer supporting different functionalities crucial for the operation and expansion of the Metaverse. In [28,36], the authors present the seven-layer architecture based on the concept of the Metaverse in the context of the value chain [61], which includes the infrastructure layer, human-interface layer, decentralisation layer, spatial computing layer, economy layer, social layer, and experience layer. These layers map closely to a broader architecture comprising the human, physical infrastructure and digital spaces highlighted in [44]. Following the concept in [44], we adopt the architecture of the Metaverse for smart cities, which consists of human interaction, the physical infrastructure, and the digital world.

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This architecture also integrates the four primary layers of the generic smart city architecture, creating a seamless interaction between these spaces. Figure 1 shows the generic architecture of the Metaverse for smart cities, showing the connection between its various components.

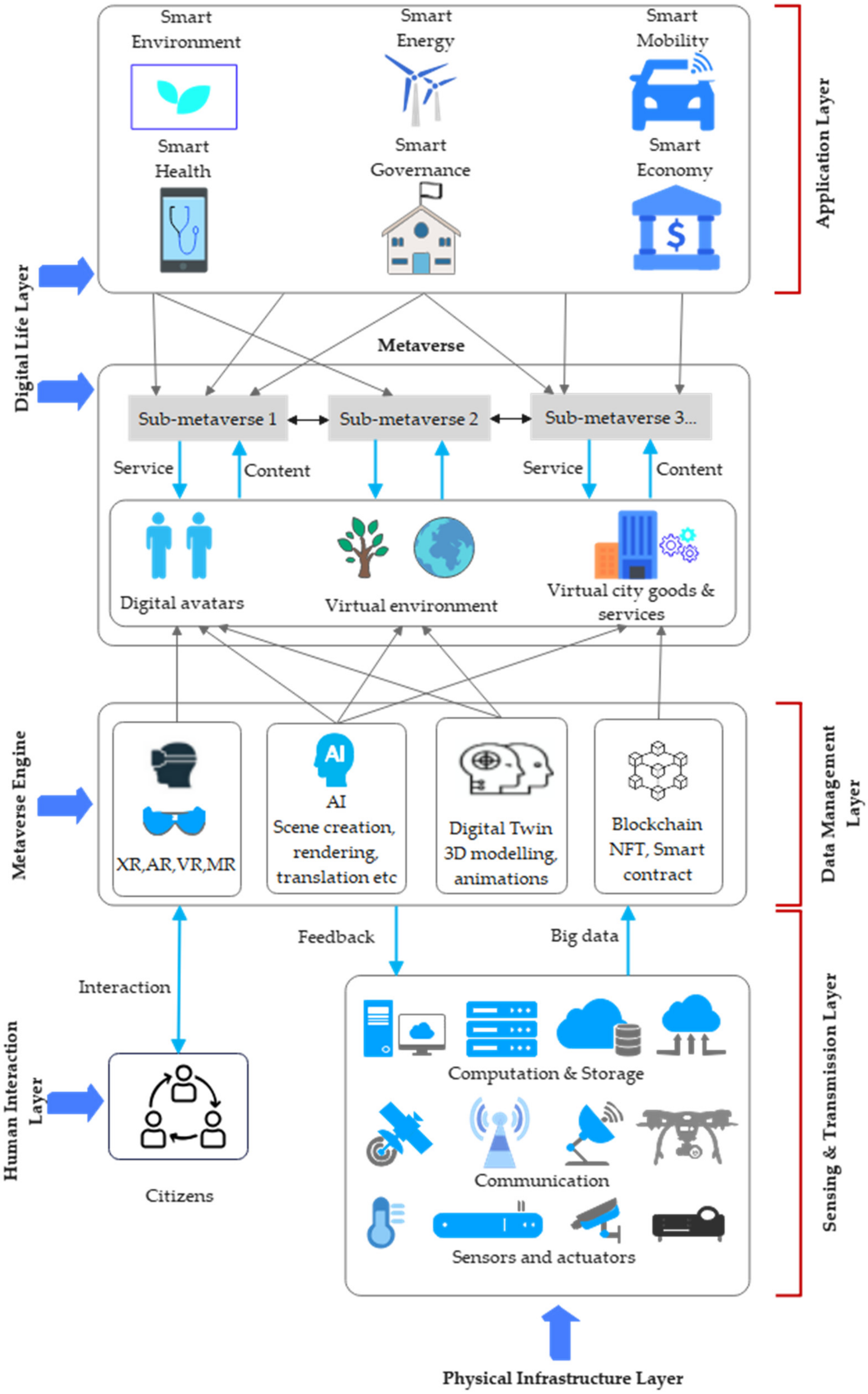

Figure 1. Generic Metaverse architecture for a smart city showing the digital, human, and physical infrastructure and the integration of the generic smart city architecture indicated in red bold square brackets.

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Human Interaction Layer: The human interaction layer, represented by digital avatars and user interactions, is linked to the Metaverse through advanced human-computer interaction (HCI) technologies and XR devices [62]. These interfaces allow citizens to engage in immersive social interactions, work, and access services within the Metaverse, seamlessly bridging the gap between the physical and digital realms [63]. In smart cities, this enables citizens to engage with both the physical and digital infrastructure through smart devices such as smartphones, AR glasses and VR headsets.

Physical Infrastructure Layer: The physical infrastructure layer includes essential components such as storage, computation, communication frameworks, and sensor networks, which correspond to the *Sensing Layer* and part of the *Transmission Layer* in the smart city architecture. These components ensure that massive amounts of data generated within the virtual world can be processed and transmitted efficiently, enabling real-time interactions [64]. It serves as the backbone for the smart city, handling physical devices and IoT sensors across the city that collect heterogeneous data in real-time. The storage and computation infrastructure stores data and performs complex processing tasks using cloud-edge-end computing [65]. Additionally, a communication network like 5G/6G provides networking connectivity. *Digital World Layer*: A digital world can consist of multiple interconnected, distributed virtual worlds [66], represents part of the *Application Layer* from the generic smart city architecture. Each virtual world, or sub-metaverses, provides citizens with various virtual environments and services or goods [24]. This layer integrates the physical world knowledge and data collected by sensors in the smart city into the virtual world, creating immersive and functional virtual environments. The virtual output from the Metaverse reflects the data created by virtual services, digital objects, and avatars that influence real-world urban management.

Metaverse Engine: The Metaverse engine is responsible for creating and maintaining the digital world, using technologies such as AI, blockchain, and digital twins to generate realistic virtual environments and facilitate trustworthy transactions [24]. This layer aligns with the *Data Management Layer* of the smart city generic architecture. AI-based algorithms generate personalised content and avatars and provide intelligent services to enhance the Metaverse ecosystem. Additionally, AI techniques and big data analysis facilitate the simulation, digitisation, and mirroring of real-world environments through DT technology, creating an immersive and realistic virtual experience for citizens.

In a smart city, the human, physical, and digital worlds are interconnected through IoT, Internet, and HCI/XR technologies. IoT sensors capture real-world data, which the Metaverse engine processes to create digital twins and simulations. For instance, smart parking systems can leverage the Metaverse to create virtual representations of parking lots, providing real-time monitoring and efficient management of parking resources [67]. Similarly, navigation systems within the Metaverse can offer personalised and real-time guidance through visual overlays and voice instructions, enhancing the overall transportation experience in smart cities [41]. Citizens interact with these virtual environments using AR/VR or smartphones. This dynamic feedback loop between the physical and digital worlds ensures real-time optimisation of city services, enhancing urban efficiency and citizen engagement.

2.3. Challenges in Metaverse for Smart City

Metaverse-based smart cities face numerous challenges, such as trust, data privacy [68], bias, and infrastructure limitations, highlighting the need for advanced technological solutions. Emerging technologies and AI have the potential to address these challenges by improving decision-making, enhancing security, and optimising resource management. For instance, the vast amount of data generated within smart cities presents challenges in data acquisition, management, analysis, and processing of heterogeneous datasets [69], prompting the development of advanced computational techniques [70]. As a result, advancements in AI, particularly machine learning techniques, have emerged, driving more efficient data analysis and decision-making in the Metaverse and smart cities. The effectiveness of urban data applications is closely linked to the advancement of smart cities in the Metaverse, making the integration of AI and other emerging technologies essential to the development and sustainability of these cities. In this section, we discuss some challenges for Metaverse in smart cities.

1. Data Acquisition, Management, Analysis and Processing Challenges

In a smart city, real-time IoT data must be collected to analyse the state of the physical world entities. This challenges data integration, interoperability, and storage, necessitating advanced data management and analytical techniques. The rapid development of multi-modal learning, particularly with large-scale pre-trained models, has opened new avenues for smart city applications. However, integrating these technologies into smart city environments faces hurdles, notably the scarcity of high-quality, large-scale urban multi-modal datasets. Although smart cities are data-rich, privacy and security concerns limit data accessibility, hindering the development of comprehensive datasets. Hence, there is a pressing need to create extensive and diverse multi-modal datasets tailored to smart cities [69] and the Metaverse. Additionally, one of the primary difficulties lies in collecting and monitoring real-time IoT data, which are crucial for accurate analysis and decision-making. This challenge is further compounded by the need to perform real-time data mining and analysis, requiring advanced algorithms and high computational power. Unlike traditional simulations, the Metaverse must support multiple simultaneous simulation processes that can interact with real-world data and provide immediate feedback for optimisation [37]. Further, the exponential growth in smart city data, e.g., mobility data, particularly with the advent of autonomous vehicles, poses significant challenges in data storage. Current storage technologies face challenges in managing the growing volume of smart city data in the Metaverse, making it necessary to explore innovative approaches such as distributed storage using blockchain networks [30].

2. Lack of Trust in AI Systems

AI is an important technology that acts as the brain in the Metaverse, powering tasks such as making accurate predictions, data computations, and improving algorithms for various tasks in a smart city. However, the Metaverse's complexity often results in black-box AI models. For instance, deep neural networks have greatly improved performance but have become much less explainable, making many of their results difficult to interpret. This is because deep neural networks are created directly from the data, introducing data bias during data processing, resulting in a lack of transparency, fairness, accountability, and trustworthiness in AI-driven decision-making [71]. Current research in smart city applications has focused on enhancing predictive power by employing more complex models, such as expandable deep networks. However, this approach often sacrifices explainability [69]. While some efforts have aimed to address interpretability in class-incremental learning [72] and smart health systems [37], there is still a significant gap in research focused on understanding the model's explainability and the rationale of its learning.

3. Privacy and Security Vulnerabilities in Smart City and Metaverse Integration

In a smart city, privacy and security are significant challenges that must be addressed to ensure safe and seamless data integration across various platforms. Moreover, integrating these systems increases the risk of cyber-attacks, where breaches could lead to unauthorised access to critical city management systems. Data privacy is another critical factor, as the city network continuously gathers and processes highly sensitive citizen information [47]. A major challenge is ensuring user data privacy while maintaining transparency in data collection, storage, and utilisation in smart city applications. In addition, merging shared user data and 3D virtual spaces with IoT systems in the Metaverse amplifies the risk of data breaches, as multiple entities must collaborate in real-time, leading to potential vulnerabilities in the system [37]. Particularly in the Metaverse, the potential for data leakage, eavesdropping, jamming, and virtual-reality-synthesized attacks can compromise the integrity and privacy of user data [73]. Moreover, the Metaverse's reliance on IoT data in a smart city introduces substantial cybersecurity risks, especially in healthcare applications. Ensuring the Metaverse's security, privacy, and trustworthiness is more challenging than in the physical world

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[24]. Additionally, AI models in the Metaverse are susceptible to poisoning attacks, where small amounts of malicious data are introduced into the system. Detecting such data in the vast datasets typical of Metaverse applications in a smart city is challenging. Over time, these poisoned inputs can degrade the AI model's performance, potentially leading to service failures. The dynamic nature of the human-machine interface in the Metaverse, particularly in applications like autonomous vehicles and industrial manufacturing, further complicates security [37]. Another challenge is the potential for misbehaviour among regulators within the Metaverse, which could lead to system breakdown. Additionally, the blurred boundary between the virtual and real worlds makes distinguishing between true and false identities difficult, with malicious avatars potentially using deepfakes to evade law enforcement efforts.

4. Technological Integration

Numerous obstacles must be overcome before AI technologies can fully realise their potential in the Metaverse for smart cities. A significant challenge lies in the need for the Metaverse to integrate with emerging technologies such as 5G/6G, Industry 5.0, and the Internet of Aerial and Ground Vehicles. This integration is crucial for handling scalability as the Metaverse grows. Still, it introduces issues related to heterogeneity, bandwidth management, energy efficiency, and security, which are yet to be fully addressed [36]. Another key challenge is the anticipated shift of AI from cloud-based systems to the network edge, enabled by 6G technologies. This shift is essential for providing low-latency responses in the Metaverse while ensuring user data privacy [67]. However, it also poses significant challenges for existing wireless networks, particularly in remote areas where high latency could lead to disconnection due to poor internet connectivity, which can be fatal for mission-critical applications in smart cities. Energy efficiency remains crucial in achieving sustainability as AI and 6G technologies are increasingly utilised to deliver immersive services in the Metaverse. Furthermore, developing AI models capable of processing diverse urban data in the Metaverse faces significant challenges. Traditional fine-tuning methods are increasingly inadequate due to the rapid growth of urban data and heterogeneous users and services. This is further compounded by the need for labelled training data, the complexity of deep learning models, and limited hardware capable of supporting new and emerging intelligent services in the Metaverse.

3. AI-enabled Metaverse for Smart City

As discussed in Section 2, AI remains critical to developing the Metaverse in smart cities. It supports everything from immersive 3D worlds to optimised intelligent systems and enhanced data protection, driving the realisation of more efficient, responsive, and secure smart cities. The following sections will focus on how AI powers the Metaverse and facilitates the development of sustainable smart cities. Special emphasis is placed on the connectivity between AI and key technologies it enables in the Metaverse, particularly to better understand their roles within smart cities.

3.1. Role of AI in the Metaverse for Smart City

We discuss the role of AI based on the layered architecture highlighted in section 2.2. AI drives the Metaverse by leveraging advanced algorithms, such as machine learning (ML) and deep learning (DL), to process the vast data generated in these virtual environments. It serves as a cornerstone, enhancing interactions between digital, human, and physical layers. In the digital layer, AI processes large datasets from IoT devices and social media to create intelligent and responsive virtual environments, which are critical for smart cities [74]. Machine learning and deep learning enable the Metaverse to automate tasks, discover patterns in unstructured data, and build models that simulate human intelligence, which is essential for smart city applications [75]. AI also powers realistic virtual environments, as seen in platforms like NVIDIA's Omniverse[2] and Spatial IO[3], where it simulates

[2] https://developer.nvidia.com/omniverse

[3] https://www.spatial.io

real-world objects for robotics and autonomous vehicle applications [36]. Moreover, AI underpins the creation and management of digital assets through smart contracts, ensuring fairness in blockchain transactions. In this instance, AI can detect modifications and anomalies for undemocratic activities in blockchain transactions, preventing such incidents. With large language models like GPT-4, AI can generate and manage NFTs and digital art [76–78], thus fostering economic sustainability within the Metaverse.

In the human world layer, AI enhances citizen experiences in the Metaverse by improving accessibility and interaction with digital interfaces. It facilitates the creation of digital avatars that recognise human emotions, body movements, and speech, providing immersive and personalised interactions that blend the physical and virtual worlds. AI technologies such as computer vision (CV) and natural language processing (NLP) further improve inclusivity, enabling users with disabilities to interact seamlessly with Metaverse platforms [36]. On a societal level, AI addresses citizen needs in smart cities by automating tasks, extracting insights from unstructured data, and integrating resources to solve complex urban challenges [79]. In addition, it enhances citizens' lives through technology, innovation, and knowledge [13,80–83]. It also supports governance, culture, and urbanisation by improving decision-making processes [49,74].

In the physical infrastructure layer, AI and IoT in smart cities are key to managing urban infrastructure, such as transportation systems, energy grids, and public safety networks. AI, combined with IoT and big data analytics, enables real-time Metaverse interactions and infrastructure management. For instance, AI-enabled edge computing allows efficient data processing and decision-making [42,83,84], which is crucial for smart transportation and urban infrastructure management. Additionally, 5G/6G networks and AI-enabled hardware and software support the seamless operation of Metaverse services from temporary data storage to cloud connectivity [36], optimising resources, reducing energy consumption, and enhancing the resilience of these systems [79]. AI technologies also address operational challenges in smart cities, such as high costs, technological limitations, and the need for skilled personnel [13]. They contribute to creating sustainable, liveable urban environments by standardising processes to meet human needs [84]. However, the integration of AI raises ethical concerns, including potential discrimination, data reliability, and privacy issues [68], while scaling up smart city technologies involves complex socio-political and cultural considerations, requiring multidisciplinary approaches to ensure responsible, equitable AI deployment [85].

3.2. AI Learning Techniques

AI techniques have facilitated seamless interaction between virtual environments and citizens in smart cities. Semantic learning, neuromorphic computing, and NLP are key AI technologies in smart cities that enable the Metaverse to understand and respond to human languages and actions in real-time [86]. NLP, in particular, is instrumental in generating meaningful human-computer interactions by processing large amounts of natural language data, such as speech and text, to enhance virtual experiences. Similarly, ML techniques, including deep learning and learning paradigms such as supervised, unsupervised, reinforcement, and self-supervised learning, have been pivotal in driving advancements in immersive applications in the Metaverse. Particularly, reinforcement learning and self-supervised learning offer more scalable alternatives, aiming to make Metaverse AI task-independent. For example, Meta AI has advanced self-supervised learning by creating the data2vec model, which combines multiple modalities like speech, vision, and NLP, enabling more adaptable and unified learning across different tasks [87].

Furthermore, foundational models (FMs), like GPT-4, driven by advanced neural architectures such as transformers, have emerged as powerful tools due to their ability to generalise across multiple tasks without task-specific programming [88]. These models leverage vast amounts of unlabelled data through self-supervised learning, which significantly differs from traditional supervised models that rely on extensive labelled datasets. Despite these advancements, self-supervised learning remains a work in progress, and further research is needed to realise its potential across different smart city Metaverse applications. Similarly, continual learning (CL) has emerged as a novel machine learning paradigm with potential in smart cities [69]. This paradigm constantly updates models to adapt to changing environments, where the learning tasks, data, and distributions can vary over time. These AI techniques, individually or collectively applied, enhance the Metaverse's ability to offer personalised, scalable, and adaptive virtual experiences across diverse smart city applications. Figure 2 summarises the role of AI, ML, and DL in the Metaverse for smart city applications.

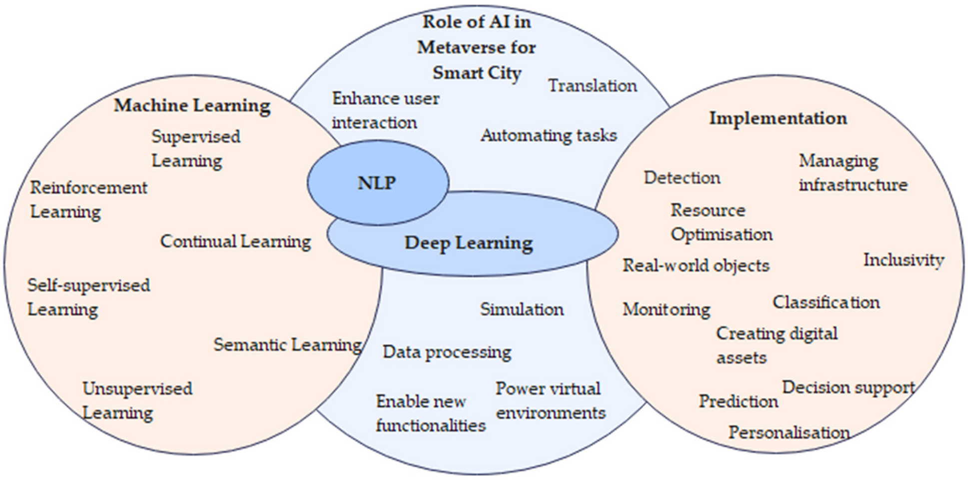

Figure 2. Role of AI, ML, and DL techniques in the Metaverse and smart city applications.

3.3. AI-Enabled Technologies for the Metaverse in Smart Cities

Smart city applications are multifaceted, with multiple dimensions that combine technology, innovation, and knowledge. This section provides an overview of advanced AI techniques for enabling the Metaverse in smart cities. It discusses key technologies such as big data, NLP, computer vision, blockchain, digital twins, IoT, edge AI, and 5G/6G in realising a ubiquitous Metaverse in smart cities. A summary of these technologies enabled by AI is presented in Figure 3.

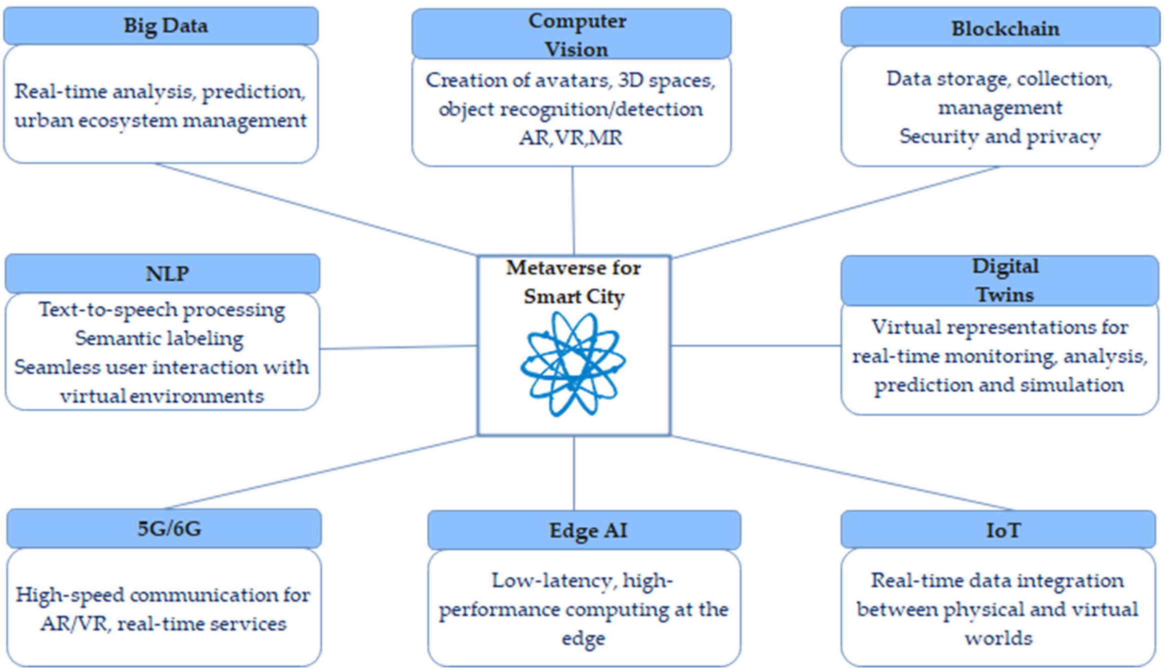

Figure 3. AI-enabled technologies in a smart city Metaverse environment.

1). Big Data

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Big data, characterised by its volume, velocity, variety, and veracity, is generated from various sources in smart cities, such as IoT devices, social media, sensors, and spatial data far exceeding traditional city data volumes. This often unstructured data covers key aspects of urban life, including transportation, energy, environment and public safety, forming the foundational basis for improving city operations [43]. Integrating AI with big data enables real-time analysis, prediction, and management of urban ecosystems, allowing for problem anticipation, optimised resource allocation, and customised services [74]. In the Metaverse, this integration becomes even more complex, relying heavily on spatial and spatio-temporal data to manage the blending of physical and digital spaces, which is critical for realistic and immersive virtual experiences. Spatial data intelligence involves acquiring, analysing and interpreting this data to understand spatial relationships, patterns, and trends [89]. In the Metaverse, where cities exist in virtual or augmented reality environments, spatial data takes on a new dimension, blending physical and digital spaces. Furthermore, spatio-temporal data intelligence, which adds the element of time and location to spatial data, plays a crucial role in understanding how these virtual environments evolve and respond to user interactions over time. Therefore, in the Metaverse, AI techniques are crucial for modelling and processing location and time information, enhancing virtual experiences' realism and immersion [86].

For instance, spatiotemporal autoregressive models, time-series clustering, and graph-based models like Graph Neural Networks (GNNs) and Graph Attention Networks (GATs), are employed to model complex spatiotemporal dependencies and patterns in the data [86]. Traffic flow prediction under uncertain data conditions is studied using an autoregressive data representation to analyse traffic patterns' temporal and spatial characteristics [90]. Similarly, autoregressive models have been used to predict traffic flow by modelling spatial correlations between locations, such as how congestion at one location affects nearby areas [86]. Time-series clustering enables the integration of real-time traffic data from sensors and connected vehicles [91], enabling dynamic updates to traffic predictions and improving traffic management [92]. Graph-based models, like GNNs and GATs, have been utilised to represent spatial relationships in the Metaverse. By utilising spatiotemporal data, the Metaverse can simulate environmental conditions like weather patterns and natural disasters [93,94], for instance, emergency response teams can practice in virtual disaster scenarios that change and develop over time [95]. Additionally, these models enable the simulation of public transportation and urban infrastructure, aiding urban planners and policymakers in visualising the impact of various strategies and making informed decisions. Furthermore, spatial-temporal models have been employed to recreate historical or real-world locations in the Metaverse, allowing users to explore different periods or witness changes in a location over time, offering immersive educational experiences [96].

2). Natural language Processing

Natural language processing, a key aspect of AI, enables the Metaverse to understand and interpret human languages, facilitating seamless interactions between users and virtual environments. These capabilities are essential for enhancing user experiences, enabling more natural and personalised engagement with virtual agents, and improving the overall immersive experience within the Metaverse [97]. Virtual agents rely on various computational models and learning processes that address tasks such as speech-to-text, text-to-speech, conversation design, and language modelling [98], which are essential for creating immersive and interactive experiences and crucial for machine translation and text recommendation in smart cities. For instance, advanced neural network architectures, including RNNs, LSTMs with attention mechanisms, and CNNs, have been employed to enhance these tasks, improving the reliability and performance of virtual assistants [99] in the Metaverse. Additionally, hybrid models, such as LSTM-CNN approaches, have been developed to generate both short and long text for image captioning and virtual question-answering tasks, thereby enriching the user experience [28].

Furthermore, deep-learning-driven semantic communication systems have been developed for efficient speech recognition and synthesis. These systems utilise CNNs and RNNs to extract text-related semantic features from input speech, reducing data transmission and optimising

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communication resources [100–102]. Moreover, NLP-based semantic communication systems for text transmission [103] have been designed to maximise system capacity while minimising semantic errors by restoring the meaning of sentences rather than merely addressing bit or symbol errors, as in traditional communication systems. In practical smart city applications, AI-enabled virtual assistants can help users navigate complex digital environments, answer questions, and perform tasks [104,105] by leveraging knowledge graphs and recommender systems to provide personalised support. Additionally, NLP-driven chatbots and dialogue systems are instrumental in facilitating social interactions and collaborations within the Metaverse in smart cities, simulating realistic conversations [106] and enabling expressive communication through avatars that mimic users' facial expressions and body language, enhanced by computer vision technologies.

3). Computer Vision

Computer vision consists of various stages that allow machines to make sense of visual inputs, which is crucial for developing systems that interact with and analyse virtual and physical worlds [107]. These stages include image acquisition, preprocessing, feature extraction, object recognition, tracking, and interpretation [108]. Computer vision also enables XR devices to interpret and comprehend user actions by processing visually meaningful data [28]. In virtual environments, users are represented as avatars, allowing them to navigate freely through 3D spaces and engage with virtual objects in the Metaverse. Deep learning, especially CNNs, has revolutionised CV by mimicking the human visual system, achieving remarkable accuracy in object and pattern recognition [107]. This progress has led to CV application in the Metaverse, which is essential for creating realistic avatars, 3D spaces, and digital twins that mirror real-world objects and environments, like ZooBuilder, for animating animals using advanced pose estimation techniques [109]. Additionally, generative AI technologies are crucial in overcoming challenges in creating diverse and high-quality 3D objects for the Metaverse in smart cities. The ongoing demand for content has led to the use of generative adversarial networks (GANs) and diffusion models, which have proven effective in generating 3D objects and environments. For instance, StyleGAN [110] has been used for image-to-image translation applications, including generating high-fidelity human faces without the need for additional facial data [111], while tools like DALL-E 2 [77] and Google’s Imagen [112] generate 2D images from text descriptions. An example using DALL-E 2 is shown in Figure 4. NVIDIA's Instant Neural Radiance Fields (Instant NERF) [113] further advance this field by creating realistic 3D scenes from 2D images, enhancing the realism of virtual environments.

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Figure 4. Generated image of a futuristic smart city using DALL-E 2.

Computer vision is also evident in designing and developing 3D spaces and virtual worlds in smart cities. These spaces allow users to interact with virtual objects and each other in a three-dimensional environment. Researchers are working on optimising these 3D spaces, with studies such as those by Lo and Tsai [114], who proposed a virtual reality architecture (VRAM) to enhance human cognition, and Gao and Yang [115], who utilised collision detection algorithms to optimise building placement and interaction in virtual worlds. Zhao et al.[116] have proposed frameworks to improve the graphics content and visual construction pipeline in the Metaverse, and Wang et al. [117] have developed a framework for creating 3D spaces based on human-computer interaction theories. Other examples in smart cities, enabled by CV technologies, include applications such as monitoring urban environments [118], enhancing public safety [119], and facilitating intelligent transportation systems [120,121]. In XR, MR holds greater potential for the Metaverse in smart cities due to its blend of physical and virtual experiences, facilitated by holographic devices with see-through displays, which enable users to handle physical objects while wearing them, and immersive devices, which allow interaction with virtual objects in the digital realm. These advancements are critical as the Metaverse continues integrating into daily life, requiring more sophisticated methods and tools to enhance user experiences within these 3D environments.

4). Digital Twin

Digital twin (DT) technology is a virtual representation of physical objects, systems, or processes to facilitate real-time analysis, learning, and reasoning [140]. They synchronise real-world objects with their virtual counterparts, allowing for real-time monitoring, predictive analysis, and remote operation through AI and machine learning algorithms. This practical method for managing interactions between AR/VR devices in the Metaverse offers advanced perception and cognition capabilities. For instance, DTs use multimodal models, knowledge graphs, and IoT-based systems to create a comprehensive understanding of device-environment interactions [86]. It monitors real-time interactions and extracts semantic knowledge [138] using lightweight AR/VR technology for real-time operation [139]. It provides a unified semantic mapping of device-environment interactions, linking entity attributes and relationship knowledge [141]. Knowledge graphs support DT by offering

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structured knowledge and connecting key concepts in the Metaverse [142–144]. IoT-based DT model also enhances connectivity and interoperability across devices using edge processing [37].

In smart cities, DTs enhance environmental sustainability by optimising space utilisation, increasing human productivity, improving maintenance efficiency, and reducing carbon emissions in building operations [145–147]. They are also used to optimise traffic flow, improve public transportation systems, facilitate urban planning [148] and minimising downtime and costs by anticipating potential issues before they arise [149]. In addition, they are also used to monitor energy consumption in buildings by analysing the interactions between energy sources, distribution networks, and consumers; energy consumption can be more accurately understood, facilitating the implementation of efficient energy-saving strategies and the integration of renewable energy sources [150]. Urban digital twins allow for multisystem simulations and visualisations, enabling city planners to model buildings and environmental factors digitally [36]. For instance, DT can model the interactions between energy-consuming systems in buildings and external factors, leading to optimised energy usage and the implementation of demand response strategies [151,152]. In industrial manufacturing, DT is used to model production processes, predict equipment failures, and plan maintenance proactively, thereby increasing productivity and reducing waste [153]. While DTs primarily enhance realism and facilitate advanced services and social interactions within the Metaverse, they are also crucial for integrating IoT networks that provide real-time data, a task that AI and machine learning continue to improve [37].

5). Blockchain

Blockchain technology enables the Metaverse by providing a decentralised, transparent, and secure digital ledger for various operations [122–124]. It has evolved into a versatile tool applicable across various domains, including healthcare, real estate and smart cities [43]. The fusion of AI with blockchain technologies in the Metaverse is a critical driver for overcoming challenges related to big data analytics, AI-enabled content creation, and intelligence deployment, which are essential for evolving digital economies and ecosystems within virtual environments [125] in smart cities. AI's role in enhancing blockchain's capabilities is particularly relevant in managing the high transaction volumes of data typical of virtual environments. In this instance, digital assets such as NFTs enable avatars to generate content that can be traded [126,127], often surpassing the scale of physical world transactions. In a secure computing environment, blockchain and AI facilitate distributed data storage and enhance the security and privacy of data within smart city infrastructures by addressing vulnerabilities and privacy concerns that traditional centralised systems often face [43,128]. For instance, Woods et al. [129], explored the fusion of AI techniques with blockchain infrastructure to address security risks in the Metaverse, and Liu et al. [130] proposed a blockchain-based spatial crowdsourcing (SC) system (BlockSC) for the Metaverse, addressing the challenges of centralised authority reliability and location privacy in conventional SC systems illustrated in Figure 5. In edge computing-based smart grids, blockchain facilitates secure transactions between energy suppliers and consumers at the network edge, though challenges such as optimising consensus among nodes persist [131].

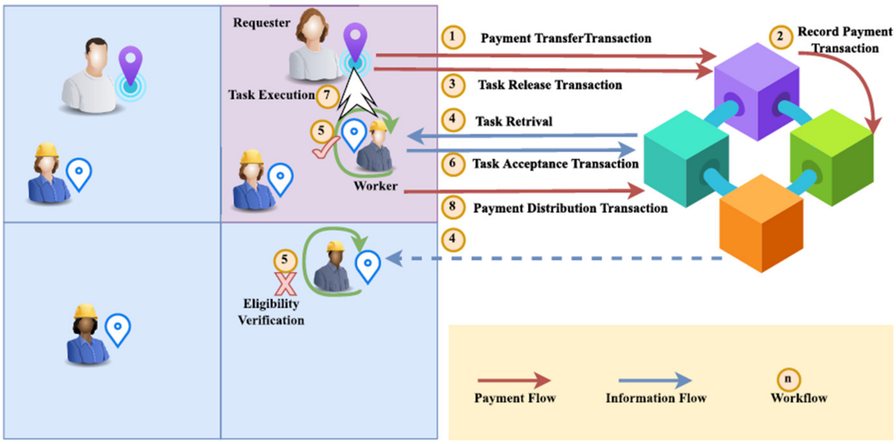

Figure 5. A blockchain-empowered spatial crowd-sourcing service in the Metaverse while pre-serving user location privacy [130].

Blockchain's application extends to smart cities, particularly Building Information Modelling (BIM) projects. For instance, Lv et al. [132] introduced BlockNet, a secure multidimensional data storage solution leveraging blockchain's immutable properties, thereby enhancing the security of digital mapping processes in IoT and improving the data reliability of digital twins. They also proposed a non-mutagenic multidimensional Hash Geocoding method to tackle challenges in multiscale spatial data processing, enabling unique indexing of multidimensional information and preventing data loss. However, the integration of these technologies also poses significant challenges. One of the major issues is the need for advanced AI techniques to manage the complex interactions and high traffic volumes generated by the numerous avatars and digital entities in the Metaverse [129]. Additionally, the economic structures within the Metaverse differ fundamentally from those in the physical world, with identity and digital creation playing central roles in value determination and transaction costs trending toward zero, necessitating innovative approaches to economic management [133]. As such, while the fusion of AI and blockchain holds immense potential for developing the Metaverse in smart cities, it also demands ongoing research to address the emerging challenges and ensure the sustainable evolution of these technologies.

6). Internet of Things

AI-driven Internet of Things (IoT) technologies are crucial in enabling immersive digital experiences within the Metaverse by mapping real-time IoT data from the physical world into virtual environments [134]. This integration enhances the experiential interface in AR/VR through IoT-enabled devices, which allows real-time control of physical or virtual objects [37]. IoT data can enhance context and situational awareness for AR/VR applications by facilitating data exchange between the digital and physical worlds [135]. For example, an AR device can respond to a user's finger gestures or activate a cyber-physical function based on an event happening in the real world. In addition, integrating semantic techniques with IoT, such as semantic communication, enables seamless interaction between real-world data and virtual environments, enhancing the functionality of AR/VR applications by addressing the variability in object meanings depending on the context [86]. These AI and machine learning-driven semantic technologies play a crucial role in understanding and processing the complex data within IoT ecosystems, allowing for more accurate and context-aware interactions in the Metaverse-based smart city. For example, semantically enhanced IoT supports interoperability and contextual information provisioning through a semantic layer that allows IoT devices to understand and communicate data despite differences in syntaxes or protocols [136]. The integration of advanced wireless technologies, such as 5G and 6G, further supports semantic IoT by enabling the transfer of resource-intensive semantic processing tasks to federated edge servers [137], thereby optimising semantic-aware networking.

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IoT systems can standardise and fuse diverse urban data from multiple sources through semantic information, improving resource usage and facilitating better decision-making processes [86] in smart cities. Semantic technologies further enhance data value by modelling and annotating various data types [138], offering standardised representations that simplify complex urban environments and improve the efficiency of city services. A practical example of this is the application of semantic IoT for managing crowd movement and mobility in cities like Gold Coast, Australia, and Santander, Spain, where semantic technologies have been employed to analyse and manage urban data effectively [139]. Another key application of IoT in the Metaverse is the creation of digital twins. In smart cities, IoT-empowered digital twins map physical elements like roads, buildings, and vehicles into a virtual city, enabling better management and simulation of urban environments using AI techniques [37].

7). Edge AI

Edge AI is a critical component in the infrastructure supporting the Metaverse within smart cities by enabling low-latency, high-performance computing directly at the network's edge. This approach leverages advanced machine learning algorithms with edge computing to optimise resource allocation, reduce latency, and enhance the quality of experience (QoE) for users engaged in immersive activities like VR/AR [154]. Edge AI computing lays the groundwork for developing mission-critical applications that demand ultra-reliable low-latency communication (uRLLC). Various AI methodologies, including deep learning, soft computing, and machine learning, have been applied to address challenges such as active user detection [155], resource allocation [156], scheduling [157], and power management [158]. For instance, AI-enabled DTs can be used for real-time synchronisation between the physical and virtual worlds by utilising distributed edge servers and devices for sensing and actuation [44], as illustrated in Figure 6, enabling users to manage and control physical devices through DTs of infrastructure, including space-air-ground integrated network (SAGIN) [159].

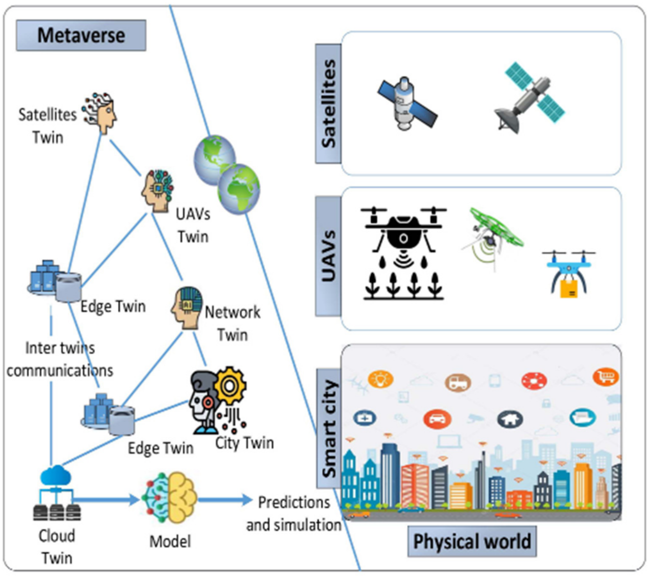

Figure 6. Real-time virtual/physical synchronisation between the intelligent edge network and the Metaverse [44].

Advancements have also seen AI utilised for mobility prediction, traffic estimation, channel prediction, and spectrum management to maintain uRLLC standards. For instance, SCGNet [160] and MCNet [161] have been introduced to enhance spectrum utilisation efficiency while ensuring accurate signal demodulation at the receiver. Additionally, a combination of CNN and LSTM has been employed to predict channel state information, thereby improving the robustness of 5G systems [162]. Another study leveraged 3D convolutional networks to forecast cellular traffic by extracting long and short-term spatial patterns from traffic data [163]. Challenges such as high energy consumption and latency have been addressed through the deployment of mobile edge computing (MEC) in DT environments, which supports URLLC models essential for real-time Metaverse interactions [164]. MEC supports this integration by providing computational resources and communications infrastructure close to users, significantly reducing response times to below human perceptible limits [37]. MEC enables various Metaverse applications in smart cities by facilitating the offloading of computationally expensive tasks to edge servers, improving performance and maintaining user immersion. For instance, Dai et al. [165] designed a 360-degree VR caching system over MECCache servers in a Cloud Radio Access Network (C-RAN) to enhance the quality of experience (QoE) for wireless VR applications. Similarly, Gu et al. [166] and Liu et al. [167] utilised sub-6 GHz and mmWave links combined with MEC resources to address the constraints of VR head-mounted displays (HMDs) and the transmission bottlenecks of panoramic VR video (PVRV).

8). 5G/6G Communication

Integrating AI within 5G and 6G communication technologies is essential for enabling the immersive and interconnected nature of the Metaverse, which is essential for smart cities. High-speed data communication is critical for supporting the connected AR/VR experiences and real-time services required by the Metaverse, where ultralow latency is necessary due to the nature of haptic signals and human perception. While 4G technologies struggle with latencies, 5G has made significant strides by enabling technologies such as mmWave, NOMA, and massive MIMO, which facilitate high-speed communication and enhance network capacity. Building on the widespread implementation of 5G networks, 6G technology is expected to connect not only individuals but also IoT devices, autonomous vehicles [168,169], wearable sensors, and even mobile robots [170]. Furthermore, this enhanced connectivity supports smart city infrastructure and security applications, addressing the rising demand for connectivity and ensuring privacy in the Internet of Vehicles (IoVs) [171] and other critical smart city applications.

Additionally, 6G networks will be particularly suited for smart city Metaverse applications that rely on deep learning, as they can handle large volumes of data and facilitate computation and storage at the network edge [172]. As 6G networks are poised to support pervasive intelligence by minimising latency and offering ultra-high bandwidth, AI-driven methods such as deep reinforcement learning (DRL) and federated learning are employed to optimise these networks. For instance, federated learning integrated with blockchain has been proposed to address the challenges of distributed AI model training in Metaverse applications, where strict security constraints limit user data sharing [173]. AI also plays a critical role in developing the Tactile Internet (TI) within the Metaverse, necessitating ultra-low latency for real-time haptic communications. AI deep learning techniques can help overcome the latency limitations inherent in traditional communication technologies, particularly in wide-area networks (WANs) [36]. However, challenges such as ensuring consistent global coverage and addressing the latency limitations imposed by physical constraints persist. These challenges highlight the ongoing need for AI-driven innovations to fully realise the potential of the Metaverse in future 6G networks.

Table 3 summarizes the key AI-enabled technologies used in Metaverse-based smart cities, provides examples of corresponding AI techniques applied, and outlines how these techniques and technologies address some challenges in such environments and general applications.

Table 3. AI-enabled Technologies, Techniques and Applications for Metaverse-Based Smart Cities.

Technology	Example of AI Techniques Used	Challenges Addressed	Some Applications in Metaverse for Smart Cities
Big Data	Spatiotemporal autoregressive models,	Manages heterogeneous data from various sources,	Real-time traffic flow prediction, environmental simulations, urban planning and infrastructure

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	time-series clustering, GNNs, GATs	realism in virtual environments, simulation	visualization, optimizing resource allocation and customized services
Natural Language Processing	RNNs, CNNs, LSTM, attention mechanisms, hybrid models, knowledge graphs	Enhances user interaction, accessibility and personalization, machine translation, enriches immersion through avatars	Speech-to-text and text-to-speech tasks, Virtual assistants for navigation and support, chatbots, avatars mimicking facial expressions and body language
Computer Vision	CNNs, GANs, Diffusion Models	Rendering of avatars and scenes, object recognition/detection, enables VR/AR/MR	Creation of realistic avatars and 3D spaces, enables MR experiences through holographic devices
Digital Twin	Multimodal models, knowledge graphs, ML algorithms	Synchronizes physical and virtual worlds, predictive maintenance, improves immersion, simulation and visualisation	Real-time monitoring and predictive analysis, remote operation of systems, optimizing space utilization and maintenance, urban planning and multisystem simulations
Blockchain	ML techniques integrated with blockchain methods	Protects data within decentralised systems, secure data storage, sharing and management, Strengthens data integrity in digital twins and IoT, digital economies	Managing digital assets and transactions, security in smart city infrastructures, virtual economies, secure mapping processes in IoT, data reliability for digital twins
Internet of Things	Semantic communication, ML-driven semantic technologies	Real-Time Data Mapping, context awareness, interoperability, data exchange challenges, creation of digital twins of physical elements	Real-time control of physical and virtual objects, context-aware AR/VR applications, optimises decision making, standardizing and fusing diverse urban data
Edge AI	DL, soft computing, ML	Enhances performance for immersive VR/AR, efficiency at the network edge, ultra-	Real-time synchronization between physical and virtual worlds, spectrum management and

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		reliable low-latency communication, energy consumption	utilization efficiency, supporting mission-critical applications
5G/6G Communication	DRL, federated learning integrated with blockchain, AI for network intelligence	High-speed data communication, ultra-low latency connectivity, edge computation and storage, IoT communication	Immersive and interconnected Metaverse experiences, optimizing network performance and resource management, enhancing connectivity for autonomous vehicles, pervasive intelligence with minimal latency and high bandwidth

4. Sustainable Metaverse for Smart City

The concept of sustainability within the Metaverse is increasingly recognised as essential in addressing environmental and social challenges in smart cities. As organisations seek to develop sustainable business strategies in response to climate change, the Metaverse emerges as a promising platform to mitigate carbon emissions through virtual interactions and digital twins. Integrating digital twin technology within urban spaces represents a significant advancement in sustainable urban development, offering city planners a dynamic and interactive tool for managing cities more efficiently. Urban digital twins mirror a city's infrastructure, services, and utilities in a virtual environment, enabling real-time monitoring, forecasting, and optimisation of urban resources such as traffic management, energy consumption, and waste generation. Digital twins can predict and mitigate waste production and energy efficiency issues by simulating various scenarios, contributing significantly to sustainability goals. The effectiveness of these digital twins relies on a robust network of IoT sensors and real-time data integration, which allows for accurate reflection of physical changes in urban spaces, ensuring that up-to-date data from infrastructure elements like roads, buildings, energy grids and bridges are seamlessly integrated into the digital model. As an example, the digital twins have achieved the best environmental sustainability in the field of building operations that could help in improving space utilisation, increase human productivity, improve maintenance and operational efficiency, and reduce carbon emission for a building [36]. Moreover, the European Space Agency's efforts to create a digital twin of Earth [174] to study human activities and their impact on climate underscores the potential of this technology in promoting environmental sustainability.

In addition to environmental benefits, digital twins significantly contribute to social sustainability by fostering inclusivity and accessibility within the Metaverse. This technology facilitates simulations and visualisations of urban environments, thereby supporting the creation of smart, sustainable cities that optimise resource use and promote equitable participation in the digital economy. The development of 6G communication is particularly relevant to this integration, as both 6G and the Metaverse emphasise democratisation, resource efficiency, and sustainability, departing from the decentralisation focus of earlier technologies. However, while the Metaverse offers a promising platform for sustainable development, it also presents significant security and privacy challenges due to the extensive collection of personal data, making it a prime target for malicious actors. Addressing these risks is essential to ensure the Metaverse's development does not compromise user safety or societal well-being. Overall, the combination of digital twins, AI, and Industry 5.0 technologies underscores the comprehensive potential of the Metaverse to drive forward-looking, sustainable urban planning and design, making it an invaluable tool in creating smart, sustainable cities. In this section, we discuss the application and use cases of the Metaverse for sustainable smart cities, summarised in Figure 7.

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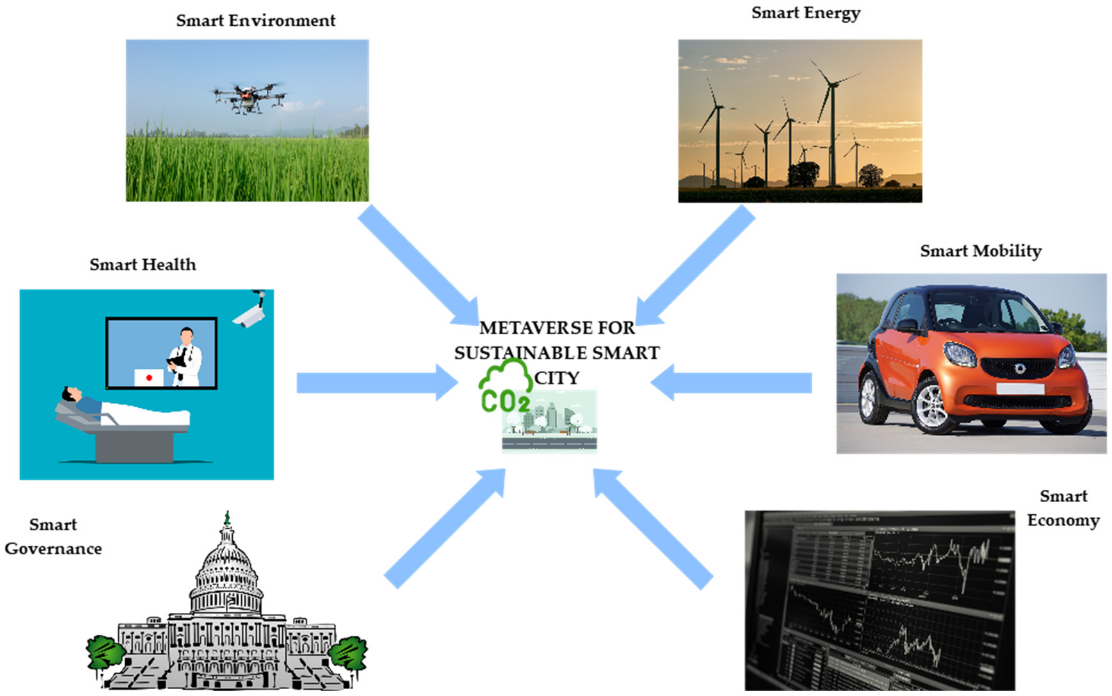

Figure 7. Summarisation of applications for sustainable smart city in the Metaverse.

4.1. Applications and Use Cases

Smart cities can be defined by the following domains: smart environment, smart mobility, smart energy, smart health, smart governance and smart economy. We consider these domains in our discussion on the applications and use cases for sustainable smart cities, and we summarise some applications in Table 4.

4.1.1. Smart Environment

A smart environment encompasses a range of services to manage pollution-related issues, including air quality, waste management, water pollution, radiation pollution, agricultural systems, and ocean environment monitoring [22,175,176]. It aims to enhance the quality of life while minimising environmental footprints through technology, contributing to sustainable urban living. The Metaverse plays a transformative role in creating smart environments for smart cities by using virtual simulations to assess the consequences of urban projects, such as new constructions or changes in land use, thereby promoting sustainable growth and reducing pollution. The Metaverse will benefit asset-heavy sectors such as utilities and power systems by leveraging AI integrated with other key technologies such as IoT, DT and XR. For instance, simulation of various environmental conditions, such as changing weather patterns, day-night cycles, or natural disasters [177–179], is made possible. Several studies have explored the integration of advanced AI techniques in environmental applications within smart cities, particularly in the areas of air quality control [180–182], pollution classification [183], waste management [184,185] , building management [151,186] and remote sensing [187] for monitoring and managing urban environments.

Table 4. A summary of AI-enabled applications and use cases in the Metaverses across various domains in smart cities.

Domain	Sub Domain	Reference
Smart Environment	Air quality control	[32,180–182]
	Environmental monitoring	[183,187]
	Disaster planning	[177–179]

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	Water management	[188]
	Agriculture	[189–195]
	Waste Management	[176,184,185,196]
	Infrastructure management	[151,186]
Smart Mobility	Traffic flow prediction	[90,92,163,197,198]
	Traffic monitoring	[199,200]
	Traffic condition analysis	[201–204]
	Autonomous vehicles & predictive maintenance	[121,205–210]
Smart Energy	Energy management & forecasting	[211,212]
	Energy optimisation	[186,213,214]
	Power grid management and monitoring	[215–218]
Smart Health	Pandemic forecasting	[219,220]
	Public health	[221]
	Medical care & management	[222–226]
	Medical training	[227,228]
Smart Governance	Electronic voting	[229]
	Decision-making and service delivery	[230–233]
Smart Economy	Smart payment systems, e-business	[234]
	Smart manufacturing	[235–237]
	Enhance customer experience	[238]

Central to this effort is the deployment of IoT-based sensors, which, despite their cost-effectiveness, face challenges related to large-scale installation and maintenance. To address these challenges, research has focused on hybrid IoT frameworks and intelligent system designs that ensure feasibility and cost-effectiveness in monitoring environmental factors such as pollution, waste, and climate-related variables [22]. For example, the application of AI and ML in these systems enables the intelligent analysis and prediction of environmental changes, contributing to better management of air quality, waste, water pollution, and climate change issues [189]. In addition, AI-driven solutions are crucial in addressing environmental inequalities in urban areas, where real-time data from air quality monitoring stations can inform policies to improve conditions in vulnerable communities [41]. AI contributes to water management by enabling efficient monitoring and prediction of water demand and reducing waste through smart network systems [188] and facilitates precision farming, disease detection, and resource management in agriculture [190–195], leading to more sustainable practices [239]. In waste management, AI can enhance the effectiveness of handling and sorting recyclables. For example, Troulaki et al. [196] introduced the RECLAIM[4] project, which integrates AI, data and a robot-based portable material recovery facility, enabling the decentralised treatment of recyclable waste in cities.

4.1.2. Smart Mobility

Smart mobility relies on technology to develop transportation and logistics networks. It encompasses a variety of transportation services, including gas and electric vehicles, traditional vehicles, taxi tracking and sharing services (e.g., Didi, Uber, Lyft), bike/scooter/bicycle tracking, rail lines augmented and educating systems related to mobility [22]. These services aim to enhance citizens' mobility by reducing congestion, improving safety, and benefiting the economy. AI enables smart mobility in the Metaverse by predicting traffic flow [197,198], monitoring traffic [199,200],

[4] https://reclaim-box.eu/

analysing traffic conditions [201–203], managing congestion [46] and developing autonomous vehicles [207–209]. Moreover, combined with DT, it simulates real-world traffic conditions, improving public transportation routes and assisting urban planners, traffic engineers, and policymakers in making better-informed decisions about urban planning [86]. For instance, in recent years, the automotive industry has seen significant advancements, particularly in autonomous vehicles, driven by technologies like IoT and AI. These technologies have enhanced vehicle features, ensuring safety and more precise operation with less human involvement. Despite these improvements, challenges remain in equipping vehicles with such capabilities, and testing in both simulated and physical worlds poses difficulties. The Metaverse offers a potential solution by providing a virtual testing environment where vehicles can be trained on extensive data from autonomous vehicles worldwide, closely replicating real-world conditions [240]. Furthermore, AI models equip vehicles to detect and classify various environmental elements by recognising stationary objects, road signs, barriers, and moving entities, such as pedestrians and other vehicles. This is crucial for safe and informed navigation, providing the comprehensive situational awareness necessary for effective decision-making by the vehicle [88]. For example, Tizedes et al. [204] developed a system utilising AI to detect road hazards like potholes and speed bumps by combining vision-based object detection with LiDAR technology for precise and efficient hazard identification.

Furthermore, predictive analytics, which relies on AI models, machine learning algorithms and data mining, is crucial in urban mobility management in the Metaverse. It achieves this by integrating historical traffic patterns, real-time vehicle flows, weather conditions, and social media trends to accurately predict traffic behaviours and congestion points and recommend efficient routes, crucial for optimising traffic flow, reducing travel times, and aiding emergency response. Additionally, AI models adapt to environmental changes and real-time events, offering a comprehensive approach to managing urban mobility through predictive maintenance [210]. For instance, Nuvvula et al. [205] introduced an innovative strategy for optimising electric vehicle (EV) fleet operations by integrating predictive analytics with renewable energy sources, utilising real-world data and advanced machine learning techniques. The approach improved predictive maintenance, charging schedule optimisation, and route planning, resulting in a reduction in greenhouse gas emissions and cost savings. Bellini et al. [206] presented a model that collects and manages diverse mobility data, including traffic patterns and sensor information, to predict and simulate the impact of different scenarios on urban transportation. The model was visualised using a 3D City Digital Twin on the Snap4City[5] platform, providing decision-makers with realistic and immediate insights for more effective urban planning.

4.1.3. Smart Energy

Smart energy involves using technologies such as AI, IoT, XR, smart grids, and renewable energy sources to create an energy system that monitors, predicts, and adapts to energy demand and supply changes. In the Metaverse, smart energy systems will enable the support of the seamless integration of renewable energy sources, intelligent storage solutions, and decentralised microgrids, which are crucial for maintaining energy stability, reliability and sustainability in urban infrastructure. The Metaverse allows for visualising, simulating, and optimising energy systems, enhancing decision-making processes and enabling proactive responses to energy demands. AI enhances the efficiency and reliability of renewable energy (RE) by enabling accurate forecasting of RE supply, energy and grid management [212,217,218], through centralised control systems [241] and analysing power systems through forecasting [211]. Integrated with DT, AI can model interactions between energy sources, distribution networks, and consumers to optimise energy consumption in buildings [214] and across the city by implementing energy-saving measures and integrating renewable energy sources [186].

Maintaining smart grids, especially when microgrids are spread across various geographical locations in a smart city, is challenging. AI, in combination with XR and IoT, can enhance the

[5] https://www.snap4city.org/drupal/node/749

efficiency of maintaining geographically dispersed generation assets by providing cost-effective remote assistance and virtual site inspections, thereby improving workforce productivity and operational efficiency through advanced data analytics and real-time monitoring [44]. For instance, an IoT-based framework for predicting power generation from renewable energy sources in smart microgrids, crucial for energy management in smart cities, was presented [215]. This framework integrates data from wind and solar sources. It employs a hybrid model combining a multi-head attention-based deep autoencoder with an extreme gradient boosting algorithm for accurate forecasting. Similarly, He et al. [216] introduced a data-driven situation awareness (SA) paradigm, DT-SA, utilising a digital twin model for the Energy Internet of Things (EIoT-DT) to address challenges in modern energy systems by combining machine learning and data technologies, improving system performance through continuous virtual-real interaction and feedback. Case studies were also presented, such as smart city EIoT-DT construction of Lingang, China and power grid monitoring—additionally, Stavropoulos et al. [213] explored how integrating IoT and smart grid technologies in residential settings could significantly enhance energy efficiency and management, balancing energy demand and supply to create sustainable urban environments.

4.1.4. Smart Health

Smart health leverages wearable devices, IoT, and wireless communication technologies to navigate health information, connect individuals and resources, and efficiently manage and respond to health environment demands intelligently [242]. In the Metaverse for smart city, AI, wearables, and the Internet of Nano-Things (IoNT) can help track infectious diseases by leveraging real-time medical data from large populations [219,220]. These technologies enable the early detection of outbreaks and allow healthcare providers to take swift action to prevent the spread of diseases [243]. For instance, Farooq et al. [219] introduced a DNN-based, data stream-driven real-time online incremental learning algorithm to analyse the transmission dynamics and prevention strategies for COVID-19, offering insights for pandemic forecasting and policy recommendations. Haptic technologies can also allow physicians to remotely interact with patients, which is particularly beneficial for high-risk groups such as healthcare workers during pandemics. Additionally, 6G technology significantly enhances emergency response efforts by improving the accuracy of positioning systems, allowing rescue teams to locate individuals whose lives might be at stake more effectively during natural disasters [221,244] like wildfires, earthquakes [243] and accidents. Integrating AI and holographic technology in ambulance services further exemplifies the potential of smart health in the Metaverse. These will enable hospitals and ambulances to be connected, where doctors can conduct rapid assessments of patients in ambulances with the support of paramedics.

Furthermore, the Metaverse enables a shift from 2D to immersive 3D virtual care, offering advanced applications such as surgery assistance, health management, and real-time monitoring of patients in a more interactive environment [44]. AI plays a crucial role in these advancements by enhancing the capabilities of Internet of Medical Things (IoMT) devices, improving the accuracy of diagnostics, and enabling continuous management and monitoring of health conditions such as heart rate and blood glucose levels [46] and chronic illnesses [223–225]. Additionally, AI-enabled healthcare simulations within the Metaverse provide a safe and controlled environment for medical professionals to practice and refine their skills through realistic, dynamic scenarios [227,228] and aid in training patients with disabilities [222]. Moreover, AI-powered virtual assistants like chatbots within the Metaverse can help users navigate healthcare services, answer health-related questions [226], and perform tasks, enhancing the user experience. The Metaverse can also enable AR/VR therapy sessions in calming or therapeutic environments, helping patients manage stress, anxiety, or other mental health conditions [86].

4.1.5. Smart Governance

Smart governance leverages technologies to enhance decision-making, policy development, and service delivery. It also involves the innovative application of ICT to facilitate information exchange, communication, and collaboration with stakeholders through various forms such as social media, blogs, public discussion forums, word of mouth and surveys to enhance the delivery of government services. Based on various studies, a generic smart governance framework involves collecting data from stakeholders like citizens, applying ICT technologies like AI to extract insights, and integrating public feedback into policy updates [22]. In smart governance, AI-based methods optimise decision-making, enhance service delivery, and increase citizen participation. Studies have shown that AI's integration with social innovation (SI) can significantly enhance smart decision-making (SDM) in governance, as evidenced in South Korea and Pakistan [230]. Abu Qasem et al. [231], in their research project, Ageing Smart[6] – Smart structured areas, demonstrated how Decision Support Systems (DSS) play a crucial role in promoting inclusiveness in smart city design by ensuring that services are accessible to all citizens, particularly those who are vulnerable. Khansari et al. [232], developed a prototype of DSS based on a multi-agent system and applied it in areas such as census data, energy reporting, and social science theories, demonstrating its potential in urban planning.

Furthermore, with IoT and blockchain, AI enhances government operations' security, transparency, and traceability, including voting systems and identity management. For instance, decentralised blockchain technologies like NFTs in electronic voting enhance transparency and security in governance processes, addressing challenges like voting fraud [245]. NFTs provide unique identities for participants, ensuring that only verified individuals can vote, thereby promoting transparency and trust in the decision-making process. As an example, Singh et al. [229], proposed a privacy-preserving and anonymous e-voting system with Proof of Vote, ensuring secure and private voting on public blockchains. Similarly, Decentralized Science (DeSci), leveraging Web3 and Decentralized Autonomous Organization (DAO) technologies, exemplifies an application of smart governance by fostering transparent, inclusive, and efficient management of scientific processes, aligning with the core principles of decentralisation and adaptive decision-making [233]. This approach can be adapted to smart city government services in the Metaverse.

4.1.6. Smart Economy

The concept of a smart economy involves the integration of advanced technologies such as AI, blockchain, and big data analytics in areas like e-business and e-commerce, including manufacturing and service delivery, to create innovative and sustainable economic models. In the Metaverse for a smart city, these technologies optimise business processes, enhance financial transactions through smart payment systems and blockchain, and drive new industries focused on sustainability, such as green energy and circular and sharing economy [46]. For instance, Abraham et al. [234] developed a smart toll transaction application with an AI-enabled multi-agent system and blockchain for dynamic pricing and traffic optimisation for smart transportation systems in smart cities. The Metaverse in a smart city offers unique marketing opportunities where brands can interact with users in immersive virtual environments, which integrates real-time advertising within gaming [36] and social media platforms. In addition, one assumption about the Metaverse is the possibility of a creator economy, where trading assets across different spaces is facilitated [246]. Additionally, blockchain technology is pivotal in the Metaverse by fostering new avenues for digital commerce and interaction [36] and overcoming trust and security challenges in peer-to-peer marketplaces [245].

AI further enhances these applications by providing personalised recommendations, virtual assistants and chatbots that mimic human interactions, creating a more engaging and tailored user experience [247]. Additionally, in a smart economy, the Metaverse supports entrepreneurship by establishing new business models, which reduce physical store costs, streamline supply chains, and enhance customer interaction through immersive experiences [248]. For instance, Kim et al. [238] explored the differences in consumer perceptions and behaviours when engaging with AR and VR technologies in virtual shopping environments, aiming to understand how these immersive technologies affect consumers' experiences, attitudes, and behavioural intentions. The consumers were provided with a realistic and enjoyable shopping experience by simulating the touch of fabric and the smell of perfume. In smart manufacturing, Sun et al. [236,237] introduced a learning-based

[6] https://www.carl-zeiss-stiftung.de/en/topics-projects/project-overview/detail/ageing-smart

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framework designed to help acquire complex 3C assembly skills using a multimodal digital-twin environment, and Hou et al. [236] developed a hybrid residual multi-expert reinforcement learning method for interactive learning in the digital industrial Metaverse. Zhang et al. [235] proposed a multicategory aggregated monitoring framework to enhance production performance monitoring under diverse working conditions, improving visualisation and interaction, helping analysts detect and understand abnormal performance in heavy-plate production data, particularly in complex operations with long steps and high precision.

6. Analysis of the Findings

In this section, we answer our main research question: How can AI-enabled technologies, integrated with key technologies like XR, digital twins, blockchain, 5G/6G, and IoT, drive the development of a sustainable smart city within the Metaverse?

1) Integrating AI with key technologies such as XR, digital twins, blockchain, 5G/6G, and IoT is essential for building sustainable smart cities within the Metaverse. AI optimises resource management, enhances energy efficiency, and supports real-time decision-making across various domains, including agriculture, transportation, energy and health. XR and digital twins simulate environmental conditions and urban scenarios, enabling cities to reduce waste, improve infrastructure planning, and mitigate environmental impacts. Blockchain ensures secure data management, while edge AI and 5G/6G enhance the seamless transmission of massive amounts of data between the virtual and physical worlds, enabling real-time responses critical for sustainable city operations. These technologies foster a sustainable, energy-efficient, and data-driven urban ecosystem.
2) Several use cases illustrate the role of AI and Metaverse technologies in advancing sustainable smart cities. For example, AI and IoT technologies in smart environments manage air quality, waste, and water pollution by leveraging real-time data for environmental monitoring and decision-making. XR and digital twins simulate environmental conditions and urban scenarios, enabling cities to reduce waste, improve infrastructure planning, and mitigate environmental impacts. In smart mobility, AI-driven predictive analytics optimise traffic flow and reduce congestion, contributing to lower emissions. Smart energy systems, supported by AI, digital twins, and IoT, allow efficient energy management and integration of renewable energy sources. Early detection of diseases and optimised emergency responses reduce strain on healthcare resources, contributing to social sustainability by improving public health outcomes. Similarly, AI-enabled decision support systems in smart governance help policymakers develop sustainable urban policies, while in the smart economy, AI and blockchain enable innovative business models, enhancing economic sustainability. A few case studies highlight the impact of AI and the Metaverse in creating sustainable smart cities. For instance, the RECLAIM Project initiative applies AI and robotics to decentralise waste management, enabling smart cities to address sustainability challenges effectively.
3) Integrating AI-enabled Metaverse technologies in smart cities presents significant benefits, highlighted above. However, challenges such as data privacy, cybersecurity, and the need for scalable infrastructure remain critical. Ensuring the interoperability of diverse systems and addressing the ethical implications of AI decisions are essential for achieving sustainability in the Metaverse for smart cities. Future research should focus on developing interoperable AI systems, explainable AI models, and enhanced privacy-preserving techniques to ensure that AI-driven smart city applications operate responsibly and equitably within the Metaverse. Further, federated learning, 6G networks, collaboration among stakeholders, and developing secure governance frameworks are essential for long-term sustainable growth.
4) While this study provides in-depth insights into current AI techniques and AI-enabled technologies and their applications within the Metaverse for smart cities, it has certain limitations. The rapid pace of technological advancement means that some of the technologies discussed may evolve, necessitating continuous updates to the findings presented. The study is also limited by its reliance on existing literature and technologies available at the time of writing. Furthermore, the paper primarily focuses on technological aspects, with less emphasis on socio-economic factors and user adoption challenges, which are critical for the successful

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implementation of AI in real-world scenarios essential for the Metaverse in smart cities. Recognising these limitations, future research should adopt a more holistic approach, incorporating technological advancements and addressing the human and societal dimensions of technology integration.

6. Future Directions

Despite all the advancements in AI and other emerging technologies, some challenges persist in Metaverse-based smart cities, as highlighted in Section 2.3. This section discusses the future directions regarding AI's integrated role in the Metaverse for smart cities and addresses how some of the challenges might be solved.

4.2. Scalability and Interoperability

One key area of focus for the future in the Metaverse for smart cities is the development of intelligent algorithms for resource allocation, such as computational power and bandwidth, based on real-time demand and user distribution, ensuring high performance as the Metaverse grows. Scalable data structures and indexing techniques are essential for managing spatiotemporal information generated by interactions within the Metaverse. Moreover, designing scalable networking and communication protocols is critical for supporting low-latency communication, large data set sharing, and complex interactions as the number of users and devices increases. To enable interoperability between diverse Metaverses, research should focus on developing cross-domain semantic mapping and alignment techniques for heterogeneous ontologies, vocabularies, and data representations while addressing inconsistencies during integration [86]. Interoperable communication protocols and APIs are necessary for seamless data exchange and AI interaction within the Metaverse. Additionally, future research should prioritise scalable and efficient algorithms for semantic data processing, enabling integration and interaction in spatiotemporal AR/VR applications for smart cities. Spatial computing can enhance interactions between IoT devices and the Metaverse, but it requires ensuring data scalability and diversity. Data fusion techniques can help regenerate comprehensive views from multiple sources, improving interoperability between platforms and systems in the Metaverse [249].

4.3. Explainability and Responsible AI

Explainability is a growing concern as AI becomes more integrated into the Metaverse for smart cities. Advanced models like deep neural networks have significantly improved performance but have become less transparent, making their results difficult to interpret. In city management, the behaviour of any decision models must be thoroughly understood and interpreted by their developers and city administrators before deployment [250]. Responsible AI must be developed to fully understand these decision-making processes while considering ethical, legal, and socio-economic impacts. Understanding a model’s explainability and the rationale behind its learning strategy is critical for ensuring responsible AI decision-making in Metaverse-based smart cities. For instance, Responsible AI can balance the benefits, risks, and impacts of AI decisions on urban planning and the environment, ensuring that the consequences of machine learning decisions are properly understood [251]. To achieve responsible AI, it is essential to address challenges related to preventing bias in AI algorithms, ensuring fairness in AI decisions, and verifying the reliability of AI systems without solely relying on their decision-making processes. Future research must focus on developing Explainable AI (XAI) and Responsible AI techniques that can bridge the gap between performance and interpretability, allowing for the creation of AI systems that are powerful but also transparent and trustworthy. This is particularly crucial as AI becomes increasingly integrated with emerging technologies like 6G and blockchain, further complicating the landscape of explainable, responsible AI in smart city Metaverse applications.

4.4. Security and Privacy

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In the Metaverse, ensuring data privacy and security is a major challenge, particularly with integrating shared user data, 3D virtual spaces, and IoT systems from multiple companies or institutions [252]. One challenge is the coordination and interaction of data between different IoT devices, which creates vulnerabilities. Another challenge is the risk of exposing sensitive user information. Attackers could exploit this information to identify users or inject poisoned data into AI models, which becomes difficult to detect in large datasets, eventually leading to service failures in the Metaverse-based smart city. To provide seamless user experiences while maintaining privacy, privacy-preserving techniques such as secure data storage, data anonymisation, cryptographic techniques, and decentralised identity management must be implemented. Data should be encrypted to ensure only authorised access, utilising secure multiparty computation to allow private inputs while computing functions jointly. Anonymisation techniques such as differential privacy should be used to prevent data from being traced back to individual users. Federated learning can play a critical role in training machine learning models on decentralised data sources without sharing raw data, ensuring that only model updates are shared while maintaining privacy [253]. Decentralised identity management systems employing blockchain technology offer a way to protect against identity theft and unauthorised data access. Cybersecurity and data storage are major concerns for deploying Metaverse applications in smart cities and ensuring long-term sustainability will require securing the Metaverse interfaces against cyber-attacks [37].

4.5. Integrated Role of AI with Emerging Technologies

Future research should focus on integrating AI with other emerging technologies to enhance the capabilities of the Metaverse in smart cities. This includes implementing 6G technologies to support Metaverse applications, edge caching to minimise transmission latency, and federated learning techniques to ensure data privacy. In addition, quantum computing, swarm intelligence, and neuromorphic computing enable researchers to develop AI systems that accelerate data processing and optimisation, enhance adaptability, and achieve energy-efficient operation crucial for the Metaverse in smart cities. Furthermore, developing multi-agent systems (MAS) [22] enhancing self-supervision and continual learning methodologies and distributing AI models across end devices, edge servers, and cloud infrastructures, as shown in Figure 8, help autonomously manage dynamic changes and dependencies typical in the rapidly evolving Metaverse environments in smart cities. This ensures a ubiquitous and sustainable experience driven by AI systems.

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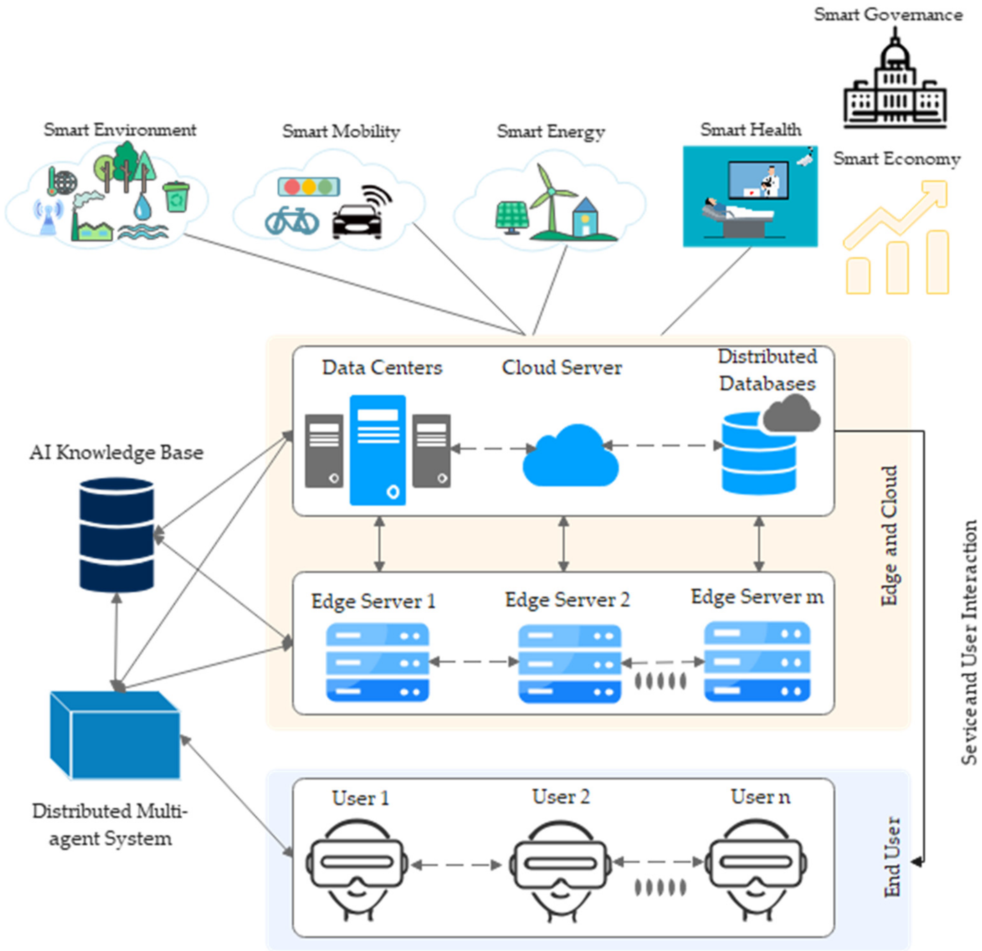

Figure 8. Generic diagram of a distributed AI system for various application areas of a smart city.

4.6. Governance and Ethics

In a smart city, the Metaverse presents challenges related to governance and ethics that necessitate the development of robust regulatory frameworks to align virtual interactions with real-world regulations and social norms and foster a fair, secure and inclusive virtual society. One major challenge is ensuring user data privacy while maintaining transparency in data collection, storage, and utilisation in smart city applications. Users should have control over their personal information and be offered options for anonymity or pseudonymity, though this must be balanced with mechanisms to prevent malicious activities by anonymous users. Additionally, the Metaverse must be accessible and inclusive, enabling individuals from diverse backgrounds to participate with equal rights. This inclusivity must also address the pervasive issues of cyberbullying, harassment, stalking, and abusive language, which are significant concerns in the Metaverse [36]. Effective measures and policies must be implemented to protect users from such harmful behaviours. Furthermore, the fairness and biases inherent in AI algorithms and platforms used to create and manage the digital realm in the Metaverse must be critically evaluated and managed. Ensuring these systems operate without discrimination is essential for maintaining a just and inclusive digital society. Accessibility guidelines should be considered for users with disabilities, and efforts should be made to promote cultural diversity and representation within the virtual environments.

Ethical considerations must also address the dynamic nature of the Metaverse, including the preservation of cultural heritage, like tourist attractions in virtual spaces. The environmental impact of the Metaverse's development and maintenance, such as energy consumption and electronic waste, should be minimised by promoting sustainable practices such as Green AI. AI and machine learning systems within the Metaverse must be designed and trained to minimise biases, thereby preventing

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discrimination or inequality. Techniques to mitigate algorithmic biases should be developed, and regular audits of AI systems are necessary to ensure fairness, particularly in the analysis and prediction of patterns. Responsible AI is essential in this context, where ethical considerations, user well-being, and long-term societal impacts are prioritised [86]. Another challenge is the potential for misbehaviour among regulators within the Metaverse, which could lead to system breakdown. To address this, dynamic reward and punishment mechanisms must be established to promote honesty and discourage misconduct. For example, the use of smart contracts to automate regulations as it reduces reliance on intermediaries [44]. These challenges underscore the need for innovative governance frameworks and ethical guidelines to ensure the secure and equitable operation of the Metaverse in smart cities.

4.7. Advanced NLP Capabilities

Future studies should focus on developing more advanced NLP models that understand and generate human language, including context awareness, sentiment analysis, and cultural sensitivity, to improve human-computer interaction within the Metaverse. This involves leveraging advanced deep-learning architectures and foundational models like GPT-4 and exploring multilingual and low-resource language processing to serve diverse urban populations. By improving NLP systems' accuracy and contextual relevance, more intuitive virtual assistants and chatbots would facilitate seamless communication and accessibility in smart city services. Concurrently, AI reasoning is being advanced to develop systems that process data and comprehend and reason about the world, similarly to human cognition. Integrating common-sense reasoning enables AI to make informed inferences based on general world knowledge, which is essential for tasks such as natural language understanding and autonomous navigation in smart city environments within the Metaverse. By focusing on these advancements, future research can facilitate the creation of intelligent agents capable of complex problem-solving and creative thinking, improving personalised services in the Metaverse for smart cities.

4.8. Virtual Collaboration

Effective collaboration among stakeholders, such as governments, citizens and technology experts, is essential for overcoming the complex challenges of implementing AI-driven technologies in the Metaverse for smart cities. Stakeholders can contribute diverse expertise, resources, and perspectives, leading to the development of more robust, scalable, and interoperable systems. Public-private partnerships (PPPs) are particularly vital, as they combine technological innovation with the financial resources necessary for large-scale projects like smart energy grids and transportation systems. Interdisciplinary collaboration is equally critical, involving experts from urban planning, computer science, data science, engineering, and environmental science to develop sustainable solutions. Moreover, citizen engagement in the Metaverse ensures that smart city initiatives remain responsive to community needs, fostering transparency, trust, and a sense of ownership among residents. The Metaverse can provide ideal platforms for multi-stakeholder integration through virtual collaboration platforms. Virtual collaborations enable real-time interactions and collaborative decision-making through digital platforms and immersive technologies. Future research should focus on developing these platforms and communication protocols that enhance virtual interaction and cooperation among stakeholders. Collaboration is crucial for setting regulatory standards, ensuring data privacy, and fostering innovation, ultimately driving the sustainable growth of Metaverse applications in smart cities.

7. Conclusion

We presented a comprehensive review highlighting the crucial role of AI in enabling the Metaverse to develop sustainable smart cities. AI, combined with the Metaverse technologies like digital twins, IoT, blockchain, and 5G/6G, offers numerous advantages in smart cities, including improved resource management, enhanced urban planning, energy efficiency, and better overall user experiences. However, challenges such as data privacy, cybersecurity, interoperability, and the need for scalable infrastructure remain critical issues that must be addressed to integrate these technologies seamlessly. Looking ahead, the success of sustainable smart cities within the Metaverse relies on developing distributed AI systems that enable decentralised, interoperable, and scalable data processing and storage while ensuring privacy, security, and explainable, responsible decision-making. AI-enabled Metaverse promises to revolutionise how smart cities are designed and managed, fostering sustainability through innovative, real-time solutions for urban challenges. By leveraging advanced technologies and fostering collaboration among stakeholders, an interconnected, sustainable smart city environment can be created that improves quality of life and addresses pressing environmental and social issues. Achieving this vision will require continued research, innovation, and policy development to ensure the responsible and equitable deployment of AI-enabled Metaverse-driven technologies for sustainable smart cities.

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