Toward Sustainable Smart Cities Through The Metaverse and Metaverse of Things: Technologies, Challenges, and Opportunities

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Abstract - The evolution of smart cities has been driven by the need to enhance urban living through digital transformation, integrating technologies like IoT, AI, and big data to optimize infrastructure, governance, and sustainability. These cities aim to improve citizen experiences by modernizing services, increasing accessibility, and reducing environmental footprints. However, the recent emergence of the Metaverse—a collective virtual space blending augmented, virtual, and physical realities—has introduced a paradigm shift in urban development. Initially popularized by science fiction and tech giants like Meta, the Metaverse promises to revolutionize smart cities by enabling immersive citizen engagement, virtual governance, and real-time simulations of urban systems 212. Its potential extends beyond entertainment, offering tools for participatory planning, remote work, and sustainable resource management, as seen in pilot projects like Singapore's Virtual Twin Initiative and Seoul's metaverse-based civic platforms. A critical advancement in this domain is the integration of the Metaverse with IoT, giving rise to the Metaverse of Things (MoT). This convergence bridges physical and digital infrastructures, allowing seamless interaction between smart city sensors and virtual environments. MoT enables real-time data analytics for energy optimization, traffic management, and predictive maintenance, thereby supporting sustainability goals 319. For instance, digital twins—virtual replicas of physical assets—can simulate climate change impacts or test urban policies before implementation, reducing costs and risks. Despite these opportunities, challenges persist, including high energy demands, data privacy concerns, and the digital divide, which could exacerbate inequalities if left unaddressed. This paper then covered the foundations of the metaverse and smart cities, the enabling technologies that come with them, the Metaverse of Things (MoT) and how it can be used to create sustainable smart cities, as well as some case studies, practical implementations, and a comparative analysis of them. In addition, we outlined the possible obstacles to the integration as well as possibilities for future growth that will further the metaverse's development and integration with smart cities.

Key words - Metaverse; smart cities; Metaverse of Things (MoT); Internet of Things; Urban environment; Virtual environment

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Introduction

The rapid rate of urbanization has created uncommon challenges in managing city resources, infrastructure, and services. Growing populations, environmental concerns, and the need for effective public services are putting greater pressure on traditional urban planning and management techniques. As a result, the idea of "smart cities" has surfaced, which uses information and communication technology (ICT) to improve urban living standards, encourage sustainability, and simplify government.

The emergence of the Metaverse—a collective virtual shared environment made possible by the fusion of physically persistent virtual spaces and virtually augmented physical reality—occurs parallel with the growing number of smart cities. The Metaverse provides immersive settings where users can engage with digital representations of real-world entities and events, made possible by technologies like blockchain, augmented reality, virtual reality, and artificial intelligence. This convergence promotes improved citizen participation, effective resource allocation, and better informed decision-making.

The metaverse aims to merge the virtual world with the real world. The target is to generate a web of virtual communities where social components play a crucial role and combine different areas such as entertainment, work, shopping, and services. The Internet of Things (IoT) is a crucial concept in the modern technology landscape, filling gaps in many traditional systems and offering a wide range of new applications and opportunities, especially in Metaverse and smart cities.

The theoretical concept of the Metaverse can be viewed as a collection of made-up depictions of potential future virtual worlds that offer both warning signs and unsettling visions. Often serving as symbols of socially alienating corporate and oppressive governmental power, fictional depictions of technologically enhanced—in this case virtualized—urban worlds in literature from the social sciences reflect the deconstructive critique of the techno-utopianism of urban imaginaries in technologically advanced societies. Furthermore, the concept of the Metaverse is often predicated on irrational expectations that have little relevance to the present world. The growth of the Metaverse is therefore largely limited to speculative or hypothetical limits.The overall objective is to create a network of digital neighborhoods that integrate a number of industries, including entertainment, employment, shopping, and services, and in which interactions with others are essential. With its ability to bridge gaps in numerous old systems and provide an extensive range of inventive uses and opportunities, especially throughout the Metaverse and smart cities, the Internet of Things (IoT) is an important concept in current technical landscape. A virtual digital environment called the Metaverse mimics and interacts with the actual world in a number of ways.

In terms of designing virtual or augmented cities based on extensive data-driven artificially intelligent (AI) systems, advancement and research of the Metaverse has emerged as a major trend in data-driven smart urbanism. A collection of socio-technical imaginaries—performed ideas of ideal future urban environments made possible and maintained by services, infrastructure, activities, and more or less common definitions of social life and social order—can be interpreted as the idea of the data-driven smart city [3]. Through the use of networked sensors, devices, and digital models, the Internet of Things enables urban infrastructure to become more responsive and intelligent. Through AR navigation, users can obtain real-time information overlays and personalized, immersive experiences.

The Metaverse of Things (MoT), which expands the Internet of Things (IoT) into the Metaverse and enables real-time data from physical devices to inform and modify virtual settings, is a crucial part of this integration. MoT makes it possible for digital platforms and urban infrastructure to interact dynamically in the context of smart cities, creating responsive, sustainable, and citizen-centric environments. The IoT and the metaverse have come together to create a new idea known as the MoT, which offers a fresh perspective on smart city living. By showcasing a highly integrated digital ecosystem where physical and virtual worlds coexist together, the MoT architecture promotes improved experiences, greater efficiency, and long-term viability in urban settings.

In order to transform urban functionality and rethink how people interact with their environment, the MoT is tearing down traditional barriers in a number of industries, including healthcare, entertainment, energy management, and transportation. MoT gives people the ability to participate in decision-making and work together to influence smart city development. Additionally, it makes participatory and inclusive urban governance easier. Modern technology is used by the MoT to improve the interconnectedness, efficiency, and responsiveness of metropolitan regions. For the system to be successful, it must have strong security features, seamless integration, and universal accessible for all city dwellers. Digital twins are digital copies of real-world assets that provide up-to-date data on the asset's behavior and performance. By modernizing government services, increasing accessibility, stimulating economic growth, and promoting sustainability, the metaverse is transforming smart cities and improving the lives of their citizens. Figure 1 shows the MoT's applications.

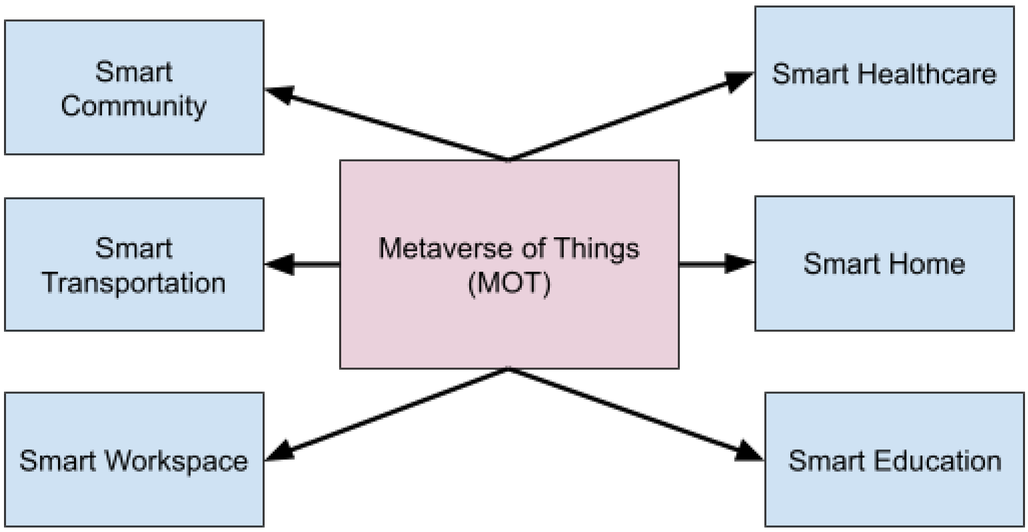

Figure 1. MoT Applications.

The MoT is the idea that reflects a new framework for smart city life and was born out of the intersection of the metaverse and the Internet of Things. Through the demonstration of a highly interconnected digital ecosystem where physical and virtual worlds fluidly combine, the MoT framework promotes improved experiences, better efficiency, and long-term viability in urban contexts. Numerous industries can profit from the use of metaverse technology, as evidenced by ongoing initiatives and recorded cases. This study carefully examines and classifies important research questions that presently stand in the way of the full potential of the metaverse. In the end, this paper makes recommendations for possible research directions to support the ongoing development of the metaverse and integration of smart cities.

1.1. Objective

The metaverse represents a transformative paradigm where physical and digital realities converge to create persistent, three-dimensional virtual environments. Building upon this foundation, the emerging Metaverse of Things (MoT) concept extends the Internet of Things (IoT) framework into these immersive digital spaces, creating a seamless integration between virtual worlds and physical infrastructure. This research investigates how MoT applications can bridge virtual and physical environments to enhance urban living through three key dimensions: (1) hyper-connectivity enabled by next-generation networks, (2) immersive experiential interfaces, and (3) intelligent data integration. A distinctive feature of the MoT ecosystem is its capacity to support avatar-mediated economic activities, where digital personas can traverse interconnected virtual spaces while maintaining persistent identities, transactional capabilities, and social capital across environments. This framework promises to revolutionize urban interactions by creating synergistic relationships between physical urban infrastructure and their digital counterparts.

1.1.1. Main Objective

The primary goal of this study is to investigate how MoT applications can transform urban living in smart cities.

1.1.2. Problem Identified

Few review papers explicitly address how the Metaverse and IOT work together to develop MoT applications that will transform urban living in smart cities.

1.1.3. Research Question

The research question was developed based on the primary goal.
RQ1: In the existing literature, what knowledge gaps exist that could aid in a deeper understanding of the MoT applications that are transforming urban living in smart cities?

We looked at the knowledge gaps in the existing literature in this review study to better understand MoT applications for transforming urban living in smart cities.

1.2. Motivation

Investigating the incorporation of the Metaverse of Things (MoT) into sustainable smart city development is driven by the pressing need to tackle the intricate, interconnected problems of contemporary urban settings. Urban planners and policymakers face increasing pressures from infrastructure stress, environmental degradation, inefficient resource management, digital inequality, and socioeconomic disparities as cities continue to grow quickly. The adaptability, real-time reactivity, and user-centricity of traditional urban management systems are sometimes lacking, even when they are digitally connected. With its smooth integration of IoT, AI, AR, VR, and immersive environments into the larger Metaverse framework, the MoT, on the other hand, presents a new paradigm. The transition from static infrastructure management to dynamic, data-driven, and interactive urban ecosystems is made possible by this convergence.

The potential of MoT to optimize urban operations across several domains by utilizing digital twins, extended reality (XR) interfaces, and real-time sensor data is what makes it so intriguing. This covers public health services, emergency response, smart governance, waste and energy management, transportation planning, and customized citizen experiences. Before putting complicated urban systems into practice in the real world, residents, developers, and city authorities can work together to model, simulate, and improve them using interactive digital twins and immersive visualization. (Park & Kim, 2022).

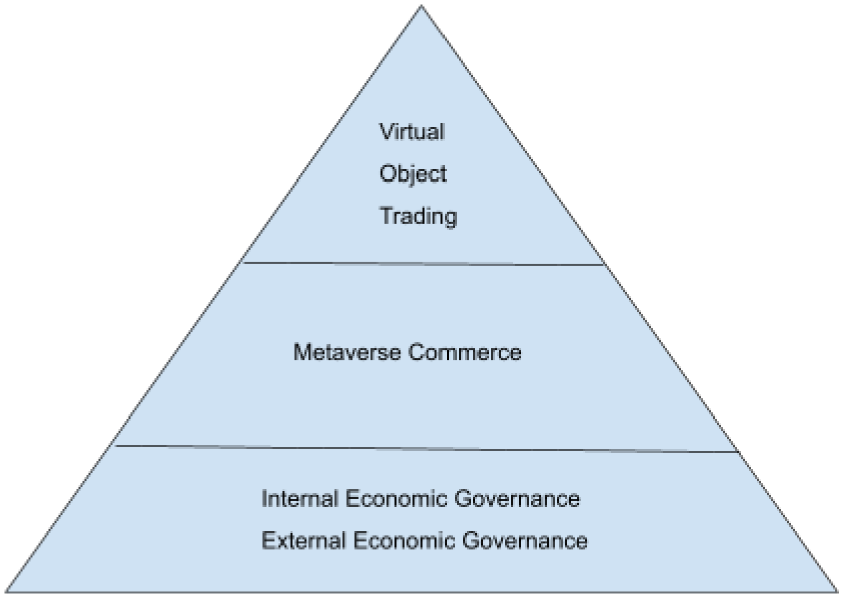

Figure 2. The Industry's Market Structure of The Metaverse. By the Author.

Furthermore, MoT promotes a digital environment that is participatory and goes beyond conventional decision-making silos, enabling a range of stakeholders, including citizens, companies, and legislators, to collaborate on solutions in real time. In addition to increasing operational effectiveness, this connection promotes sustainability, social inclusion, and urban resilience.

Essentially, the understanding that MoT-enabled metaverse platforms have the potential to convert urban areas into intelligent, flexible, and human-centered settings serves as the driving force behind this study. Future cities can become more sustainable, equitable, and habitable by embracing the synergy of physical and virtual elements. This will meet long-term objectives for cultural preservation, economic vibrancy, and climate action in addition to current urban issues.

Literature Review

The integration of Metaverse technologies into smart city frameworks has garnered significant attention in recent academic discourse. This convergence aims to enhance urban experiences, governance, and sustainability through immersive technologies.

According to Yaqoob et al. (2023)[4], the Metaverse has the potential to transform smart cities. They talk about enabling technologies like blockchain, digital twins, and extended reality (XR), emphasizing their functions in citizen involvement, urban planning, and government. The study highlights how the Metaverse can be used to build inclusive and dynamic urban settings. (Research Output from Charles Sturt University). The Metaverse is examined by Allam et al. (2022)[5] as a virtual extension of smart cities, with an emphasis on the consequences for social, economic, and environmental sustainability. They contend that by encouraging effective resource management and boosting community involvement, the Metaverse can support sustainable urban development.

In order to create the Metaverse, Aloqaily et al. (2022)[6] talk of combining digital twins with cutting-edge intelligent technology. To provide continuous and immersive Metaverse services in smart cities, they suggest an architecture that integrates digital twins with blockchain, 6G networks, and artificial intelligence[7]. The intersection of the Internet of Things (IoT) and the Metaverse is examined by Li et al. [8], who emphasize how IoT applications might improve immersive experiences in smart cities. They list essential needs for creating an IoT-inspired Metaverse, including authenticity, interactivity, and immersion.

There are ethical and governance concerns with the use of Metaverse technologies in smart cities. The ethical ramifications of hyper-connectivity, datafication, and algorithmization in the Metaverse are examined in a research that was published in Computational Urban Science. It highlights the necessity of open and accountable governance frameworks.

In their analysis of the idea, Dienhart et al. (2025)[9] portray the Urban Metaverse as a development of the smart city. They talk about the potential for inclusive, interactive, and real-time infrastructure applications in cities, stressing the value of proactive regulatory frameworks and user-centered design. There are two primary areas of research in the Metaverse. Technology, applications, opportunities, trends, problems, open topics, agendas, conceptual frameworks, and other technical components of the Metaverse are the main focus of the first strand. The adoption of Metaverse technologies in smart cities raises governance and ethical issues. A study published in *Computational Urban Science* discusses the ethical implications of hyper-connectivity, datafication, and algorithmization in the Metaverse, emphasizing the need for transparent and accountable governance structures [11].The related works are represented in Table 1.

Table 1. Summary of the related papers.

Reference	Authors	Year	Focus	Methodology
[1]	Florian et al.,	2024	Metaverse Meets Smart Cities—Applications, Benefits, and Challenges	metaverse; smart city; smart municipality
[2]	Zefeng et al.,	2024	Metaverse for smart cities: A survey	Metaverse Smart citie
[3]	Zaheer et al.,	2022	The Metaverse as a Virtual Form of Smart Cities: Opportunities and Challenges for Environmental, Economic, and Social Sustainability in Urban Futures	metaverse; smart citie digital twins
[4]	Haider et al.,	2023	The Metaverse: Applications, Concerns, Technical Challenges, Future Directions and Recommendations	Metaverse, Internet of Things (IoT), wearabl technology
[5]	Simon et al.,	2024	Metaverse of Things (MoT) Applications for Revolutionizing Urban Living in Smart Cities	Internet of City Thing Metaverse; Artificial Intelligence of Things
[6]	T. Alam	2024	Metaverse of Things (MoT) Applications for Revolutionizing Urban Living in Smart Citie	Metaverse of Things (MoT); smart cities; internet of things;

				virtual reality
[7]	Simon et al.,	2023	Harnessing the Potential of the Metaverse and Artificial Intelligence for the Internet of City Things: Cost-Effective XReality and Synergistic AIoT Technologies	Internet of City Thing Metaverse; Artificial Intelligence of Things IoT applications; Extended Reality; Virtual Reality
[8]	Saeed et al.,	2023	Toward Metaverse of everything: Opportunities, challenges, and future directions of the next generation of visual/virtual communications	Metaverse, web 3.0, digital twin
[18]	Kourtesis	2024	Multimodal XR in Metaverse: Applications, Risks, and Ethics	XR; Metaverse; Ethic Challenges
[19]	Yazici, Özkan, and zkan	2024	XR-AR-MR and Mirror World Technologies' Business Impact	XR; AR; MR; Busine and Industry
[20]	Zhang et al.	2025	AI-Enhanced Digital Twin Systems for Industrial Metaverse	Digital Twin; AI; Industry 5.0
[21]	Ruiu et al.	2024	Human Digital Twin: Identity, Biometrics, and Privacy	Digital Twin; Biometrics; Privacy
[22]	Otoum et al.	2024	Machine Learning in Metaverse Security	ML; Cybersecurity; Metaverse
[23]	Awadallah et al.	2024	AI-Based Cybersecurity in the Metaverse	AI; Security; Researc Challenges
[24]	Ghosh et al.	2024	Decentralized Metaverse via Blockchain and Web 3.0	Blockchain; Web 3.0; Applications
[25]	Meng et al.	2025	Blockchain-Enabled Metaverse: Development & Applications	Blockchain; Metavers Use Cases

5. Foundations of Metaverse and Smart Cities

5.1 Defining the Metaverse

The Metaverse represents a convergence between persistent digital worlds and enhanced physical reality, creating a unified virtual space where users can interact. Virtual reality (VR), augmented reality (AR), artificial intelligence (AI), and blockchain are just a few of the many technologies that make it possible for people to engage with digital representations of real-world objects and situations in immersive ways. In Snow Crash, Stephenson imagined individuals entering a digital virtual reality environment to escape the harsh realities of the world's failing economy. Stephenson's books contain a variety of notions and ideas, including as "headsets" and "goggles," which enabled readers to enter a fictitious world before goggles and other technology, thereby driving the worldwide market for these goods in a profitable direction. These ideas are especially related to Paul Milgram's concept of "Extended Reality" (XR).

A wide range of technical elements are necessary for the Metaverse to function, and these elements can be arranged using many conceptual models. An integrated set of technologies, frameworks, and tools is referred to as a "technology stack," a term borrowed from computer science and software engineering [20]. This framework shows the key elements and how they work together to create a certain platform or application. The core technologies that support the Metaverse's virtual ecosystem and enable user activity are included in the technological stack [21]. We mainly use the technological foundation put forth by Lee et al. [1] for this investigation, supplemented by additional knowledge from Kaya Kuru's work [22]. Our illustration of the main layers in this structure is shown in Figure 3.

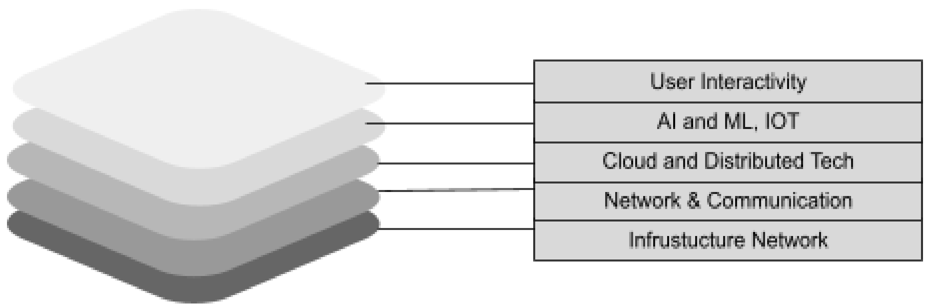

Figure 3. Metaverse Technology Stack. By the Author.

5.1.1 Foundational Infrastructure and Hardware

The operational backbone of the metaverse consists of critical physical components that facilitate interaction with virtual environments. This foundational layer encompasses high-capacity server systems, advanced networking infrastructure, and specialized processing units such as GPUs (Graphics Processing Units) and TPUs (Tensor Processing Units). These elements collectively ensure seamless, low-latency performance essential for immersive user experiences [19].

5.1.2 Network Infrastructure and Data Transmission

Robust communication networks and efficient data protocols are indispensable for handling the metaverse's massive data demands while maintaining minimal latency. Wireless technologies are particularly vital, offering superior quality of experience (QoE) through enhanced mobility and accessibility compared to wired alternatives. Beyond bandwidth considerations, network scalability emerges as a critical factor in sustaining low-latency connectivity across expanding virtual environments [8].

5.1.3 Decentralized Computing Architectures

The integration of Distributed Ledger Technology (DLT), including blockchain systems, facilitates secure and transparent data management within virtual ecosystems. These technologies provide frameworks for digital asset protection, user authentication, and verifiable transaction mechanisms, establishing trust in metaverse interactions [22].

5.1.4 Intelligent Systems Integration

Artificial intelligence and machine learning form the cognitive core of metaverse environments, enabling responsive and adaptive virtual spaces. These technologies power personalized user experiences through intelligent avatars, behavioral adaptation systems, and real-time language processing capabilities. Complementary IoT networks further enhance realism by streaming live environmental data into virtual settings [10].

5.1.5 Immersive Interaction Technologies

User engagement with metaverse platforms occurs through diverse interface modalities, including motion-sensing controllers, gesture recognition systems, and advanced visual displays. Spatial computing solutions enable natural navigation through digital spaces, while augmented reality interfaces facilitate seamless interaction with virtual objects [23].

The computational foundation relies on high-performance server infrastructure equipped with specialized processing units (GPUs/TPUs) to deliver uninterrupted event experiences. Concurrently, wireless communication networks provide attendees with flexible, location-independent participation capabilities. Security and transactional integrity are maintained through distributed cloud architectures and blockchain-based verification systems. The platform's adaptive functionality stems from artificial intelligence algorithms that tailor content and interactions to individual users, while interconnected IoT devices feed live environmental data to enhance realism. This technological synergy creates a dynamic virtual space where participants can engage through intuitive interfaces, mirroring physical-world interactions while offering digital conveniences.

By allowing individuals to see and model urban environments, the Metaverse has the potential to revolutionize urban development by improving decision-making and encouraging citizen participation.

5.2 Evolution and Characteristics of Smart Cities

Smart cities have evolved as a response to the challenges posed by rapid urbanization, aiming to enhance the quality of urban life through the integration of Information and Communication Technologies (ICT). There is a wide range of services and applications shown in Table 1. These services cover fields such as transportation (intelligent road networks, connected cars and public transport), public utilities (smart electricity, water and gas distribution), education, health and social care, public safety. Emerging applications and services are extended into diverse fields such as everyday life of citizens, disaster management, smart buildings, logistics and intelligent procurement. The applications for this portfolio include implementation for the connected city such as: smart grid, smart home, security, building automation, remote health and wellness monitoring, location aware applications.

There are many policies to encourage the formation of smart cities, and there are some prototypes of smart cities. For example, the ASEAN1 smart cities network (ASCN) aims to promote the cooperation of smart cities and make efforts to build these smart cities into a complete network [16]. The European Union has been working on a strategy for the growth of intelligent cities in metropolitan areas [56]. The Ministry of City Development, Government of India, spearheaded “The Smart Cities Mission”. The government of India has the ambitious vision of developing 100 cities by modernizing existing mid-sized cities2 . Some larger IT, telecommunications, and energy management companies launched market initiatives for intelligent cities. For instance, Alibaba has created the City Brain3 . Microsoft has a solution for smart cities named Citynext4 . In addition, Cisco, launched the global “Intelligent Urbanization” initiative to advocate for cities to use the Internet as a fourth tool for integrated city management, improvement of citizens’ quality of life, and economic development

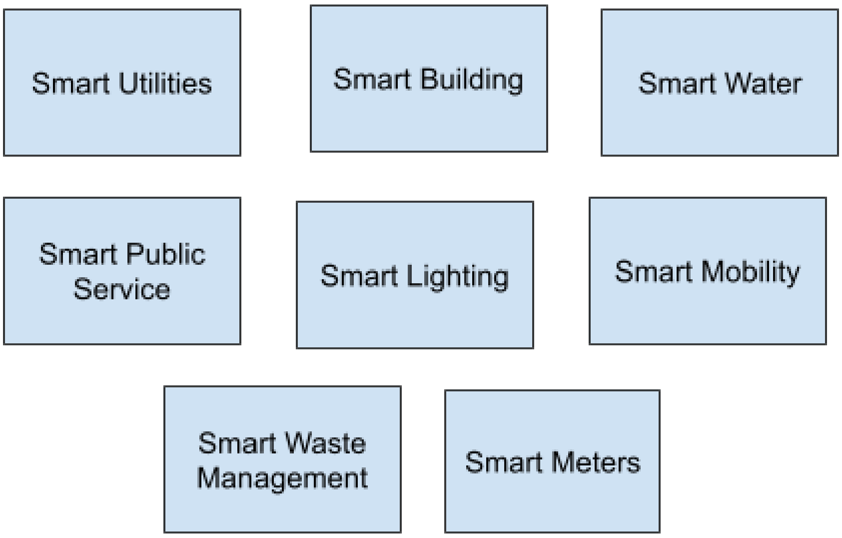

Figure 4. Smart City Applications. By the Author.

The evolution of smart cities reflects a shift from technology-centric models to more holistic approaches that prioritize sustainability, inclusivity, and resilience. Challenges for the planning, development, and operation of cities are encouraging new thinking in various professions. Professionals across architecture, urban planning, engineering, construction, information technology, systems and environmental science, property development, finance, and municipal government acquire a stronger understanding of stakeholders and receive insights as to how best to engage them. Systems models that are capable of seeing deeply into how cities work, how people use the city, how they feel about it, where the city faces problems, and what kinds of change can be applied could be used for smart city developments.

5.3 Convergence of Metaverse and Smart Cities

The Metaverse has been made possible by the rapid pace of progress in the development of the core enabling technologies, notably AI, Big Data, the Internet Things (IoT), Edge Computing, Blockchain, Digital Twins (DT), Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and high-speed 5G networks. While these technologies are not of equal importance in terms of enabling the Metaverse as a “sophisticated” computing Smart Cities 2022, platform, their convergence has expedited the integration of the independent virtual spaces owned by various high-tech and platform companies [10]. Several studies have addressed the state-of-the-art and technical aspects of the Metaverse in terms of the convergences of computing technologies and immersive technologies [30,58,142,143]. At present, the focus of the Metaverse is to build a decentralized computing platform that convenes numerous sub-platforms based on computational-immersive mediations. Innovations in platforms are increasingly unfolding around VR, AR, and MR. These immersive technologies fall under the umbrella term of XR through which human users can access the Metaverse, as it bridges the virtual entities with the physical environments together to create the so-called post-reality universe. These technologies are associated with the fourth wave in technology, which is seen as the next paradigm of UbiComp—the Metaverse—subsequent to AmI and the IoT—with respect to a large number and wide range of applications across various urban sectors and spheres of urban life

Table 2 provides an overview of fields of metaverse applications in a smart city context and the corresponding applications. In addition, it addresses the stakeholders responsible for providing the metaverse infrastructure and the individual components, as well as those who benefit significantly from the applications. Further details on each field are provided below.

Table 2. Summary Smart city metaverse applications..

Field of Application	Application	Stakeholders
City Planning & Simulation	Urban planning	Administration, planning offices, pub authorities
	Risk planning	Administration, public authorities
	Digital City Twin	Administration, industry, building yard
	Environmental monitoring and management	Administration, legislator
	Planning tool for renewable energies and potential savings	Administration, citizens, authorities
Administration & Optimization	Monitoring of Smart Buildings	Administration, property manager
	Tracking the use of resources and consumption optimization	Administration, building yard
Citizen Services & Participation	Digital administration services	Administration, citizens
	Digital forms	Administration, citizens
	Virtual customer centers	Administration, citizens
	Digital citizen ID	Administration, citizens
	Citizen participation and virtual voting	Administration, citizens, politics
	Provision of city-related real-time information	Citizens, tourists
	Provision of information on measures and funding opportunities	Citizens, industry, clubs
Entertainment & Life Quality	Virtual events and exhibitions	Citizens, tourists
	Social meeting places	Citizens
	Support for local clubs, voluntary work, and charitable projects	Citizens, clubs, non-governmen organisations (NGOs)
	Inclusive and barrier-free offers	Citizens

Education & Universities	Virtual classrooms	Students, teachers
	Virtual education and training of adults	Citizens, industry, job center
	Interactive learning media	Students, teachers, citizens
	Research environment and meeting place for experts	Students, teachers, experts
Healthcare	Telemedicine	Doctors, patients, health insuran companies
	Preventive courses and training	Doctors, patients, health insuran companies
	Expert exchange	Doctors, medical staff
	Remote monitoring of health parameters	Health insurance companies, citizei doctors
Tourism	Virtual city tours	Citizens, tourists, retail
	Virtual sights	Citizens, tourists
	City Marketing	Administration, citizens
Public Authorities	Real-time status and response options	Administration, public authorities
	Realistic training environment	Public authorities
	Monitoring compliance with laws and safety standards	Public authorities
	Optimization of workflows and processes	Administration, public authorities
Transportation, Infrastructure & Grids	Status Visualization	Administration, citizens
	Planning and forecasting of capacity utilization	Administration, citizens, public authoriti
	Development of smart grids in the water, electricity, gas and internet sectors	Administration, energy providers, ci services
Economy	Payment platform	Administration, banks, industry
	Digital properties	Administration, citizens
	Digital products	Administration, industry

	Digital jobs and placement of the unemployed	Industry, job center
Retail & Industry	Virtual shopping centers and retail platforms	Retail, industry, citizens
	Marketing platform for local businesses	Retail, industry
	Provision of digital workplace offerings	Administration, industry, citizens
	Provision of a platform for SMEs to simulate and optimize production and logistics	Industry
Governance & Policy Making	Platform for strategic decision-making	Politics, administration
	Simulation of legislative procedures	Politics, administration
Cultural Heritage Preservation	Presentation of local cultural assets	Administration, clubs, citizens, tourists
	Community offerings for the preservation of culture and customs	Administration, clubs, citizens

City Planning and Simulation: The application of the metaverse in a smart city opens up new horizons for advanced urban planning and simulation tools that enable a comprehensive digital representation of the urban environment. Using sophisticated algorithms and real-time data integration, stakeholders are immersed in highly detailed virtual environments that accurately reflect the complexity of the physical urban landscape. These urban planning simulations in the metaverse facilitate joint decision-making between administrations, planning offices, and public institutions. By simulating different urban development scenarios and risk assessments, stakeholders can evaluate the potential impact of proposed changes on infrastructure, the environment, and community wellbeing [**25**]. The city's digital twin provides a dynamic platform for continuously monitoring and managing environmental parameters to ensure sustainable growth and resilience. Stakeholders use these simulations to optimize the use of renewable energy, minimize resource consumption, and increase efficiency. The integration of predictive analytics and scenario planning allows administrators to anticipate future energy needs and strategically allocate resources to maximize savings and minimize environmental impact [**25**].

This collaborative approach encourages innovation and data-driven decision-making, leading to more resilient and sustainable urban development. From the expert interviews, it became clear that planning components can have particular benefits regarding the more efficient use of resources, better quality of life for citizens, and a more robust infrastructure for the future.

Figure 5. Metaverse Applications Stack. By the Author.

5.4 Sustainability Dimensions in Smart Urban Environments

The integration of Metaverse technologies with smart city development represents a transformative approach to urban planning and management, creating a seamless blend of physical and digital environments. By developing sophisticated digital twins—virtual replicas of urban infrastructure—cities can achieve real-time monitoring, predictive analysis, and immersive simulation capabilities. This technological convergence facilitates more efficient resource allocation, collaborative governance, and enhanced public participation in urban decision-making processes. The COVID-19 pandemic accelerated this digital transformation, as remote work and virtual collaboration became normalized, fundamentally altering urban living patterns and creating new opportunities for immersive urban solutions[12].

At its core, the Metaverse smart city paradigm relies on interconnected technologies including VR/AR interfaces, AI systems, IoT networks, and blockchain infrastructure, which collectively create an interactive digital layer over physical urban spaces. This integration aligns closely with several Sustainable Development Goals, particularly SDG 9 (Industry, Innovation and Infrastructure) through applications like AR/VR-enabled infrastructure monitoring and digital twin-based urban planning[13]. The economic dimension supports SDG 8 (Decent Work and Economic Growth) through the emergence of new digital professions and virtual tourism opportunities, while social benefits advance SDG 11 (Sustainable Cities and Communities) via enhanced civic participation and cultural preservation initiatives.

By combining digital augmentation with physical infrastructure, the nexus of metaverse technologies and smart city development is transforming urban paradigms. Through immersive technologies like VR, AR, digital twins, AI, and IoT—all of which together allow for real-time system optimization, participatory governance, and sophisticated urban simulation—this synthesis tackles conventional urban constraints. Several SDGs are directly supported by these technological developments, especially SDG 8 through the creation of new jobs in the digital economy, such as virtual designers and metaverse consultants, and SDG 9 through innovations in infrastructure monitoring and maintenance, as exemplified by Catbas and Avci' swork on AR/VR applications for bridge inspections [14].

Environmental benefits arise from digital tools that optimize construction and transportation systems and from virtual scenario testing that reduces the usage of physical resources, as demonstrated in Deveci et al.'s study on sustainable decision-making[15]. Significant implementation obstacles still exist, though, such as the high capital needs that could exacerbate urban inequality and the ongoing digital divide that might prevent all people from having equal access to these technological developments [16]. Policymakers trying to strike a balance between innovation and inclusive, sustainable urban development must take into account metaverse platforms' energy-intensive operations and potential to exacerbate socioeconomic disparities, even as they increase service accessibility through virtual public services and educational materials [17].

While metaverse platforms expand service accessibility through virtual public services and educational resources, their energy-intensive operations and potential to deepen socioeconomic disparities present critical considerations for policymakers aiming to balance innovation with inclusive, sustainable urban development.

6. Enabling Technologies

6.1 Extended Reality (XR): AR, VR, and MR

According to Kourtesis [18] and Yazıcı et al. [19], Extended Reality (XR)—encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—plays a crucial role in the advancement of the Metaverse. These technologies improve immersion, realism, and interactivity by merging the physical and digital realms. XR allows users to interact seamlessly through gestures, voice, and movements while fostering a realistic social presence and collaborative experiences in virtual spaces.

Virtual Reality immerses users completely in crafted environments utilizing devices such as the Oculus Rift and HTC Vive. Essential features include motion tracking, eye tracking, spatial audio, and haptic feedback. VR finds extensive use in gaming, training, and therapeutic contexts. Anticipated advancements like brain-computer interfaces (BCIs) and light-field displays are expected to offer even more intuitive and lifelike experiences.

Augmented Reality (AR) integrates digital information with the physical environment through smartphones or AR glasses. It employs cameras, LiDAR, inertial measurement units (IMUs), and simultaneous localization and mapping (SLAM) technologies to position virtual components in the real world. AR finds applications in sectors such as retail, maintenance, and education. Emerging developments like Neural Radiance Fields (NeRFs), AR contact lenses, and 5G-capable solutions are designed to enhance the immersiveness and accessibility of AR.

Mixed Reality (MR) combines actual and virtual worlds, enabling interactive experiences with both simultaneously. Technologies including depth sensors, spatial anchors, and sophisticated tracking elevate the effectiveness of MR in areas like design and healthcare. The future of MR is expected to feature holographic displays and AI-driven contextual awareness.

Although XR holds significant potential, it also presents ethical dilemmas. Kourtesis [1] points out the dangers associated with the misuse of biometric information, advocating for frameworks that comply with GDPR regulations. Furthermore, accessibility issues and cybersickness are other obstacles that can be tackled using open-source resources, high frame rates, and cost-effective hardware.

The progression of XR will depend on enhanced displays, accurate neural tracking, AI-based customization, and secure, decentralized identity systems. Both references concur that XR technologies are set to shape the forthcoming era of immersive digital engagement within the Metaverse.

6.2 Digital Twins and Virtual Simulations

According to the research of Zhang et al. [20] and Ruiu et al. [21], digital twinning involves creating a virtual version of a physical object, system, or process. This interactive model utilizes real-time information, simulations, and advanced analytics to replicate physical systems in a digital environment. Within the Metaverse, digital twins are crucial as they facilitate immersive realism, predictive analysis, and enhanced virtual interactions. They act as a connection between the physical and virtual worlds, providing high-fidelity representations of humans and objects that continuously evolve. Human Digital Twins (HDTs), as explained by Ruiu et al., improve personalization and realistic interaction in virtual settings by gathering behavioral and biometric data.

Zhang et al. highlight that the incorporation of digital twins within the Industrial Metaverse enables industries to model their operations, execute predictive maintenance, and facilitate real-time remote collaboration. These systems depend on a variety of cutting-edge technologies, such as IoT for gathering real-world data, AI for forecasting capabilities, and AR/VR for immersive experiences. Blockchain technology provides security and ownership of the data, while 5G and edge computing allow for the low-latency synchronization required for real-time applications. Additionally, biometric sensors and wearables collect emotional and physiological data, which allows for more precise and responsive digital representations of humans.

Nevertheless, the implementation of digital twinning within the Metaverse encounters significant challenges. Ruiu et al. emphasize the issues surrounding data privacy due to the large amounts of biometric data gathered, while Zhang et al. identify problems related to interoperability and the complex computations required to maintain accurate simulations. Limitations of sensors and the difficulty in accurately representing human emotions and cognitive processes further hinder the advancement of digital twins.

To address these challenges, new technologies are being developed. Self-sovereign identity (SSI) and zero-knowledge proofs (ZKPs) empower users to manage their own data while maintaining privacy and trust. Semantic Web technologies and universal ontologies enhance interoperability across various platforms. Innovations in quantum computing, neuromorphic sensors, and energy-efficient AI models such as TinyML seek to lessen the computational burden while enhancing accuracy. Moreover, brain-computer interfaces (BCIs) are being investigated to convert human thoughts and emotional states directly into digital twin responses, fostering richer, more human-oriented engagement.

Looking forward, both studies propose that the future of digital twinning in the Metaverse will involve the development of interconnected digital ecosystems that cater to smart cities, healthcare, and industry. These ecosystems are expected to operate under ethical principles focusing on data ownership and sustainability, relying on collaborative initiatives to establish universal standards for the deployment and integration of digital twins.

6.3 Artificial Intelligence and Machine Learning

Machine Learning (ML) and Artificial Intelligence (AI) are crucial in influencing the Metaverse by creating intelligent, immersive, and safe virtual spaces. These technologies enable tailored experiences, lifelike avatar interactions, and real-time content creation using computer vision, natural language processing, and generative models. According to Yazan Otoum et al. [22], ML improves security by identifying anomalies, phishing threats, and deepfake avatars, while AI-powered biometric authentication methods—such as facial recognition and voice analysis—provide reliable identity verification. A. Awadallah et al. [23] further underscore the importance of AI in automated moderation, which helps to mitigate harassment and cyberbullying, as well as its ability to identify adversarial threats like spoofing and data poisoning.

A range of sensors and devices, such as XR headsets, AR glasses, biometric wearables, and haptic feedback systems, facilitate immediate interaction and realism in the environment. AI processors like NVIDIA's Omniverse and Google's Tensor TPUs enable real-time rendering and model training. Nonetheless, there are ongoing challenges. Privacy issues arise due to the gathering of sensitive biometric data, and high computational requirements put pressure on edge devices. Additional problems include the vulnerability to adversarial attacks, interoperability challenges among platforms, and network latency linked to cloud usage.

New technologies are being developed to tackle these challenges. Federated Learning and Homomorphic Encryption improve data privacy by allowing decentralized training and encrypted computation. Quantum Machine Learning and neuromorphic computing present energy-efficient processing solutions and quicker AI training. As mentioned by Awadallah et al. [22], edge AI and 6G networks offer ultra-low latency, while blockchain-integrated AI ensures secure transactions and identity verification. Generative AI simplifies content creation, and self-supervised learning enhances AI adaptability without requiring extensive labeled data. Collectively, these innovations are poised to make the Metaverse more secure, efficient, and scalable, as highlighted by both Otoum et al. [22] and Awadallah et al. [23].

6.4 Blockchain and Decentralized Systems

The incorporation of blockchain and decentralized systems within the metaverse provides solutions to critical issues like data security, trust, and user autonomy. As noted by Ghosh et al. [24] and Meng et al. [25], the decentralized characteristic of blockchain eliminates dependency on central authorities, thus improving transparency and resilience. Technologies such as smart contracts and NFTs on networks like Ethereum enable secure management of virtual assets, while consensus mechanisms like Proof of Stake (PoS) and Proof of History (PoH) provide scalable and energy-efficient options compared to traditional models. Cryptographic techniques, including zero-knowledge proofs (ZKPs) and homomorphic encryption, maintain privacy without sacrificing verification, while immersive experiences are facilitated by AR/VR technologies and biometric sensors.

Nonetheless, several challenges still exist. Scalability is a significant concern, with many blockchains unable to manage high transaction volumes effectively. The public nature of blockchains can jeopardize privacy, and the lack of interoperability among platforms leads to fragmented user experiences. Additionally, expensive hardware, bandwidth limitations, and vulnerabilities in smart contracts pose further obstacles to adoption. To mitigate these issues, emerging solutions involve Layer-2 technologies (such as rollups and sharding), cross-chain protocols (like Polkadot and Cosmos IBC), and the use of AI for enhancing security and automation. Progress in edge computing, 5G/6G networks, and more affordable hardware is also helping to alleviate technical and financial challenges [26].

In conclusion, blockchain and decentralization are crucial for creating a secure and user-centric metaverse. As emphasized by Ghosh et al. [24] and Meng et al. [25], embracing innovative technologies is vital to overcoming current limitations and achieving a scalable, private, and interoperable virtual landscape.

6.5 5G/6G Connectivity and Network Infrastructure

The metaverse, conceptualized as a harmonious fusion of physical and digital experiences, is fundamentally dependent on high-speed, ultra-reliable, and low-latency connectivity. Emerging sixth-generation (6G) networks are poised to serve as the foundational support for this transition, providing revolutionary features to accommodate immersive applications like extended reality (XR), holographic communications, and digital twins. As stated by Pennanen et al. [27], 6G utilizes cutting-edge technologies such as terahertz (THz) communication, reconfigurable intelligent surfaces (RIS), and ultra-massive multiple-input multiple-output (UM-MIMO) systems to achieve unparalleled data rates and spectral efficiency. Together, these innovations facilitate the real-time transfer of rich, multi-sensory content while ensuring extensive coverage, even in crowded or obstructed areas.

To boost interactivity, 6G networks integrate sensing and communication (ISAC) capabilities, making them aware of and reactive to their surroundings. Chang et al. [2] highlight the significance of edge artificial intelligence (AI) in analyzing data near the user, which diminishes dependence on centralized cloud systems and decreases latency. This is enabled through federated learning frameworks that permit devices to collaboratively train AI models without infringing on user privacy. Meanwhile, real-time feedback is gathered by sensors such as LiDAR, eye-tracking devices, and haptic wearables, allowing for personalized and immersive user experiences. Nonetheless, the considerable energy requirements of these systems—especially in wearables and XR headsets—create challenges regarding power efficiency and extended usability.

Despite these technological advancements, notable obstacles still exist. While THz communications can achieve extremely fast speeds, they are hindered by significant propagation losses and signal obstructions. Furthermore, both RIS and UM-MIMO technologies encounter concerns related to energy efficiency, particularly when associated with battery-operated devices. The computational requirements of the metaverse also put pressure on the existing infrastructure, leading to issues with latency and scalability. In addition, the absence of standardized protocols and interoperability among different devices complicates widespread implementation.

To address these challenges, both studies suggest promising technological pathways. Pennanen et al. [1] investigate the potential of quantum communication for highly secure data transmission and neuromorphic computing for low-power, real-time AI operations. Chang et al. [28] also mention the potential of biodegradable bio-batteries for sustainable power supply to wearables, as well as holographic beamforming to improve the reliability of THz signals. Additionally, decentralized identity systems based on blockchain are recommended to ensure secure, seamless interactions across various platforms, thereby promoting interoperability and trust.

In summary, the achievement of a genuinely immersive and responsive metaverse hinges on the ongoing advancement of 6G technologies and edge AI. Although current solutions provide a solid groundwork, future investigations must tackle enduring challenges concerning energy efficiency, latency, interoperability, and sustainability. As noted by both Pennanen et al. [27] and Chang et al. [28], the incorporation of quantum encryption, neuromorphic chips, and federated learning within a robust 6G framework is essential to fully realize the transformative capabilities of the metaverse.

6.6 Cybersecurity and Data Privacy Mechanisms

The Metaverse, imagined as a smooth integration of digital and physical realities, combines technologies such as Extended Reality (XR), Artificial Intelligence (AI), blockchain, and the Internet of Things (IoT) to facilitate immersive interactions, decentralized virtual marketplaces, and continuous environments. However, this integration presents intricate security and privacy issues. As emphasized by Huang et al. [29] and Chen et al. [30], the vast accumulation and processing of sensitive user information—including biometric data like facial characteristics and eye movements, behavioral trends, and financial details—render users particularly vulnerable to identity theft, deepfake manipulation, and invasive surveillance. XR devices, which encompass virtual, augmented, and mixed reality headsets, enhance immersion through features like motion tracking, haptic feedback, and environmental sensing. Nevertheless, these devices frequently lack end-to-end encryption, leaving real-time user information susceptible to unauthorized interception and misuse, as observed by Hector et al. [31].

Moreover, IoT-enabled digital twins that replicate real-world systems in virtual environments face threats such as spoofing, tampering, and Man-in-the-Middle (MITM) attacks due to inadequate authentication processes. While blockchain is often regarded as a foundation for decentralization—protecting digital assets via NFTs and smart contracts—it continues to struggle with problems like limited scalability, vulnerability to quantum computing breaches, and smart contract weaknesses. AI-driven systems add complexity to the situation by raising issues related to algorithmic bias, adversarial inputs, and the generation of deepfakes, which could lead to misinformation and identity misrepresentation (Huang et al. [29]; Hector et al. [31]).

Despite ongoing advancements, enduring deficiencies in security infrastructure persist. Centralized storage of biometric data, inadequate data anonymization methods, and fragmented global regulations enhance user exposure to cross-platform tracking and jurisdictional uncertainties (Chen et al. [30]). To address these challenges, researchers are exploring advanced technologies. Post-quantum cryptography—including encryption techniques based on lattices and hashes—provides a strong defense against quantum-enabled decryption, securing future blockchain and identity systems (Huang et al. [29]). Decentralized identity (DID) systems, facilitated by blockchain, encourage self-sovereign identity management, eliminating reliance on insecure centralized databases (Hector et al. [31]). Additionally, federated learning and homomorphic encryption allow AI to learn from distributed data while safeguarding the privacy of user inputs, a vital feature for collaborative Metaverse applications (Chen et al. [30]).

Furthermore, neuromorphic computing—a biologically inspired design—offers a promising avenue for detecting deepfakes in real-time while ensuring energy efficiency. Zero-trust architecture (ZTA) has surfaced as an essential framework for enforcing strict access controls and ongoing identity verification, thereby reducing insider threats and data leaks (Huang et al. [29]). Innovations such as lightweight post-quantum signatures and AI-driven anomaly detection deployed at the edge of the network further bolster the security of IoT infrastructures by minimizing response times to emerging threats (Hector et al. [31]). However, the effective implementation of these technologies will rely on globally coordinated regulatory frameworks, standardized interoperability protocols, and privacy-by-design principles that prioritize user rights. Only through this multi-faceted, cooperative approach can the Metaverse transform into a secure, ethical, and scalable digital landscape.

7. Metaverse of Things (MoT)

7.1 Conceptual Framework of MoT

The core structure of MoT is based on the smooth merging of IoT devices with metaverse platforms, allowing for instantaneous interactions between physical and digital entities [32]. They outline essential criteria for MoT systems, including immersion, interactivity, authenticity, and autonomy, highlighting the necessity for solid frameworks that ensure these qualities [33]. Expanding on this base, Aloqaily et al. (2022) introduce a detailed framework that combines digital twins with cutting-edge technologies such as 6G networks, blockchain, and AI to provide continuous, integrated metaverse services. This combination seeks to tackle challenges related to scalability and user experience, guaranteeing that metaverse environments can offer immersive services across multiple areas [34].

7.2 Integration of IoT Devices in the Metaverse

The incorporation of IoT devices into metaverse environments requires frameworks that promote interoperability and intuitive user interfaces. Kurai et al. [35] present "MetaGadget," a framework designed to facilitate the integration of IoT devices into commercial metaverse platforms through HTTP-based event triggers. This method streamlines the management of devices without the need for constant client connections, thus lowering technical barriers and encouraging collaborative interactions in multi-user VR environments. Furthermore, the combination of IoT with the metaverse has been examined in relation to smart buildings. Masubuchi et al. [36] describe a digital twin environment that connects IoT sensors from a smart building to a commercial metaverse platform. Their system includes a standardized IoT sensor framework, a real-time data relay mechanism, and an environmental data visualization system, allowing for innovative forms of collaboration that overcome spatial limitations.

7.3 Real-time Data Synchronization and Analytics

Achieving real-time synchronization between physical IoT devices and their virtual counterparts is essential for the effectiveness of MoT systems. Han et al. (2022) suggest a dynamic hierarchical framework that utilizes IoT-assisted synchronization to uphold the precision of digital twins in the metaverse. Their approach incorporates evolutionary and differential game theories to enhance synchronization strategies, guaranteeing that virtual representations accurately mirror their physical conditions [37].

7.4 Applications of MoT in Urban Infrastructure

Maier and Weinberger et al. [38] discuss that utilizing the Metaverse of Things (MoT) in urban environments presents valuable opportunities for improving infrastructure management and engaging citizens. The metaverse acts as a venue for testing and assessing new transportation technologies, infrastructure ideas, and strategies for network management in virtual settings. By leveraging the capabilities of the metaverse, municipalities can develop transportation and infrastructure systems that are more efficient, sustainable, and resilient, catering to citizens' needs while also fostering economic growth and development.

7.5 Challenges and Considerations in Implementing MoT

Integrating IoT devices into the metaverse demands advanced computing infrastructure, which includes powerful servers, high-speed networks, and sophisticated software tools. This presents significant challenges, particularly for large-scale implementations intended to accommodate millions of users, as highlighted by Gupta et al. [41]. Common issues include computational complexity, connectivity challenges, and the need to provide immersive user experiences. Furthermore, achieving interoperability among various platforms and devices remains a vital obstacle, stressing the necessity for common data standards and protocols to ensure fluid experiences across virtual realms (Gupta et al. [41]). The extensive use of MoT technologies also brings up concerns regarding energy consumption and environmental sustainability. Pereira et al. [40] indicate that the infrastructure that underpins the metaverse, which includes data centers and network gear, requires a substantial amount of energy, thereby contributing to a notable carbon footprint. In addition, social issues such as the risk of sedentary lifestyles, digital divides, and the marginalization of specific communities need to be handled through the adoption of energy-efficient technologies and inclusive policies. The deployment of MoT solutions involves significant financial investments in hardware, software, and infrastructure, posing particular challenges for small and medium-sized enterprises, as noted by Li et al. [42]. The absence of standardized governance frameworks and the requirement for skilled personnel well-versed in both IoT and metaverse technologies further complicate adoption, highlighting the importance of cost-effective training initiatives and regulatory standards. Lastly, incorporating IoT devices into the metaverse results in intricate security and privacy issues. The vast amounts of data generated by interconnected devices and platforms elevate the risk of cyberattacks and unauthorized access, emphasizing the need for strong encryption, authentication protocols, and comprehensive privacy policies, as addressed by Li et al.[39] and Gupta et al. [40].

8. Applications in Sustainable Smart Cities

8.1 Urban Planning and Virtual City Modeling

Masubuchi et al. (2025) created a system that connects IoT sensors from smart buildings to a metaverse platform, allowing for real-time monitoring and virtual engagement. This application enhances building operations, optimizes energy consumption, and enables remote collaboration on architectural design and maintenance activities. [43]. Pham et al. (2025) applied VR simulations within a digital twin to analyze urban walkability. This approach assists in evaluating pedestrian experiences, spotting flaws in urban design, and guiding inclusive mobility planning for both new and existing city layouts. [44]

Li (2024) introduced a comprehensive architectural framework for cities in the metaverse, allowing for dynamic interactions between physical and virtual urban elements. Applications cover AI-driven zoning analysis, responsive infrastructure development, and mixed-reality prototyping for large-scale urban projects. [45]. Hudson-Smith (2022) characterized the metaverse as a means for participatory urban planning, enabling collaboration between citizens and policymakers to visualize and refine proposals for urban development in immersive settings. This approach promotes more democratic planning processes and increases transparency and public engagement. [46]

8.2 Smart Governance and Citizen Engagement

Innovative government metaverse platforms allow citizens to participate in virtual consultations and planning sessions, facilitating immediate feedback and enhancing transparency in the creation and approval of urban development projects, as noted by Al-Adwan et al. [47]. Moreover, citizens have the opportunity to engage in interactive simulations to evaluate the social and environmental repercussions of suggested policies, thereby improving participatory planning (Allam et al. [48]). Dynamic civic digital twins replicate real-world conditions, enabling citizens to co-create urban solutions and test potential outcomes, as illustrated by Luca et al. [49]. In addition, Metaverse of Things (MoT) platforms utilize IoT data to offer interactive dashboards and real-time feedback loops from citizens, which promote smarter and more flexible governance, as explained by Dienhart et al. [50].

8.3 Sustainable Transportation and Mobility Solutions

Transitioning to electric buses and trains plays a crucial role in lowering greenhouse gas emissions and air pollution in urban areas, significantly aiding in climate change mitigation and enhancing public health, as emphasized by Jelti et al. [51]. The electrification of public transportation stands as a fundamental strategy for cities striving to achieve ambitious sustainability objectives while ensuring efficient transportation systems. Mobility as a Service (MaaS) platforms integrate various modes of transport—including buses, trains, ride-sharing, and micro-mobility—into a unified digital platform, improving user convenience and minimizing reliance on cars by encouraging the adoption of shared and public transit options, according to Shah et al. [52]. These platforms also support seamless trip planning, payment integration, and real-time updates, making sustainable transportation more accessible and attractive to a wider audience.

Demand-responsive transport solutions, like flexible shuttle services and on-demand rides, enhance accessibility in outlying and low-density areas where traditional fixed-route transit may not be effective or available. This method caters to the specific mobility needs of rural and suburban communities, reducing social exclusion and promoting equitable access to transportation, as noted by Shibayama and Emberger [53]. Furthermore, real-time transport monitoring utilizing IoT sensors and advanced data analytics allows cities to enhance traffic flow, identify congestion hotspots, and decrease idle emissions by adaptively managing traffic signals and transit schedules. These intelligent systems boost operational efficiency and lessen environmental impacts, as detailed by Shah et al. [54]. Collectively, these advancements illustrate a comprehensive approach to developing sustainable, inclusive, and efficient transportation systems.

8.4 Environmental Monitoring and Resource Management

Real-time monitoring of air quality has become increasingly essential in urban areas, as IoT sensors are utilized to track pollutants like CO_2, NO_2, and PM2.5, allowing cities to quickly identify dangerous conditions and take prompt action to safeguard public health, as highlighted by Lakshmi Narayana et al. [55]. In addition to air monitoring, the integration of IoT greatly enhances water quality and resource management; sensors that measure factors such as pH, turbidity, and levels of contaminants in water bodies help guarantee safe drinking water and enable early detection of pollution incidents, thereby decreasing risks to both ecosystems and communities, according to Malche et al. [56]. The use of low-power IoT sensors to continuously monitor water levels in rivers and urban drainage systems also improves flood detection and management, providing essential data for early warning systems and bolstering urban resilience to climate-related calamities (Hsu and Gourbesville [57]).

Understanding urban heat island effects, which worsen temperature extremes in cities, can be improved through sensor networks that track temperature changes across various urban areas, aiding planners in formulating mitigation strategies like increasing green spaces or reflective surfaces, as explained by Lakshmi Narayana et al. [55]. Additionally, monitoring noise pollution through acoustic sensors aids in enforcing noise regulations and enhancing the overall quality of urban life by pinpointing problematic areas in real time (Allam et al. [58]). Smart waste management systems that utilize sensor-equipped waste bins to gauge fill levels can optimize collection routes and schedules, resulting in reduced operational expenses and lower environmental impact, thus promoting more sustainable and efficient urban services (Allam et al. [58]). Collectively, these IoT-driven environmental monitoring functions create an integrated decision support system that equips cities to proactively address environmental issues, furthering sustainability and resilience objectives.

8.5 Healthcare and Telemedicine Services

The integration of IoT and metaverse technologies is transforming healthcare delivery by offering improved remote monitoring, tailored care, and immersive medical education. With Remote Patient Monitoring (RPM) through IoT-enabled wearables, continuous observation of vital signs such as heart rate, blood pressure, and oxygen saturation is possible, enabling timely management and early intervention for patients, as mentioned by Elmi et al. [59]. Telemedicine platforms gain significantly from IoT integration, facilitating seamless virtual consultations, diagnostics, and treatment strategies, thereby greatly enhancing access to healthcare services in rural and underserved areas (Elmi et al. [17]). In the educational sector, Virtual Reality (VR) and Augmented Reality (AR) technologies replicate complex clinical situations, providing healthcare professionals with realistic training environments that boost skill development (Chengoden et al. [60]).

Digital twins are emerging as a groundbreaking strategy in personalized healthcare, as real-time patient data is utilized to craft virtual models that simulate and anticipate health outcomes, enabling customized and adaptive treatment plans (Chengoden et al. [60]). The management of chronic diseases is likewise enhanced through the deployment of connected IoT devices that facilitate ongoing care for conditions like diabetes and hypertension, minimizing the necessity for frequent hospital visits (Chengoden et al. [60]). To guarantee secure data management, blockchain technology is increasingly being utilized to safeguard health records and enable reliable, decentralized sharing among authorized parties (Chengoden et al. [60]). Furthermore, remote rehabilitation programs supported by virtual platforms allow patients to participate in physical therapy from home, under real-time supervision, making the recovery process more accessible and consistent (Chengoden et al. [60]).

8.6 Education and Virtual Learning Environments

The combination of IoT and metaverse technologies is transforming the educational sector by fostering more interactive, tailored, and accessible learning experiences. Immersive virtual classrooms equipped with Virtual Reality (VR) and Augmented Reality (AR) enable learners to interact with 3D models, take virtual field trips, and investigate simulated scenarios, which significantly improves understanding of abstract and complex ideas (Damaševičius and Sidekerskienė [61]). Supporting these experiences, IoT-enabled smart classrooms utilize connected technologies like smart boards, sensors, and automated attendance systems to provide real-time feedback and enhance classroom management (Ghashim and Arshad [62]). These innovations not only boost engagement but also enable a data-driven educational approach; performance data gathered from IoT devices can be analyzed to tailor content delivery to meet the individual learning styles and preferences of students (Spaho et al. [63]).

Virtual laboratories further enhance these capabilities by allowing students to conduct experiments in a safe, simulated environment that is both cost-effective and scalable, which is particularly beneficial in STEM fields (Zhang [64]). Concurrently, remote learning platforms backed by IoT and metaverse technologies offer seamless tele-education, providing learners from various geographic locations equitable access to educational resources and interactive experiences (Braguez et al. [65]). Moreover, collaborative virtual spaces foster teamwork by enabling students to partake in real-time project-based learning without regard to physical location (Damaševičius and Sidekerskienė [61]). These spaces increasingly incorporate AI-powered translation tools to facilitate multilingual education, removing language obstacles and creating more inclusive global learning communities (Damaškevičius and Sidekerskienė [61]).

8.7 Cultural Heritage Preservation and Tourism

The convergence of Metaverse, VR, AR, and XR technologies is transforming how cultural heritage is preserved, displayed, and made accessible. Immersive virtual heritage experiences enable individuals to navigate historical sites, ancient towns, and museum displays from anywhere globally, providing an engaging and educational substitute for in-person visits (Anwar et al. [66]). These technologies improve not just visual authenticity but also sensory involvement, fostering a stronger emotional and cognitive engagement with historical stories. The landscape of cultural tourism is also changing, with metaverse platforms replicating heritage sites like the ancient city of Babylon, making virtual tourism available to audiences worldwide, transcending geographic and economic limitations (Almasooudi [67]).

Incorporating interactive storytelling within these platforms boosts user involvement by merging factual history with gamified experiences—this method combines learning with entertainment, referred to as "edutainment"—making the cultural learning experience more engaging and unforgettable (Anwar et al. [66]). Additionally, educational institutions and heritage organizations are creating tailored platforms in the metaverse to instruct on history, archaeology, and conservation methods, giving learners the chance to delve into reconstructions of ancient cultures and grasp preservation techniques through an intuitive, hands-on approach (Anwar et al. [66]). This comprehensive strategy is altering how communities engage with and preserve their cultural identities in the digital age.

8.8 Emergency Response and Disaster Management

The adoption of cutting-edge technologies like IoT, AI, XR, and robotics is transforming disaster and emergency management, creating systems that are more proactive, responsive, and efficient. The rise of the Internet of Emergency Services (IoES) facilitates real-time monitoring of crises through a network of interconnected IoT devices, enabling quick data gathering and better coordination among emergency response organizations, which is essential during major disasters. Virtual Reality (VR) and Augmented Reality (AR) further enhance this by creating simulations of high-risk situations in safe environments, significantly improving both disaster preparedness and the training programs for emergency responders. These immersive technologies allow trainees to engage in real-world decision-making without facing actual risks.

Artificial Intelligence (AI) is crucial in developing smart infrastructure and emergency response systems. By processing real-time information from sensors, social media, and environmental data, AI assists authorities in evaluating risks, efficiently distributing resources, and effectively responding during emergencies. Additionally, AIoT-enabled robots are proving to be vital assets in search and rescue missions. With their ability to navigate autonomously, detect environmental conditions, and communicate, these robots can reach dangerous zones, identify victims, and transmit important information back to command centers, thereby speeding up the rescue efforts.

Evacuation plans have progressed thanks to IoT advancements. Intelligent evacuation systems leverage real-time information to determine the safest and quickest escape routes, dynamically adjusting to changing scenarios such as fires, floods, or structural failures. Furthermore, AR and VR technologies are being incorporated into emergency management processes to aid in planning and operational decision-making by providing improved spatial awareness and visualization resources for emergency managers. Together, these advancements are enhancing the speed, safety, and effectiveness of disaster response efforts.

9. Case Studies and Real-world Implementations

Several cities worldwide have emerged as frontrunners in implementing metaverse technologies to revolutionize urban services and governance. These initiatives demonstrate how digital innovation can transform city management, citizen engagement, and infrastructure development.The examination of these initiatives reveals distinct approaches to metaverse integration in urban contexts. While Seoul focuses on comprehensive citizen services, Singapore emphasizes urban planning simulations, and Dubai targets infrastructure management. These case studies collectively demonstrate the metaverse's potential to enhance urban sustainability, improve governance transparency, and foster innovative citizen engagement models.

9.1 Seoul's Comprehensive Metaverse Platform

South Korea's capital launched the groundbreaking "Metaverse Seoul" initiative as part of its "Seoul Vision 2030" strategy, becoming the first major city to establish an official municipal metaverse platform. The project, recognized with the Smart City 2022 award, employs a phased implementation approach scheduled for completion by 2026. Currently operational services include virtual city exploration through avatars and digital civic assistance for tax inquiries and administrative processes. The platform's ambitious framework encompasses seven key domains: economic development, education, civic communication, cultural promotion, urban planning, public administration, and taxation systems. Developers can leverage specialized tools to create applications for these sectors, including modules for citizen data management, educational programming, and tourism services. Beyond streamlining government operations, Seoul's metaverse aims to address pressing urban challenges like air pollution and healthcare accessibility through technological innovation [32,33].

9.2 Singapore's Pioneering Digital Twin System

As an early adopter of urban digital twin technology, Singapore launched its "Virtual Singapore" platform in 2014. This sophisticated system integrates diverse datasets including geographic information, demographic statistics, climate patterns, and population movement analytics. The platform enables comprehensive urban simulations that inform solutions for logistics optimization, emergency preparedness, infrastructure maintenance, and public service delivery. By modeling various urbanization scenarios, city planners can assess potential impacts and develop data-driven strategies for sustainable growth [12].

9.3 Dubai's Infrastructure Management Solutions

Dubai's transportation authority has implemented augmented reality systems to monitor its metro network through a digital twin interface. This application analyzes both historical performance data and real-time operational metrics to identify maintenance requirements and potential service disruptions. The proactive monitoring approach significantly reduces system downtime while optimizing rail network efficiency [15].

9.4 Comparative Analysis of Global Initiatives

The integration of the metaverse into urban development represents a transformative approach to enhancing sustainability, governance, and citizen engagement in smart cities. This review examines key global metaverse initiatives, analyzing their applications, technological frameworks, and contributions to sustainable urban development. By comparing case studies from Seoul, Helsinki, Catalonia, Barbados, London, New York, Santa Monica, Shanghai, Singapore, Dubai, and Benidorm, Cities worldwide are pioneering distinct approaches to integrating metaverse technologies into urban ecosystems, reflecting varying priorities, governance models, and implementation frameworks. These initiatives can be analyzed through several critical dimensions that highlight their strategic differences and evolutionary trajectories.

Governance and Implementation Models: Seoul's "Metaverse Seoul" initiative (2023-2026) exemplifies a top-down, government-driven approach, systematically incorporating seven municipal service areas into a unified digital platform[17]. In contrast, Helsinki adopted an incremental strategy, beginning with cultural and tourism applications in 2018 before expanding to civic functions. The organizational structures range from Shanghai's centralized government platform to Barbados' decentralized model developed through partnerships with private metaverse providers like Decentraland. Barcelona's CatVers demonstrates a unique approach by deliberately incorporating Catalan-language interfaces to strengthen regional identity rather than pursuing global interoperability[18,19].

Functional Specialization: Application focus varies significantly across cities, reflecting tailored solutions to local priorities. Infrastructure simulation dominates in London and Singapore's implementations, while New York concentrates specifically on intelligent traffic management using predictive analytics. Dubai represents the most targeted application with its metro-specific augmented reality system for maintenance optimization. These specializations reveal how cities align metaverse technologies with their most pressing urban challenges.

Economic and Engagement Frameworks: The initiatives showcase fundamentally different value propositions. While Seoul prioritizes public service delivery, Santa Monica developed a commerce-oriented gamified environment, and Shanghai explicitly ties its platform to economic development targets. Citizen interaction models range from Seoul's service accessibility focus to Santa Monica's experience-driven design and Barbados' innovative virtual embassy for diplomatic engagement.

Temporal Evolution: The implementation timeline shows a clear progression from early digital twins to contemporary comprehensive platforms. This evolution mirrors both technological advances and growing institutional understanding of how virtual environments can enhance urban systems. Later implementations benefit from lessons learned by pioneers, demonstrating an accelerating sophistication in urban metaverse applications.

10. Challenges and Limitations

As a response to contemporary urban problems, the concept of smart cities—urban areas improved by digital technologies—has been pushed. In a similar vein, the Metaverse is frequently portrayed as a cutting-edge virtual environment that has the potential to raise living standards. Both ideas, nevertheless, have shortcomings that call into question their utopian assertions. History demonstrates that freedom and justice are not necessarily the results of technological advancement. Digital tools are already being used by some governments to keep an eye on its citizens, limit their liberties, and enforce conformity. For example, the COVID-19 pandemic showed how exaggerated control may be justified by crisis measures, making it difficult to distinguish between oppression and safety. Making sure that digital innovations—whether in the Metaverse or smart cities—are created morally, with protections against misuse, inequality, and loss of autonomy, is the difficult part.

10.1 Technical Challenges: Scalability and Interoperability

Realizing this vision requires substantial technological infrastructure investment and long-term development commitment. Current enabling technologies include:

Augmented Reality (AR) and Virtual Reality (VR): Notwithstanding the remarkable potential of IoT devices and the market's rapid expansion, VR and AR technologies encounter a number of obstacles that limit their applicability in many IoT applications. The absence of hardware and rules/documentation about its use and appropriateness in various applications, the lack of innovative content for new applications, public skepticism, and physical safety hazards are some of the major obstacles. More significantly, one of the biggest obstacles to the general adoption of VR and AR is the high cost of the hardware and software components.
The needs of the IoT applications determine whether VR/AR solutions should be integrated with IoT devices. For example, affordable VR/AR solutions with basic HMDs make sense when home automation and appliance management are required on IoHT. Utilizing cost-effective VR/AR equipment could not be obvious in applications that demand high performance, such image or video processing, and hybrid solutions might make sense in these situations.

Blockchain: The requirements of the IoT applications determine which VR/AR solutions should be integrated with IoT devices. For example, affordable VR/AR solutions with basic HMDs make sense when home automation and appliance management are required on IoHT. It might not be obvious to employ cost-effective VR/AR equipment in applications that demand high performance, such image or video processing, and hybrid solutions.

Immersive Digital Twins: A number of significant obstacles stand in the way of the successful development of smart cities (SCs) based on Digital Twins (DT). First, regional differences in the conceptual framework of smart cities continue to be a major source of disagreement, leading to disjointed technical approaches and inadequately established implementation models. Second, many projects suffer from poor top-down planning, which includes inadequate socio-technical component consideration, appraisal, and exploratory study. This frequently takes the form of an excessive focus on technology infrastructure at the expense of public opinion and governance frameworks, as well as a lack of standardized operational models that are adapted to various metropolitan situations.

As mismatched government platforms produce isolated information silos that impede interoperability, data fragmentation poses a significant hurdle to the establishment of integrated smart city ecosystems. Systemic cybersecurity flaws, such as insufficient emergency response procedures and a lack of public awareness of digital hazards, exacerbate these technological challenges, and a lack of people with both technical know-how and urban governing experience further stifles creativity. Since many initiatives suffer from low private sector participation, unsustainable finance structures, and inefficient public engagement channels, financial and institutional constraints pose equally important challenges. By upholding sectoral boundaries that encourage redundant systems, ineffective resource allocation, and entrenched data isolation, traditional bureaucratic structures make these issues worse and eventually jeopardize the development of cohesive, citizen-focused urban ecosystems.

10.2 Ethical and Privacy Concerns

There are intricate cybersecurity and ethical issues with the use of Metaverse of Things (MoT) technologies in smart cities that demand immediate legislative attention. Because augmented reality interfaces allow for ongoing data collecting in public areas, frequently without explicit consent procedures or openness regarding data usage, the immersive aspect of these applications creates serious privacy problems. Through algorithmically tailored urban experiences, this ubiquitous surveillance capability creates new avenues for behavioral manipulation while also endangering individual autonomy. At the same time, MoT systems greatly increase the attack surface of smart cities by adding vulnerabilities that may allow for ransomware attacks against municipal services, massive data breaches, or even the manipulation of vital infrastructure through compromised AR gadgets.

In terms of cybersecurity, MoT deployments significantly increase the number of possible attack avenues, opening the door for disastrous system breaches that might use augmented reality devices to control vital infrastructure or initiate coordinated ransomware attacks against vital municipal services. Through the MoT, the physical and virtual realms are deeply convergent, creating risky failure modes where digital disruptions could lead to real-world urban problems. Implementing strict, multifaceted measures is necessary to mitigate these threats. These include mandatory security validation for all immersive technologies, zero-trust network architectures for municipal systems, and data protection laws influenced by the GDPR. Crucially, these technical measures must be complemented by participatory governance models that incorporate citizen perspectives into digital urban planning processes, ensuring ethical frameworks evolve alongside technological capabilities.

10.3 Economic and Accessibility Barriers

The Metaverse's present development exposes concerning accessibility flaws, especially when it comes to supporting users with a range of physical and cognitive requirements. Despite the speed at which technology is developing, most development roadmaps still glaringly lack inclusive design principles, resulting in virtual worlds that routinely exclude groups like people with dementia or cognitive disabilities. This oversight persists even as research demonstrates XR's potential therapeutic benefits for these groups, highlighting a fundamental disconnect between technological capability and equitable implementation. Progress is hampered by three systemic issues: the wide range of user requirements, the lack of agreement on accessibility guidelines, and the difficulties in conducting representative user research.

The Metaverse ecosystem has to give priority to user-controlled customization capabilities, modular interaction paradigms, and adaptive interfaces in order to address these shortcomings. In order to achieve this goal, prompt, concerted effort is needed to develop evidence-based accessibility guidelines through participatory research involving clinicians, human-computer interface experts, and disability communities. In order to ensure that the Metaverse lives up to its promise as a truly inclusive platform and to stop the reproduction of physical-world boundaries in digital places, such cooperative efforts are essential. We risk creating a virtual environment that reinforces and possibly intensifies current trends of digital exclusion if we don't take aggressive action at this critical juncture.

10.4 Environmental Impact and Energy Consumption

Improved internet connectivity and the expanding use of extended reality and digital twin (DT) technologies are changing how urban resource consumption is done. The need for real assets like office buildings, transit systems, and entertainment venues may decline significantly as people spend more time in virtual settings. As virtual equivalents take the place of some physical functions, this shift may result in less material being extracted and less energy being used for operations in traditional built settings. The environmental math is still complicated, though, as the Metaverse ecosystem creates new energy requirements for high-resolution rendering, data processing, and network maintenance, even as less use of energy-intensive physical infrastructure may result in sustainability benefits.

According to a recent study, fewer emissions from travel and less physical facility operating may somewhat offset the energy footprint of maintaining immersive digital worlds. Furthermore, the carbon intensity of virtual platforms may be reduced by the technology sector's rapid shift to renewable energy sources, as seen by pledges made by large firms. According to this changing dynamic, the overall environmental impact will rely on how energy-efficient virtual infrastructure is, how quickly renewable energy sources are adopted, and how much digital contact replaces rather than enhances physical activity. Therefore, it is imperative that urban policymakers create integrated sustainability frameworks that take into consideration the energy needs of sustaining digital infrastructure as well as the dematerialization potential of virtual surroundings.

10.5 Regulatory and Policy Frameworks

The integration of Metaverse technologies into smart city ecosystems presents complex legal and governance challenges that demand a balanced, multidimensional approach. At its core lies the tension between fostering innovation and establishing necessary regulatory safeguards, requiring policymakers to navigate jurisdictional ambiguities in hybrid physical-virtual spaces while addressing intellectual property rights and liability issues arising from user-generated content and virtual interactions. The transnational nature of Metaverse platforms fundamentally disrupts traditional legal paradigms, creating significant gaps in consumer protection, data sovereignty, and the enforcement of digital rights across borders. This situation calls for the development of participatory governance models that engage diverse stakeholders through transparent policymaking processes, allowing for the co-creation of standards that can keep pace with rapid technological evolution while protecting public interests.

A balanced, multifaceted strategy is required to address the numerous legal and governance issues raised by the integration of Metaverse technology into smart city ecosystems. Policymakers must handle jurisdictional ambiguities in hybrid physical-virtual spaces while addressing intellectual property rights and liability issues arising from user-generated content and virtual interactions. This is the fundamental conflict between promoting innovation and putting in place the necessary regulatory safeguards. Traditional legal paradigms are profoundly upended by the global character of Metaverse platforms, which results in serious gaps in data sovereignty, consumer protection, and cross-border enforcement of digital rights. In order to co-create standards that can defend the public interest while keeping up with the rapid advancement of technology, it is necessary to create participatory governance models that involve a variety of stakeholders through open policy making procedures.

11. Future Directions and Research Opportunities

11.1 Progress in MoT and Smart Infrastructure

The combination of the Metaverse of Things (MoT) with intelligent infrastructure is reshaping urban areas by promoting sustainability, improving operational efficiency, and enhancing citizen engagement. By merging IoT with metaverse technologies, cities can facilitate real-time data visualization and interactive urban design, which supports responsive and adaptive infrastructure development. Artificial Intelligence (AI) plays a crucial role in boosting smart city features by aiding predictive analytics, optimizing resource allocation, and providing personalized services. Furthermore, AI-driven customization encourages increased public involvement by tailoring governance services to individual preferences, fostering more inclusive and effective urban management.

11.2 AI-Enhanced Personalization in Urban Services

AI technologies are becoming increasingly vital for personalizing urban services, delivering better user experiences while optimizing resource allocation. In terms of mobility, AI-driven traffic management evaluates traffic trends, reducing congestion and improving transportation system efficiency. Likewise, AI supports the delivery of customized public services like healthcare and education by analyzing user preferences and data. This level of customization ensures that services remain relevant and responsive. Additionally, machine learning is employed to predict urban growth patterns, offering essential insights for strategic planning and infrastructure investments.

11.3 Creation of Sustainable Virtual Economies

The emergence of virtual economies within the metaverse offers significant potential for promoting sustainable development. Decentralized economic frameworks, backed by blockchain technology, are evolving as transparent and user-driven alternatives to conventional systems. These frameworks facilitate direct peer-to-peer transactions and community governance, transforming how value is generated and exchanged. Furthermore, virtual settings promote sustainable consumption habits by lessening dependence on tangible goods and encouraging digital substitutes, thus reducing environmental impact. The broader transition to digital economies affects sustainable development by modifying production and consumption behaviors, creating new employment opportunities, and advancing economic inclusivity in digital realms.

11.4 Promoting Inclusivity and Accessibility

As the metaverse advances, ensuring inclusivity and accessibility is crucial for enabling equal participation. Designing platforms with universal access in mind, including the incorporation of assistive technologies, allows individuals with disabilities to effectively navigate and interact with virtual spaces. Encouraging diversity through culturally inclusive avatars and digital settings contributes to building a more welcoming and representative virtual community. Moreover, tackling the digital divide is a significant priority, necessitating efforts to increase affordable internet access, enhance digital literacy, and provide essential devices and infrastructure to underserved communities. These approaches work together to ensure the metaverse serves as a means of empowerment rather than exclusion.

11.5 Recommendations for Policy and Standardization

The prudent advancement of the metaverse relies heavily on the creation of clear policies and standardized frameworks. Establishing technical standards is vital to guarantee interoperability, security, and uniformity across metaverse platforms. These standards facilitate seamless interactions among various virtual environments and protect user data. Governance frameworks are equally important to address ethical, legal, and societal concerns, such as digital identity verification, content moderation, and intellectual property rights. Furthermore, international cooperation is essential for harmonizing regulations and advocating best practices. By encouraging cross-border collaboration, stakeholders can jointly craft a metaverse that is secure, ethical, and inclusive on a global level.

12. Conclusion

The merging of the metaverse with the Internet of Things, creating the Metaverse of Things (MoT), holds significant promise for the evolution of sustainable smart cities. This paper has examined the theoretical underpinnings, supporting technologies, and practical implementations of this integration, providing an in-depth perspective on how immersive digital environments and connected devices can transform urban living. By enabling real-time data synchronization, engaging virtual experiences, and AI-informed personalization, MoT fosters improved urban planning, responsive public services, and active citizen participation.

Progress in smart infrastructure, bolstered by the combination of AI, IoT, and extended reality technologies, is paving the way for predictive, adaptable, and interactive systems that elevate the quality of life in urban environments. Virtual economies and digital governance frameworks are enhancing economic resilience and sustainability, while initiatives aimed at inclusivity strive to close social and digital gaps.

Nonetheless, the path to achieving genuinely sustainable smart cities through the metaverse presents various hurdles. Technical constraints, ethical dilemmas, and the environmental impacts of large-scale digital infrastructures necessitate thorough examination. Policy frameworks, standards for interoperability, and international cooperation will be crucial for securing, fair, and eco-friendly implementations. As urban areas continue to develop, the fusion of the metaverse and MoT unveils fresh opportunities for innovation in governance, education, transportation, healthcare, heritage conservation, and emergency management. Future investigations should concentrate on closing existing technological divides, enhancing regulatory frameworks, and creating scalable models that maintain a balance between innovation and sustainability.

List of Acronyms used in this manuscript.

Acronyms	**Definition**
ML	Machine Learning
AI	Artificial Intelligence
MoT	Metaverse of Things
VR	Virtual Reality
MR	Mixed Reality
AR	Augmented Reality
XR	Extended Reality

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