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Review

A Review of Urban Digital Twins Integration, Challenges, and Future Directions in Smart City Development

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Abstract: This review paper explores Urban Digital Twins (UDTs) and their crucial role in developing smarter cities, focusing on making urban areas more sustainable and well-planned. The methodology adopted an extensive literature review across multiple academic databases related to UDTs in smart cities, sustainability, and urban environments, conducted by a bibliometric analysis using VOSviewer to identify key research trends and qualitative analysis through thematic categorization. This paper shows how UDTs can significantly change how cities are managed and planned by examining examples from cities like Singapore and Dubai. This study points out the main hurdles like gathering data, connecting systems, handling vast amounts of information, and making different technologies work together. It also sheds light on what is missing in current research, such as the need for solid rules for using UDTs effectively, better cooperation between various city systems, and a deeper look into how UDTs affect society. To address research gaps, this study highlights the necessity of interdisciplinary collaboration. It also calls for establishing comprehensive models, universal standards, and comparative studies among traditional and UDT methods. Finally, it encourages industry, policymakers, and academics to join forces in realizing sustainable, smart cities.

Keywords: environmental sustainability; artificial intelligence; smart cities; sustainable urban planning; data integration; edge computing; multidisciplinary collaboration

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1. Introduction

The concept of Digital Twins (DTs), particularly in urban settings, has surged to prominence recently, propelled by their potential to revolutionize the planning of smart city infrastructures for enhanced environmental sustainability [1]. Defined as a live virtual model that mirrors a physical system, including its surroundings and operational processes, DTs facilitate a continuous flow of data between the virtual and physical worlds, enriching the understanding and management of urban ecosystems [2]. The proliferation of UDTs draws heavily from advancements in smart city technologies, positioning UDTs as a cornerstone for in-depth analysis and modeling of urban physical systems (Figure 1).

This integration is particularly impactful in the sphere of environmental sustainability, where UDTs, in conjunction with technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and Big Data (BD), herald a new era for sustainable urban design and planning [1].

Since their introduction in the early 21st century, DTs have seen a surge in adoption, facilitated by the swift integration of digital infrastructure and data-centric technologies within urban landscapes [3]. Despite their application across diverse sectors—from transportation to health monitoring—the essence of DTs lies in providing a simplified yet functional representation of complex real-world systems. DTs, and by extension UDTs, embody a transformative approach to urban system modeling [1]. This approach prioritizes strategic simplification and functionality over exhaustive replication, aiming to enhance multiple urban domains, including planning, infrastructure management, and disaster response [4].

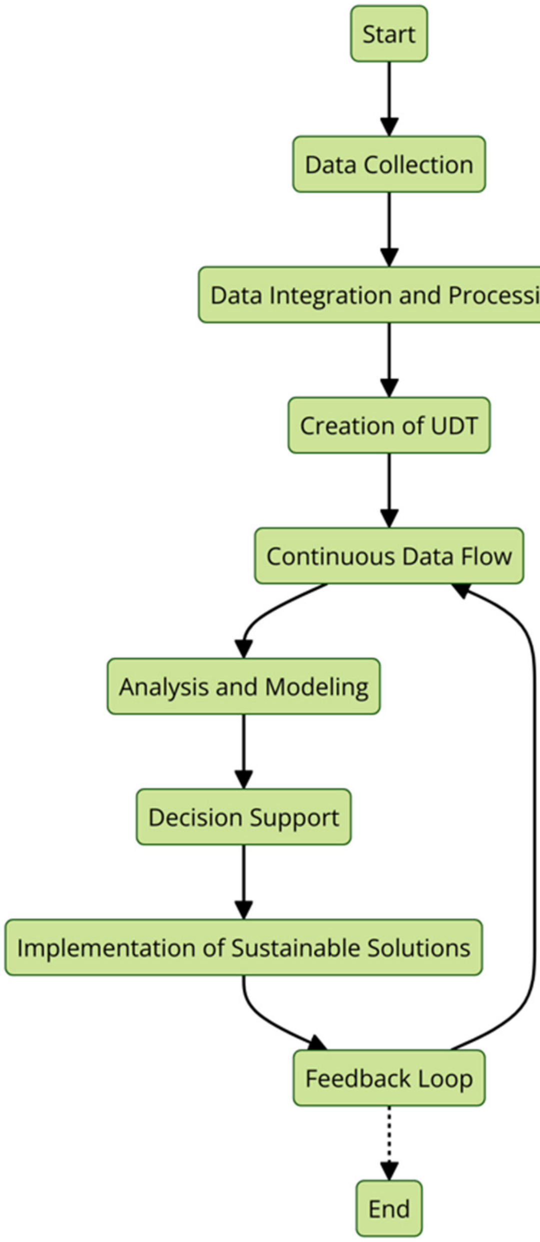

Figure 1. Framework for Urban Digital Twins, detailing the progression from data collection to implementing sustainable solutions within a smart city framework.

In the digital age, UDTs have positioned themselves as a critical metaphor within sustainable smart cities, likened to concepts such as 'city brain' and 'platform urbanism' [5]. It highlights UDTs' advanced modeling and simulation capabilities in developing innovative solutions for environmental sustainability [1]. This shift towards a UDT-empowered approach in urban management and planning represents a broader ambition to redefine smart cities as sustainable ecosystems [6]. These ecosystems aim to leverage Information and Communications Technology (ICT) and other innovative tools to improve urban life and operational efficiency and safeguard future generations' well-being in line with sustainability goals [7].

Moreover, the collaboration between UDTs and emerging technologies like BIM, ML, IoT, and drones is forging new paths for urban sustainability [8]. This partnership enhances the granularity and responsiveness of UDT models, allowing for the simulation of urban dynamics with unparalleled accuracy and detail [9]. Such comprehensive modeling is crucial for imagining sustainable urban futures, facilitating informed decision making, and shaping policy development [9].

According to White et al. [10], information is layered to create a comprehensive and dynamic model in the development of a digital twin for a smart city. The model encompasses six layers that progressively add depth and detail about the city's buildings, terrain, infrastructure, IoT devices, mobility, and the overarching digital layer.

This structure allows for an intricate simulation of urban life, from the basic terrain layer, detailing the natural and constructed geography, to the sophisticated digital layer that collects city-wide data for analysis and simulation in the Virtual Layer or Digital Twin. These simulations can address various urban challenges, including mobility optimization, infrastructure placement, and renewable energy projects, with outcomes directly influencing physical implementations within the city. Each layer, therefore, serves as a foundational block, contributing vital information that, when processed through the Digital Twin, enables a feedback loop that continually enhances urban spaces' physical and digital harmony.

However, despite the promising trajectory of UDTs, research in this domain is still developing, often focusing narrowly on particular urban challenges. The current status of the research highlights the need for systematically exploring UDTs' diverse challenges and opportunities within the sustainable smart city framework (Figure 1). This study seeks to provide an in-depth review of the current state of UDT studies, highlighting the main challenges connected with their integration into smart cities and exploring future advancements. The research questions driving this study are the following:

1. How can UDTs overcome technical, social, and regulatory barriers to create more sustainable urban environments?
2. What role will the emerging field of UDTs, combined with growing technologies such as the IoT, AI, and BD, play in this transformation?
3. Can we combine all the extraordinary challenges emerging worldwide and base them on the UDT to create dynamic and responsive urban management systems that support sustainable growth?

The research aims to shed light on UDTs' future direction in enhancing the development of sustainable smart cities, advocating for a collaborative effort among academia, industry, and governance to fully realize UDTs' potential in shaping the urban landscapes of tomorrow.

Smart City Development

In recent decades modern urban management approaches have been adopted by municipalities in response to a number of growing variables, including the persistent shortage of data, the increasing impact of Information and Communication Technologies (ICT), and the increasing importance of incorporating transportation and engineering networks into a single management system. Introducing digital technologies based on energy-saving techniques, creating effective systems for processing and disposing of trash, and implementing e-governance platforms to automate administrative functions and infrastructure control are some important responses to these challenges of growing contemporary cities [11].

These efforts are the main objectives of contemporary urban development, including fulfilling the growing demand for public services, improving quality of life, and safeguarding socioeconomic levels. The "smart city" concept has become a key foundation for the growth of large and medium-sized cities in recent years. The objective of smart city initiatives is to manage and optimize infrastructure, including public utilities, transit networks, and services for the general public, through the use of technological innovations and digital tools. This integration reduces operating costs, improves resource efficiency, and improves service delivery to citizens.

Urban settings require creative, tech-driven solutions even more since urbanization is predicted to worsen, and city population densities will climb dramatically by 2050 [12]. With a focus on using technology to push forward urban growth and development, initiatives related to smart cities aim to establish new interactions among stakeholders [13]. Roads, bridges, subways, airports, ports, water supply, and drainage systems are just a few of the infrastructure components that make up the Smart City model [14,15]. These components are all interconnected to optimize city resources, improve service quality, and ensure sustainability. Using a coordinated approach, resilient neighborhoods can be developed more effectively by integrating business, social interactions, IT, and environmental infrastructure.

The intelligent use of digital information to address resource consumption, investment in social capital and human resources, and the fast progress of intellectual infrastructure is what contributes to the Smart Cities' development. By embracing the Internet to assist companies, provide employment, and empower individuals through data exchange, smart cities promote social integration. Smart Cities improve urban settings by utilizing data-driven decision making on garbage disposal, housing, renewable energy integration, and ecological challenges. Furthermore, e-government initiatives are aligned with behavioral economics and social investment and supported by this digital foundation.

ICT companies contribute significantly to the development of Smart City programs as they work with local governments to offer technological solutions. Building smart societies, delivering tailored assistance in public administration, education, and citizen participation in the rise of technology could represent the primary objectives of future urban development. Smart City features aspire to boost the quality of life and city branding by constructing comfortable, efficient urban neighborhoods. At the same time, growth leads to congested towns and a lower standard of life.

The idea of "smart governance", which integrates technology, society, and government to improve urban living in areas involving economics, mobility, environment, and healthcare, has recently gained popularity. Smart Cities develop in phases, with Smart City 3.0 focusing on improving the life quality for residents by using "smart" solutions that maximize efficiency and resources [16].

Digital transformation transforms organizations and society through data, new business models, and technology breakthroughs. This shift is essential for improving worker productivity, optimizing economic structures, and promoting socioeconomic growth. Effective digital transformation necessitates coordinated policy initiatives across access, innovation, social prosperity, and market openness to achieve a comprehensive approach to implementing Smart City principles.

In response to growing urban challenges such as resource shortages, the impact of ICT, and the need for integrated management systems, cities have adopted smart city initiatives that use digital technologies to optimize city growth and create resilient, sustainable, and efficient urban environments.

What is the present status of research on smart cities and smart technologies, specifically UDTs? How can these technologies effectively address urban challenges in light of the fast-emerging urban digital transformations?

2. Materials and Methods

2.1. Literature Collection

To construct a comprehensive foundation for these questions, an extensive literature review search was conducted across several academic databases, including Web of Science, Scopus, IEEE Xplore, and Google Scholar (Figure 2). The search strategy employed a combination of keywords and phrases to capture the breadth of UDT research.

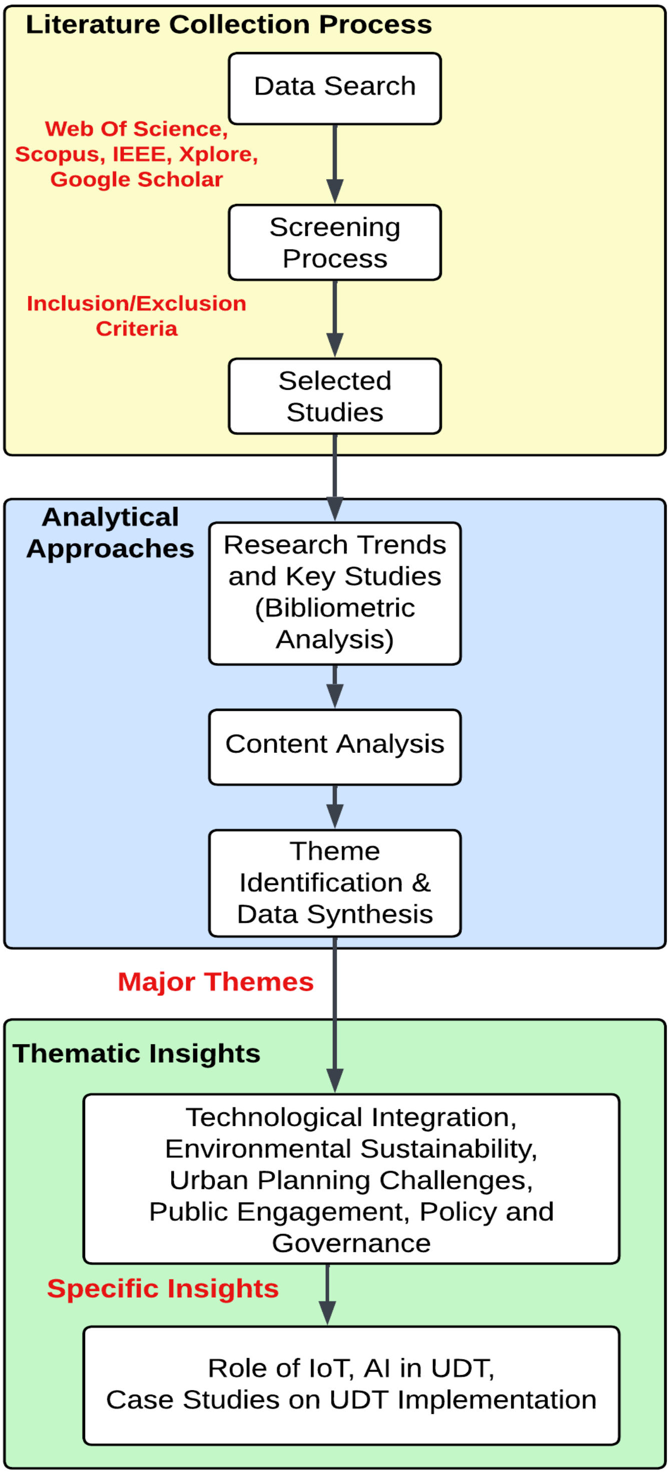

Figure 2. Framework for the methodology of the proposed literature review.

An expanded set of keywords and phrases has been selected to ensure a comprehensive exploration of the literature surrounding UDTs and their integration into smart cities with a focus on sustainability and urban planning. These include "Urban Digital Twin Applications", "Digital Twin Technology in Urban Development", "Sustainable Urban Design AND Digital Twins", and "Smart City Infrastructure AND Digital Twins", among others. The selection further encompasses keywords like "Integration of BIM and Digital Twins in Smart Cities", "AI Enhancements in Urban Digital Twins", "IoT Solutions AND Urban Digital Twins", and "Digital Twin Adoption in Urban Environments", aiming to cover a wide array of subtopics from energy efficiency, smart urban mobility, and water management to disaster management and public engagement in smart cities. This broadened keyword strategy is designed to encapsulate the diverse facets of UDT research, ensuring that the literature review spans the full spectrum of technology implementations, sustainability considerations, and planning methodologies within the evolving urban landscapes. Out of that, the first search found 371 documents.

Moreover, the inclusion criteria involved studies published in English from January 2005 to March 2024, reflecting the recent surge in UDT research. Studies were selected based on their relevance to UDTs' development, application, and impact in urban environments, specifically focusing on environmental sustainability (Table 1).

Table 1. Detailed Inclusion Criteria.

Criteria	Inclusion	Rationale for Inclusion
Time Frame	January 2005 to March 2024	Focuses on capturing the evolution of UDTs and related technologies in the last decade, reflecting current trends and advancements.
Language	English	Facilitates broader accessibility and ensures the review can serve as a global resource.
Relevance	Studies primarily focus on UDT applications within smart cities, particularly emphasizing environmental sustainability.	Ensures direct relevance to the scope of urban sustainability and smart city development.
Technological Focus	Studies integrating AI, BIM, and IoT within the framework of UDTs for smart cities.	Targets research that contributes to understanding how specific technologies (AI, BIM, IoT) enhance UDT applications in smart cities.
Publication Type	Ranked journal articles, book chapters and conference proceedings.	Prioritizes high-quality, scholarly research that undergoes peer review, ensuring credibility and reliability.
Application Domain	Papers detailing the use of UDTs and DTs in applications such as urban planning, infrastructure management, environmental monitoring, and public services.	Highlights studies demonstrating UDTs' practical application and impact in urban environments.
Methodological Rigor	Studies employing robust quantitative, qualitative, or mixed methods research designs and clear methodologies.	Ensures the inclusion of research that provides substantive insights and evidence-based conclusions on UDTs.
Interdisciplinary Approach	Studies that demonstrate an interdisciplinary approach, combining insights from urban planning, environmental science, computer science, and engineering.	Encourages a comprehensive understanding of UDTs by drawing from diverse fields and perspectives.

Exclusion criteria were applied to filter out non-academic articles, opinion pieces, and studies that focused on DT technology outside the urban context or those not addressing sustainability aspects. The final selection encompassed peer-reviewed journal articles, book chapters, and conference proceedings that provided insights into UDTs' challenges, applications, and theoretical advancements. Hence, the related documents have been reduced to 129 documents.

2.2. VOSviewer Analysis

VOSviewer software 1.6.20 was utilized for the bibliometric analysis to visualize the network of publications, co-citation patterns, and the clustering of themes within the UDT literature. This analysis facilitated the identification of key research trends, the most influential studies, and the evolution of research themes over time. The process began with the extraction of bibliometric data from the selected articles, including publication year, authors, institutions, countries, and keywords. The software tools then mapped these data points to reveal the structure of the research domain, highlighting the relationships between different studies and pinpointing emerging areas of focus within the UDT and smart cities research landscape.

2.3. Qualitative Approach

A qualitative approach in context analyses was adopted to integrate the findings from the literature, utilizing a thematic analysis framework to categorize the content into coherent themes. This involved a detailed review of the selected studies to extract information on the challenges identified in UDT development and implementation, the solutions proposed, and notable case studies that exemplify the practical applications of UDTs in enhancing urban sustainability. The analysis aimed to collect vast research findings into actionable insights, focusing on how UDTs can be provided to address specific urban sustainability challenges. The case studies, in particular, provided a grounded understanding of UDTs' potential impacts and the practical considerations in deploying these systems in real-world settings. Through this methodical examination, this review highlights the critical areas for future research and the strategic directions for advancing UDTs in sustainable smart cities.

3. Bibliometric Analysis

The bibliometric analysis serves as a cornerstone for understanding the evolution and current landscape of research within the given field. This section delves into the multifaceted dimensions of scholarly publications, offering insights into the trends that shape the domain's trajectory. The search begins by examining the publication trend, which maps the volume and frequency of research outputs over time. It probes into the research gaps, identifying areas that, despite their importance, have received relatively less attention. Furthermore, the section sheds light on the pivotal contributors to the field, spotlighting top journals whose work has significantly influenced the direction and quality of research.

3.1. Publications Trend

As shown in Figure 3, the number of publications on the subject has risen dramatically over the past two decades Figure 3.

Commencing with a modest scattering of articles in 2005, there has been a noticeable surge in scholarly interest, culminating in an impressive peak by 2023. The years leading up to this zenith, particularly from 2020 onwards, have been characterized by a steep and sustained increase in output. This suggests that the area under investigation has garnered significant attention, potentially due to breakthroughs, regulatory shifts, or a pivotal event that has propelled the scholarly community into action. While the data for 2024 are not yet complete, the trend persists, indicating ongoing engagement with the topic and its continued relevance within the academic landscape.

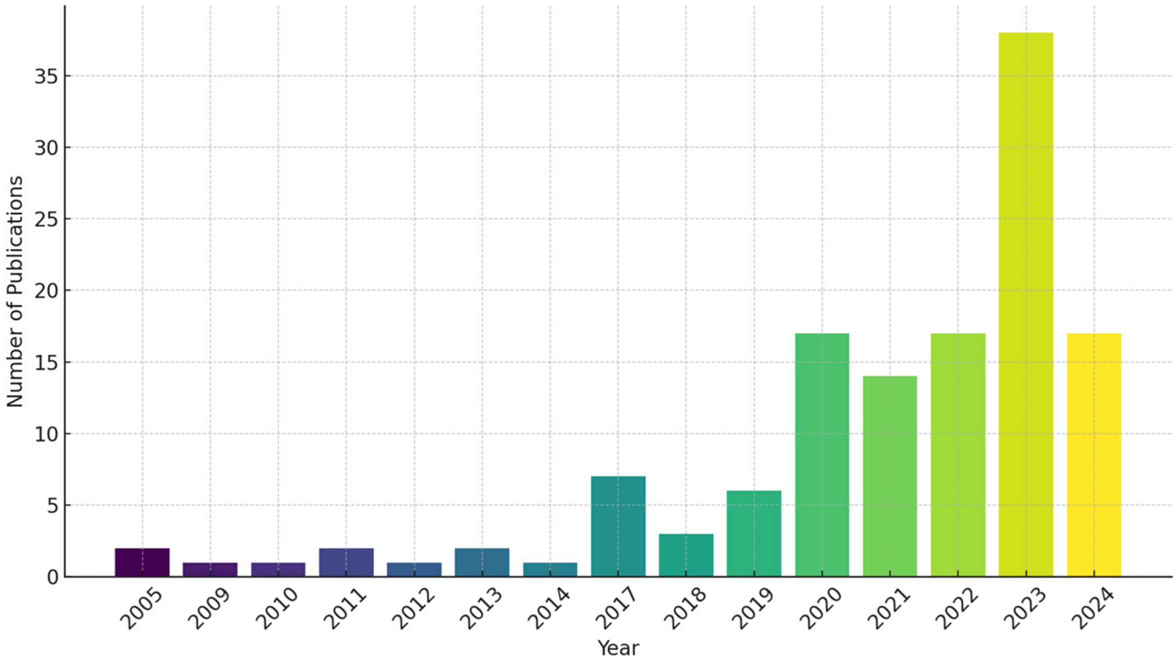

Figure 3. The trend of publications over time.

3.2. Leading Academic Journals in the Field

Within the landscape of research dissemination, the prominence of certain academic journals becomes apparent when considering the distribution of publications. Figure 4 delineates this, ranking the top 10 journals as stated by the number of publications.

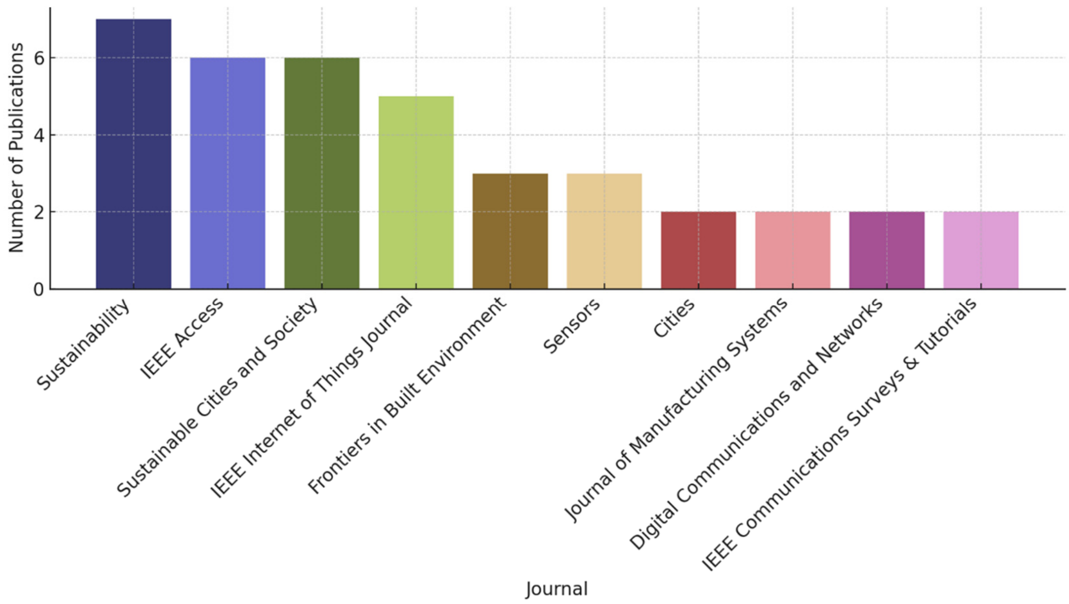

Figure 4. Top 10 journals.

The data captured in this visualization allows us to discern these journals' pivotal role in shaping the field's discourse. It becomes evident that journals such as 'Sustainability' and 'IEEE Access' lead the pack with the highest number of published articles, suggesting their centrality to the dissemination of new findings and theories. Other noteworthy journals follow, each contributing significantly to the spread of knowledge within the academic community. This chart reflects the output of these journals and implicitly suggests the areas within the field that are receiving the most attention, guiding researchers toward the most influential platforms for their work.

3.3. Interconnectivity and Emerging Trends in Research

The intricate web of terms presented in the visual network captures the interconnected nature of current research themes. Lines weaving through the diagram represent thematic ties between various concepts, signifying the extent to which areas such as 'smart cities', 'internet of things', and 'artificial intelligence' overlap and influence each other using VOSViewer [17] based on the documents chosen to review (Figure 5). The color coding of these lines denotes different clusters of interconnected topics, suggesting areas of research that are frequently explored in tandem, such as 'digital twin' and 'IoT', which may be seen within the same color spectrum.

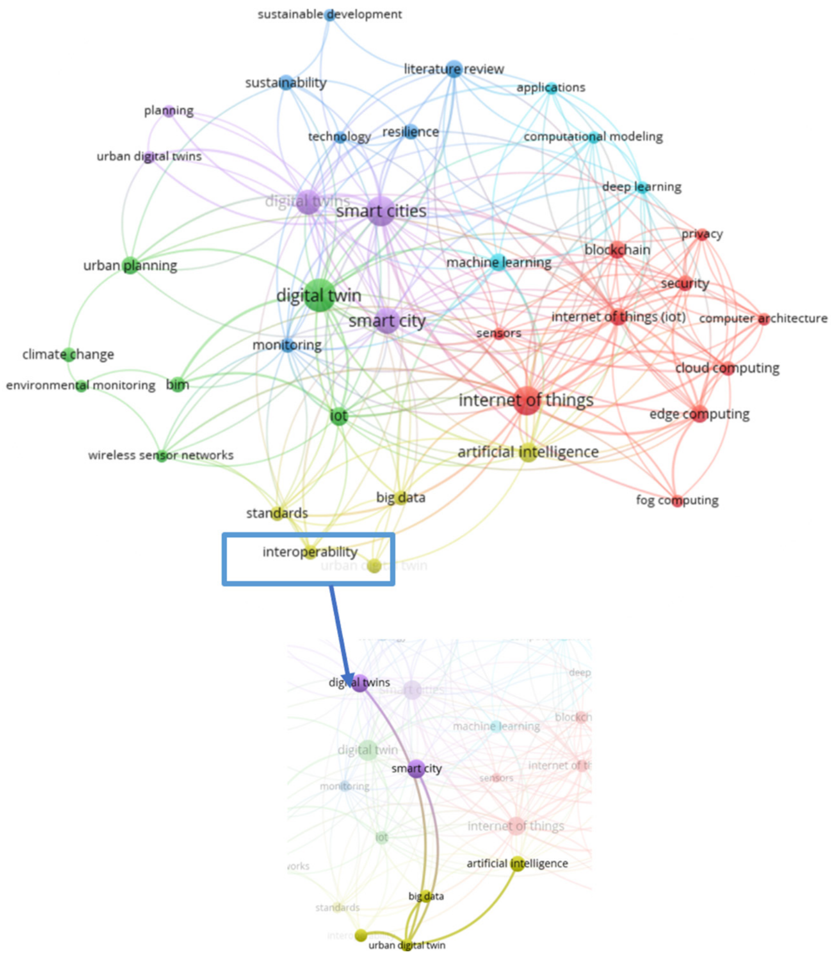

Figure 5. Conceptual network map using VOSViewer depicting the interconnections between various research themes related to urban and smart cities based on Google Scholar, Scopus, Web of Science, and IEEE Xplore.

In this network, the size of each circle corresponds to the volume of research dedicated to each topic, with smaller circles indicating less investigated areas. These underrepresented topics highlight the gaps within the field, offering guidance on where future research could be most impactful. This visual analysis provides a structured overview of these research gaps (Table 2). These circles may be key to novel discoveries and advancements, beckoning the scholarly community to venture into less-trodden paths. Thus, the visual representation reflects the current state of research and strategically directs attention to the fertile ground for new inquiries and explorations.

Table 2. Overview of the research gaps based on the VOSViewer analysis.

Research Gap	Explanation
Fog Computing	Less discussed within smart city literature, it focuses on efficiency and data processing at the network's edge.
Wireless Sensor Networks	Crucial for data collection; potentially under-discussed in their role within smart city data integration and synthesis.
Environmental Monitoring	May need more focus on how smart cities interact with and impact the natural environment.
BIM (Building et al.)	Despite its potential to improve building construction and management efficiency, it needs to be explored better in the smart cities' context.
Climate Change	The interaction between smart city initiatives and climate change adaptation or mitigation may be a less explored area.
Urban Digital Twin	While digital twins are a discussed concept, UDTs' specific applications and implications in smart cities could represent a research gap.
Standards and Interoperability	Critical implementation of smart city technologies, but potentially less prominently discussed than the technologies themselves.
Nanosensors in UDTs	As mentioned minimally, nanosensors in UDTs could provide unprecedented monitoring details, but these have yet to be widely discussed.
Socio-technical Analyses	Identified as a gap, the interaction between society and technology in smart cities requires more in-depth analysis.
Public Engagement	Limited discussion was found; engagement strategies and the role of the public in shaping smart city initiatives are areas that need more research.
Policy and Governance	According to the database search, although crucial, policy and governance in the smart cities' context are less emphasized in the literature.

4. Content Analysis

4.1. Intersections and Synergies

The intersection and synergy between various advanced technologies and UDTs are pivotal in driving the evolution of smart cities toward achieving sustainable development goals [18]. The combination of Building Information Modeling (BIM), Machine Learning (ML), the IoT, and drones with UDTs exemplifies a multifaceted approach to urban planning that enhances the efficiency of urban systems and contributes to the resilience and sustainability of urban environments [9]. Each technology brings a unique set of capabilities that, when harmonized within the UDT framework, enables a more comprehensive and dynamic understanding of urban ecosystems [8]. For instance, BIM's detailed spatial and material data contribute to accurately modeling urban infrastructures within UDTs, facilitating better decision making regarding construction, maintenance, and energy consumption [19].

Conversely, ML introduces predictive analytics and data-driven insights to the UDT ecosystem [6]. ML algorithms can forecast urban dynamics such as traffic flow, energy demand, and environmental impacts by analyzing patterns from vast datasets collected via IoT devices and other sources [20]. This predictive capability allows city planners and policymakers to anticipate future challenges and opportunities, leading to more proactive and informed urban management. Thus, ML integration within UDTs stands as a cornerstone for developing adaptive and intelligent urban systems that can evolve in response to changing conditions and requirements [21].

Furthermore, the IoT has a critical role in realizing the full potential of UDTs by ensuring a continuous stream of real-time data from various urban components [1]. IoT sensors and devices embedded throughout the urban fabric provide live updates on various parameters, from air quality and noise levels to water usage and traffic conditions [22]. This constant influx of data enriches UDT models with actionable insights, enabling real-time monitoring and management of urban environments [23]. The seamless integration of IoT with UDTs creates an interactive model of the city, which can be used to simulate the effects of different urban interventions before they are implemented, thereby optimizing urban operations and improving the quality of life for residents [24].

Moreover, the deployment of drones complements the data collection and monitoring capabilities of IoT and ML within the UDT framework [25]. Drones offer a versatile aerial surveying, mapping, and inspection platform, providing valuable perspectives that ground-based IoT devices cannot capture [26]. They can quickly gather data on hard-to-reach areas, monitor the progress of infrastructure projects, and assess the impact of natural disasters [27]. When integrated with UDTs, the aerial insights from drones enrich the urban model with high-resolution imagery and topographical data, facilitating more accurate simulations and analyses [18]. Through the synergistic integration of BIM, ML, IoT, and drones, UDTs become a powerful tool for enhancing urban planning and advancing sustainable development goals, demonstrating the transformative potential of technological convergence in shaping future cities [28].

4.2. Challenges and Proposed Solutions

This subsection explores the multifaceted dimensions of advancing DT technology, specifically focusing on the intricacies of data collection, connectivity, computing power, and interoperability within smart cities and healthcare frameworks [29]. Table 3 shows the current challenges and proposed solutions in UDT technology with data collection technologies, as highlighted in recent research across various domains, including smart cities, healthcare, and more. The subsequent subsections will explore these topics in greater detail, exploring the importance of each challenge, the practicality of proposed solutions, and the future outlook of digital twin technologies as informed by the latest scholarly contributions (Table 3).

Table 3. Challenges and proposed solutions in advancing UDTs with data collection technologies.

Challenges	Proposed Solutions	Key References
Data Collection for DTs in Smart Cities and Healthcare: - Integration of diverse data collection technologies. - Real-time data analytics and processing. - Sensor data overload and multitasking conflicts.	- Utilization of edge and fog computing to manage data flow. - Adoption of AI for efficient data collection and processing. - Enhancing sensor capabilities to support comprehensive data sets.	[30,31]
Data Connectivity in DT-Supported Smart Cities: - Interoperability issues among different data domains. - Complexities in data exchange and infrastructure demands.	- Implementation of cross-domain data mining. - Development of a standardized data framework. - Exploration of 5G and edge - cloud computing for enhanced data sharing.	[32,33]

Table 3. *Cont.*

Challenges	Proposed Solutions	Key References
Computing Challenges in DT-Supported Smart Cities: - Need for real-time data analysis and visualization. - High computing power demand for complex simulations.	- Edge computing is adopted for decentralized data processing. - Integration of cloud computing for scalable resources. - Fog computing is utilized for a hybrid solution.	[34,35]
Interoperability Challenges in DT-Supported Smart Cities (SCs): - Disparate data formats and standards. - Lack of universal protocols for data exchange.	- Establishment of open data standards and APIs. - Adoption of semantic web technologies for data integration. - Implementation of service-oriented architecture for system communication.	[36–38]

4.2.1. Advancing UDTs with Data Collection Technologies

Digital twin (DT) technology, essentially a sophisticated computer program, provides real-world data to simulate how various entities, from products to processes, will perform [33]. This capability necessitates gathering extensive data from the physical counterpart to accurately mirror it within a virtual environment [39]. Such data encompasses various operational facets, including production, maintenance, and business operations [39]. The process of creating and continuously updating digital models within a DT framework heavily relies on data collection through sensors from the object or its environment [40]. In smart transportation systems, for example, GPS sensors are predominantly utilized to gather critical data about passengers and vehicles [41]. However, the limitations of GPS technology in capturing comprehensive data sets, such as acceleration or magnetic fields, have led to the integration of additional tools like Inertial Measurement Units (IMUs) to fill these gaps [42]. Moreover, to overcome the reliance on historical data and include real-time analytics, newer methodologies have been employed to collect and process data from multi-networked environments, enhancing traffic forecasting systems [43].

The advent of wireless sensors in wearable devices has notably advanced health monitoring by collecting data on individuals' physical conditions, thereby rendering health surveillance more intelligent and responsive [44]. When integrated with Geographic Information Systems (GISs), this data offers valuable insights into the spatial distribution of health-related issues, such as identifying stress hotspots among the elderly population [45]. Beyond health, BIM technology has facilitated data collection for DT-supported Smart Cities (SCs), especially in disaster prevention and mitigation [46]. Combining BIM with IoT technology can establish an intelligent monitoring system capable of real-time, precise observations [47]. Integrating BIM and IoT extends further into environmental monitoring and enhancing user experiences on smart campuses by detecting emotional responses to the environment, thus providing actionable insights into comfort levels and urban livability [48].

While the integration of various technologies has significantly bolstered the capability of DTs in smart cities, challenges remain, particularly in data collection and sensor processing [49]. The issue of sensors being overwhelmed by simultaneous data requests from multiple systems has prompted the exploration of edge and fog computing solutions to alleviate data congestion and ensure seamless data flow [50]. Moreover, incorporating AI into smart sensors has emerged as a solution to multitasking conflicts, enhancing the efficiency of data collection across distributed systems [51]. However, alongside the technological advancements in data collection and processing, security and privacy concerns in DT-supported SCs have become increasingly prominent, necessitating rigorous attention to developing robust frameworks to safeguard sensitive information [51].

4.2.2. Data Connectivity Challenges in DT-Supported Smart Cities

In the field of DTs for cities, data connectivity emerges as a foundational element crucial for ensuring seamless interoperability among systems spanning various domains [2]. Interoperability issues often arise due to the distribution of data across disparate industrial platforms, presenting significant challenges in creating a cohesive DT-supported data ecosystem [52]. Efforts to bridge the gaps between differing data domains have led to innovative approaches, such as cross-domain data mining, to enhance compatibility and facilitate comprehensive urban models [53]. These endeavors underscore the necessity of a standardized framework to enable efficient data sharing within individual cities and across them, fostering a learning ecosystem among SCs [54–56]. However, achieving such interoperability poses substantial obstacles, necessitating models that can universally apply across diverse urban settings, thereby laying the groundwork for interconnected DT-supported SC modeling [46].

The efficiency of data sharing in DT-supported SCs is paramount, given the vast quantities of information that must be communicated [46]. Advanced technologies, including 5G, have been identified as potential accelerators of data exchange within DT environments, promising to enhance the speed and efficiency of information dissemination [57]. However, implementing 5G technology introduces complexities, such as increased infrastructure demands and compatibility issues, which could hinder its adoption [58]. Alternative strategies like edge-cloud computing are being explored to optimize knowledge sharing within DT frameworks, aiming to alleviate the computational burden and ensure timely and effective data exchange [59]. These technological solutions, while promising, confront challenges related to cost, complexity, and interoperability, highlighting the ongoing struggle to streamline data connectivity in SCs [60].

Security and privacy concerns further complicate the landscape of data sharing within DT systems [61]. Blockchain technology has emerged as a leading solution, offering a secure and decentralized platform for data exchange, crucial for protecting sensitive [62] information in interconnected urban environments [63]. Innovative privacy models [64] leveraging blockchain enable selective data sharing, enhancing the security of the Internet of Vehicles [65] (IoV) and other edge network applications [66]. Despite these advancements, the integration of blockchain with existing SC technologies requires careful consideration of data processing capabilities and the need for real-time analysis [67]. Challenges persist in balancing data privacy and security demands with the need for efficient, large-scale data utilization in DT-supported SCs, underscoring the complexity of creating secure and interoperable digital urban ecosystems [68].

4.2.3. Overcoming Computing Challenges in DT-Supported Smart Cities

As SCs evolve, the computational demands for processing, analyzing, and storing vast amounts of data from diverse sources, including IoT devices, sensors, and systems across the urban landscape, escalate significantly [69]. The challenge arises from the need to perform real-time data analysis and visualization, support complex simulations, and enable intelligent decision-making processes, all requiring substantial computing resources [70]. This demand stretches beyond the capabilities of traditional computing infrastructure, leading to potential bottlenecks in data processing, delayed decision making, and reduced efficiency in urban management systems [71].

Addressing the computing power challenge necessitates innovative solutions providing advanced technologies [72]. One such solution is the adoption of edge computing, which decentralizes data processing by performing it closer to the data source, thereby reducing latency, minimizing data transmission costs, and alleviating the load on central computing resources. Edge computing's proximity to data sources allows for quicker response times and supports the real-time functionality essential for DT applications in SCs [73]. Another approach is the integration of cloud computing, which offers scalable and flexible computing resources that can be adjusted based on the demands of the DT system [74]. Cloud computing facilitates the storage and analysis of large datasets, empowering DTs with the capacity to harness BD for urban planning and operational efficiency [75].

Furthermore, the implementation of fog computing presents a hybrid solution that bridges the gap between edge and cloud computing [76]. Fog computing enables data processing to be distributed in a hierarchical manner, offering a balance between the immediacy of computing edge and the expansive power of cloud computing [77]. This model ensures efficient data handling, supports advanced analytics, and maintains the integrity of real-time applications within SCs [78]. Additionally, providing advancements in AI and ML can optimize data processing workflows, automate complex analyses, and predict urban system behaviors, thus efficiently utilizing available computing resources [79]. To fully harness these technologies, ongoing research and development, alongside investments in upgrading digital infrastructure, are crucial for overcoming the computing power challenges inherent in DT-supported SCs, paving the way for smarter, more efficient, and more responsive urban environments [80].

4.2.4. Overcoming Interoperability Challenges in DT-Supported SCs

In SCs, systems from different domains, such as transportation, energy, healthcare, and public services, rely on interoperable data exchange to function cohesively [81]. The challenge arises from the disparate data formats, protocols, and standards used across these systems, hindering data's efficient sharing and utilization [46]. This lack of interoperability complicates the development of a unified DT model that can accurately represent and simulate the variety in nature of urban environments, thereby limiting the potential of DTs to improve urban planning, management, and decision-making processes [82].

Addressing system interoperability requires a multifaceted approach encompassing the development and adoption of universal standards and protocols [83]. One such solution is the establishment of open data standards that ensure compatibility and facilitate smooth data exchange between different systems and platforms [84]. Construction Operations Building Information Exchange (COBie) and the Industry Foundation Classes (IFC) Standards for BIM, are examples of efforts to standardize data formats in specific domains [85]. Expanding these standards to cover a broader range of urban systems could significantly enhance interoperability in SCs [85]. Additionally, presenting Application Programming Interfaces (APIs) that act as intermediaries, allowing disparate systems to communicate and share data efficiently, can play a crucial role in overcoming interoperability challenges [86].

Another promising approach is the adoption of semantic web technologies and ontologies, which provide a framework for data integration and interoperability by defining standardized vocabularies and relationships between different data elements [87]. These technologies enable different systems to understand and interpret the meaning of shared data, thus facilitating seamless data exchange and integration [87]. Furthermore, adopting service-oriented architecture (SOA) and microservices can enhance system interoperability by decomposing complex systems into smaller, loosely coupled services that can interact and communicate through well-defined interfaces [88]. Through these strategic approaches, including the adoption of standards, APIs, semantic technologies, and microservices, DT-supported SCs can overcome interoperability challenges, enabling more integrated, efficient, and responsive urban management systems [80].

4.2.5. Enhancing DT-SCs: Public Engagement, Policy, and Governance Challenges

Engaging the public effectively requires transparent communication channels and participatory mechanisms that allow citizens to contribute to the planning and decision-making processes [89]. The challenge lies in developing systems that gather feedback from diverse urban populations and integrate this feedback into the DT models to reflect community needs accurately [90]. Policy and governance frameworks must also evolve to address the rapid advancements in DT technologies, ensuring that they foster innovation while protecting citizens' privacy and security [91].

To enhance public engagement, policy, and governance in DT-supported SCs, a multi-faceted strategy incorporating digital platforms for citizen participation, policy development guided by ethical considerations, and adaptive governance structures is essential [68]. Digital participation platforms can facilitate two-way communication between city officials and citizens, enabling real-time feedback, suggestions, and collaborative problem solving [92]. These platforms should be designed to be inclusive and accessible, ensuring that all community members have the opportunity to contribute [92]. Furthermore, policies governing the deployment and operation of DTs in SCs need to be developed with a focus on ethical standards, data protection, and privacy to build public trust and support [93]. Establishing clear data usage, sharing, and security guidelines can help mitigate privacy concerns and enhance the societal acceptance of DT technologies [94].

Adaptive governance structures are crucial for navigating the complexities of DT implementation in urban environments [95]. Such structures should promote collaboration across different sectors and levels of government, facilitating the integration of DTs into existing urban systems and policies [96]. Governance frameworks should also be flexible enough to accommodate emerging technologies and adapt to the dynamic needs of urban populations [97,98]. Moreover, establishing public advisory boards and including citizen representatives in decision making can ensure DT projects align with public values and priorities [99]. DT-supported SCs can achieve sustainable urban development that reflects the collective vision and needs of their communities, thereby fostering a more democratic and participatory urban future by focusing on robust public engagement mechanisms, ethical policy development, and adaptive governance [99–102] (Table 4).

Table 4. The challenges and proposed solutions related to Digital Twin (DT) technology in smart cities (SCs).

Aspect	Challenges	Proposed Solutions	Technologies Involved	Impact on Smart Cities (SCs)
Advancing UDT with Data Collection Technologies	Gathering extensive real-world data is challenging due to technological limitations (e.g., GPS's limitations) and the need for real-time analytics.	We are integrating additional tools like IMUs, employing methodologies for real-time data collection from multi-networked environments.	GPS, IMUs, GIS, BIM, IoT, AI in smart sensors	Enhanced traffic forecasting, health monitoring, disaster prevention, and urban livability.
Data Connectivity Challenges in DT-Supported SCs	Issues with interoperability due to data distribution across different platforms and the complexity of implementing 5G technology.	Cross-domain data mining, standardized frameworks for data sharing, edge-cloud computing, and blockchain for secure data exchange.	5G, Blockchain, Edge-Cloud Computing	Improved data sharing efficiency, secure and decentralized data exchange, fostering a learning ecosystem among SCs.
Overcoming Computing Challenges in DT-Supported SCs	The necessity for real-time data analysis and visualization exceeds traditional computing infrastructure's capabilities.	Adoption of edge computing, cloud computing, fog computing, and advancements in AI and ML for optimizing data workflows.	Edge Computing, Cloud Computing, Fog Computing, AI, ML	Smarter, more efficient, and responsive urban management through reduced latency and advanced analytics.

Table 4. *Cont.*

Aspect	Challenges	Proposed Solutions	Technologies Involved	Impact on Smart Cities (SCs)
Overcoming Interoperability Challenges in DT-Supported SCs	Disparate data formats, protocols, and standards used across various systems hinder efficient data sharing and utilization.	Development and adoption of universal standards and protocols, APIs, semantic web technologies, and microservices.	COBie, IFC, APIs, Semantic Web Technologies	More integrated, efficient, and responsive urban management systems through enhanced data exchange and system communication.
Enhancing DT-SCs: Public Engagement, Policy, and Governance	Challenges in developing systems for diverse feedback integration, evolving policy, and governance frameworks to address DT advancements.	Digital platforms for citizen participation, policy development focusing on ethical standards, and adaptive governance structures.	Digital Participation Platforms, Ethical Policy Development	Sustainable urban development that reflects community needs, fostering a democratic and participatory urban future.

4.3. Future Research Directions

4.3.1. Implementation and Standards

An important area for future exploration within UDTs revolves around developing and adopting universally recognized standards and protocols [103]. This approach is essential for streamlining UDTs' design and implementation phases and ensuring their scalability across different urban contexts [1]. The absence of standardized practices currently poses a significant barrier to UDT systems' efficient deployment and interoperability [104]. As such, there is a pressing need to establish comprehensive frameworks and guidelines that can harmonize the development processes of UDTs, ensuring consistency and compatibility across various applications and systems within smart cities [1].

Future research should focus on identifying and developing these potential frameworks and guidelines, considering urban environments' diverse technological and operational landscapes [105]. This entails a collaborative effort among technologists, urban planners, policymakers, and standardization bodies to define clear, actionable standards that address the technical specifications, data formats, privacy concerns, and ethical considerations inherent in UDT systems [106]. Such standards should facilitate seamless data exchange, integration of disparate systems, and the adoption of new technologies as they emerge, thereby enhancing the robustness and adaptability of UDT platforms [107].

Moreover, these standards and protocols must be designed to foster innovation while ensuring data security, privacy, and ethical information use. Future research can lay the groundwork for a more cohesive, efficient, and scalable UDT implementation, driving the evolution of smart cities toward more integrated, responsive, and sustainable urban ecosystems [1].

4.3.2. Integrability and Holistic Approaches

The complexity of sustainable smart cities, encompassing environmental, social, and economic facets, demands UDT solutions that transcend traditional domain-specific boundaries [108]. Integrative prototypes capable of operating across diverse application domains on a unified data and algorithmic platform are essential for this endeavor [109]. These prototypes would enable the seamless interaction of disparate systems and data sets, ensuring coherent functionality and enhancing the efficacy of UDTs in comprehensive urban management [110].

Future investigations should concentrate on devising holistic models that accurately reflect the multifaceted nature of urban environments [111]. Such models would integrate environmental sustainability metrics, social dynamics, and economic indicators, offering a comprehensive view of the city's health and progress [112]. By simulating these interconnected processes, UDTs can facilitate informed decision making, predictive analytics for urban planning, and strategic interventions to foster sustainable urban development [1].

4.3.3. Empirical Comparisons

Proposing empirical studies to compare UDTs with traditional and contemporary simulation methodologies could shed light on several critical aspects [113]. These aspects include the comparative performance, accuracy of results, and the overall costs associated with implementation and maintenance [113]. Such empirical comparisons are essential to clearly understand where UDTs stand in the spectrum of urban simulation technologies and their potential to redefine urban planning practices [114].

Conducting these studies requires a well-structured research design that focuses on quantitative metrics such as computational efficiency and cost-effectiveness and qualitatively assesses the complexity and depth of insights generated. For instance, evaluating how UDTs can simulate complex urban systems with interdependent variables versus the capabilities of other tools could offer profound insights into the versatility and depth of UDT models [115]. Additionally, examining the implementation costs in detail, from initial setup to ongoing operation, will provide valuable data for urban planners and policymakers considering the adoption of UDT technologies [116].

Furthermore, such empirical comparisons could explore the scalability of UDT applications across different sizes and types of urban areas, from small towns to mega-cities and their adaptability to various urban challenges [116]. These studies could contribute to a body of knowledge that supports decision making in urban development, highlighting the situations where UDTs offer superior solutions, or identifying areas where traditional tools still hold relevance [1]. By rigorously evaluating UDTs against other simulation tools, the urban planning community can better understand the practical implications of deploying UDTs, ensuring that investments in these technologies are both strategic and beneficial for sustainable urban development [117].

4.3.4. Conceptual Linkages and Priority Matrix

The complex web of relationships between urban management, urban planning, and governance necessitates a good understanding to harness the full potential of UDTs in enhancing smart city initiatives [28]. Advocating for focused research that delineates these conceptual linkages lays the groundwork for more cohesive and effective urban development strategies [118]. Stakeholders can gain insights into how UDTs can be provided to optimize urban environments, streamline governance processes, and foster more inclusive and sustainable urban planning practices by illuminating the synergies and dependencies among these domains [110]. This holistic perspective is essential for addressing the multifaceted challenges faced by modern cities, from environmental sustainability to social equity [119].

In this context, developing a priority matrix emerges as a pivotal tool for stakeholders engaged in deploying UDT technologies [120]. Such a matrix would categorize challenges and opportunities based on their impact and urgency and align them with the overarching goals of urban development [119]. This systematic approach enables stakeholders to prioritize actions and allocate resources more effectively, ensuring that critical issues are addressed promptly and laying a strategic foundation for long-term urban resilience and prosperity [121]. The priority matrix can guide decision-making processes, highlighting areas where UDT interventions can yield significant benefits and identifying potential barriers to their successful implementation [1].

Furthermore, by establishing clear conceptual linkages across the urban management, planning, and governance spectrum, the priority matrix can facilitate better coordination and collaboration among different stakeholders, including city planners, policymakers, technology providers, and the community [122]. It serves as a roadmap for integrated urban development efforts, ensuring that UDT projects are technologically sound and aligned with the city's broader social, economic, and environmental objectives [5]. Encouraging research in this area and the subsequent creation of a priority matrix represents a critical step towards a more strategic, informed, and cohesive approach to urban digital twin initiatives, ultimately contributing to the creation of smarter, more livable cities [123].

4.3.5. Cost–Benefit and Socio-Technical Analyses

Implementing UDTs within smart cities presents a complex interplay of technological innovation, financial investment, and societal impact, necessitating a thorough evaluation through comprehensive cost–benefit and socio-technical analyses [1]. These analyses are important in quantifying UDTs' tangible and intangible impacts on urban ecosystems, providing a nuanced understanding of their value proposition [124]. Operational efficiency gains, and societal benefits against the costs of development, deployment, and maintenance, stakeholders can make informed decisions about investing in UDT technologies through assessing the economic feasibility [116].

Furthermore, socio-technical analyses contribute critical insights into UDT implementation's human and organizational aspects, examining how these technologies integrate with and transform urban governance structures, community engagement practices, and service delivery models [6]. This perspective helps to identify the social, cultural, and institutional factors that influence the acceptance and effectiveness of UDT solutions [1]. Urban planners and policymakers can devise strategies that align UDT initiatives with community needs and values, fostering broader support and minimizing resistance by understanding the interdependencies between technology and society [8].

Moreover, these analyses can illuminate the barriers to UDT adoption, ranging from financial constraints and technological challenges to regulatory hurdles and privacy concerns [116]. Identifying these obstacles early in the planning process allows for developing targeted interventions to mitigate risks and enhance the likelihood of successful UDT integration into urban management and planning practices [125]. Ultimately, conducting in-depth cost–benefit and socio-technical analyses is crucial for validating the strategic importance of UDTs in advancing smart city objectives, ensuring that these initiatives deliver meaningful improvements in urban quality of life, sustainability, and resilience [8].

4.3.6. Nanosensors in UDTs

The advent of nanosensors marks a significant milestone in enhancing the accuracy and efficiency of UDTs [126]. These miniature sensors can collect highly detailed environmental, structural, and social data at an unprecedented scale, offering a granular view of urban dynamics that was previously unattainable [127]. Integrating nanosensors into UDT systems presents a unique opportunity to monitor urban environments in real time, capturing the minutiae of city life and the physical condition of infrastructure with remarkable precision [128]. This capability is crucial for developing responsive and adaptive UDT models that accurately reflect the current state of urban areas, thereby facilitating more informed decision making and proactive urban management [106].

Future research in UDTs should prioritize exploring the potential of nanosensors to revolutionize data collection methodologies [129]. This involves the technological development of more advanced nanosensors and the creation of frameworks for their deployment, data integration, and analysis within UDT platforms [19]. The challenges associated with managing the vast amounts of data generated by nanosensors, ensuring their interoperability with existing UDT systems, and addressing privacy and ethical considerations related to pervasive monitoring need to be addressed [104]. Moreover, the potential of nanosensors to enable new applications of UDTs in areas such as environmental monitoring, public health, and disaster response should be thoroughly investigated [130].

4.4. Case Studies and Practical Implementations

The exploration of UDTs in urban design and planning offers a fascinating glimpse into the future of city management and sustainable urban development [107]. The case studies exemplify the diverse applications of UDT technology, showcasing its potential to revolutionize how cities are planned, built, and managed. Each case presents unique insights into the integration of DTs in urban environments, their challenges, and the lessons learned, contributing significantly to the broader understanding and adoption of this technology in sustainable urban development, as listed in Table 5.

Table 5. Overview of Urban Digital Twin applications in global urban design and planning projects.

City/Project	Location	Objective	Key Features	Outcomes
Virtual Singapore	Singapore	To create a dynamic 3D city model and collaborative data platform to support urban planning and decision making.	3D modeling, real-time data integration, analytics for urban planning, and environmental simulation.	Improved urban planning and decision making, enhanced public services, and policy formulation.
City Zenith's Smart World OS	Various Locations	To provide a digital twin platform for building, city, and infrastructure projects to optimize performance and reduce carbon emissions.	IoT integration, predictive analytics, and scenario simulation.	Energy savings, operational efficiency, and reduced carbon footprint for multiple projects.
Helsinki 3D+	Helsinki, Finland	To support city planning and promote open data usage through a comprehensive 3D model of the city.	Open data platform, 3D visualization, integration with planning tools.	Increased public engagement, improved planning processes, and development of new digital services.
Plan IT Valley	Paredes, Portugal	To build from scratch a smart city incorporating digital twin technology for sustainability and urban planning.	Urban operating system, real-time data analysis, sustainability models.	(The project was ambitious; specific outcomes depend on current project status and execution.)
Dubai's Digital Twin Initiative	Dubai, UAE	To transform Dubai into a smart city by using the technology of digital twin to enhance urban planning and infrastructure.	3D models, AI, and IoT integration for real-time governance and urban planning.	Enhanced city management, improved infrastructure planning, and better emergency response.
The National Digital Twin programme	UK	To pioneer a unified approach to digital twinning in the built environment, facilitating data integration and sharing to improve infrastructure management.	Development of UDTs, focus on interoperability and data sharing standards.	Informed, sustainable, and resilient urban development through enhanced decision making and planning.

4.4.1. Virtual Singapore

Virtual Singapore is a pioneering UDT application example, aiming to create a dynamic 3D city model to support urban planning, decision making, and public service enhancement [131]. This ambitious project provides real-time data integration, analytics, and environmental simulation to address complex urban challenges [132]. The success of Virtual Singapore lies in its comprehensive approach to urban modeling, providing invaluable tools for city planners and policymakers [133]. However, analyzing and managing huge amounts of data is a challenge that highlights the need for robust data governance and analytics capabilities [134]. Lessons from Virtual Singapore (Figure 6) emphasize the importance of interdisciplinary collaboration and the potential of open data to foster innovation and public engagement in urban development [135].

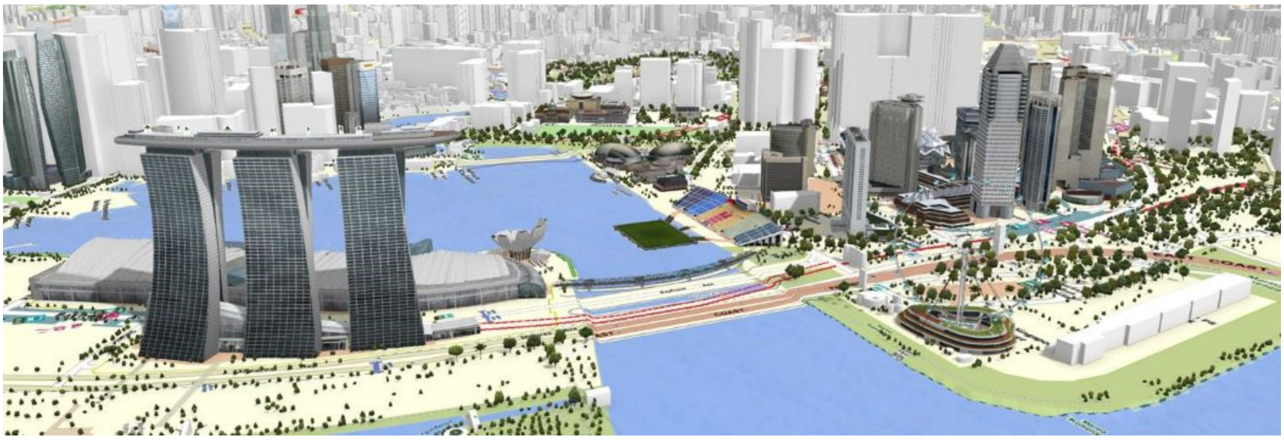

Figure 6. Singapore's digital twin [136] (Credits: https://skedgo.com/leveraging-digital-twins-to-improve-urban-transport/ accessed on 17 September 2024).

4.4.2. CityZenith's SmartWorldOS

CityZenith's SmartWorldOS offers a versatile platform that demonstrates the scalability of UDT technology across various locations and projects [137]. SmartWorldOS addresses critical aspects of sustainable urban development by optimizing performance and reducing carbon emissions. Integrating IoT, predictive analytics, and scenario simulation enables efficient urban infrastructure management, showcasing the potential for DTs to drive energy savings and operational efficiencies [138]. Challenges such as integrating disparate data sources and ensuring system scalability underscore the need for flexible and adaptable technology solutions [139] (Figure 7).

Figure 7. A dual perspective of the Amaravati greenfield city, by Cityzenith's Smart World Pro Digital Twin solution [140](credits: https://www.prnewswire.com/news-releases/cityzeniths-smart-world-pro-digital-twin-software-platform-selected-for-new-capital-city-in-india-300767327.html accessed on 17 September 2024).

4.4.3. Helsinki's 3D+

Helsinki's 3D+ initiative illustrates the power of open data and community engagement in urban planning. Helsinki has fostered a more inclusive approach to city development by developing a comprehensive 3D model accessible to both professionals and the public [141]. This initiative demonstrates how DTs can facilitate better planning processes and encourage the creation of digital services tailored to citizen needs [142]. Maintaining the model's accuracy and relevance is the main challenge, requiring continuous data updates and public participation [143]. Helsinki 3D+ teaches us that transparency and open data can enhance public trust and stimulate innovation in urban development (Figure 8).

Figure 8. Helsinki's 3D+ [144] (credits: https://kartta.hel.fi/3d/mesh/ accessed on 17 September 2024).

4.4.4. PlanIT Valley

PlanIT Valley in Paredes, Portugal, represents an ambitious attempt to construct a smart city from scratch, incorporating digital twin technology to enhance sustainability and urban planning [145]. This case study highlights the potential of UDTs in designing cities that are sustainable from their inception [146]. However, the project also illustrates the complexities and risks associated with large-scale urban innovations, including technological integration challenges and the need for long-term investment [147]. The lessons from PlanIT Valley emphasize the importance of phased implementation and the need for robust public–private partnerships to support such pioneering urban development projects [145] (Figure 9).

Figure 9. Plan IT Valley Digital Twin in Paredes, Portugal [148] (credits: https://www.dailymail.co.uk/sciencetech/article-2045577/Urban-Operating-System-revealed-run-PlanIT-Valley-super-city-Portugal.html accessed on 17 September 2024).

4.4.5. Dubai's Digital Twin

Dubai's Digital Twin Initiative showcases the city's dedication to transforming into a smart city by leveraging digital twin technology. By enhancing urban planning and infrastructure management through 3D models, AI, and IoT, Dubai aims to improve city management, infrastructure planning, and emergency responses. The initiative's success is marked by its comprehensive approach to integrating DTs into various aspects of urban governance. However, Dubai's experience also points to the challenges of ensuring data security and privacy when deploying DTs. This case underscores the critical role of cybersecurity measures in successfully implementing UDT technology.

These case studies collectively illustrate the transformative potential of UDTs in achieving sustainable urban development. Successful integrations reveal the ability of UDTs to optimize city operations, engage communities, and drive environmental sustainability. Challenges such as data management, technological integration, and privacy concerns provide valuable lessons for future implementations. As cities continue to evolve, the insights gained from these pioneering projects will undoubtedly shape the next generation of urban design and planning, emphasizing the role of DTs in creating more sustainable, efficient, and inclusive urban environments (Figure 10).

Figure 10. Dubai's Digital Twin [149](Credit: https://www.youtube.com/watch?app=desktop&v=qklaJtOITuE accessed on 17 September 2024).

4.4.6. NDTp

The National Digital Twin Program (NDTp) in the UK [150] aims to pioneer a comprehensive approach to digital twinning in the built environment, facilitating integrating, and sharing data across various sectors to improve infrastructure management and decision making. Central to this initiative is the development of UDTs, which are sophisticated digital models of urban areas that simulate real-world conditions and scenarios. These models enable urban planners, architects, and policymakers to visualize the impact of changes in infrastructure, environment, and social dynamics, leading to more informed, sustainable, and resilient urban development. The NDTp's focus on interoperability and data sharing standards is crucial for the scalability and effectiveness of UDTs, supporting a cohesive strategy for the digital transformation of urban spaces across the UK.

4.4.7. Neom's Urban Digital Twin

Neom, a megacity initiative in Saudi Arabia, exemplifies a state-of-the-art application of UDTs [151]. This futuristic city uses digital twin technology to efficiently plan and manage its infrastructure and sustainability goals. Neom incorporates advanced instruments such as AI, IoT, and renewable energy systems to optimize city functions, reduce environmental impact, and ensure a high life quality for its residents. The digital twin of Neom permits a real-time simulation and monitoring of urban processes, providing a crucial tool for sustainable urban planning and development. However, the scale and ambition of the project pose significant challenges in data integration and maintaining the accuracy of the digital twin, necessitating continuous updates and expert involvement (Figure 11).

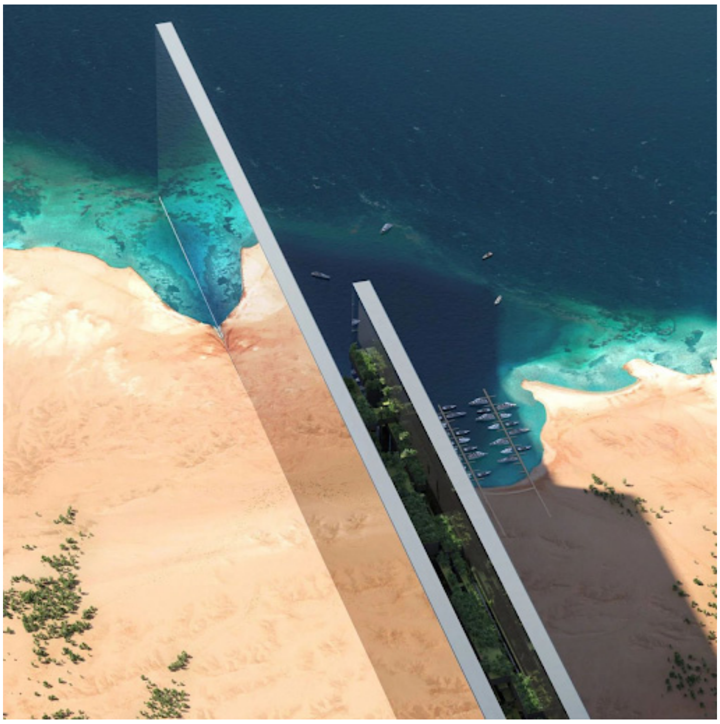

Figure 11. "The Line" project as part of the Neom development in Saudi Arabia [151] (Credits: https://parametric-architecture.com/ot-sky-released-photos-of-neoms-the-line-project-construction/ accessed 17 September 2024).

4.4.8. Riyadh's Smart City Initiative

Riyadh's Smart City initiative utilizes urban digital twin technology to transform its urban landscape [152]. Riyadh aims to enhance urban planning, traffic management, and public services by integrating 3D modeling and real-time data. The initiative focuses on improving energy efficiency and reducing carbon footprints through smart technology applications. Riyadh's digital twin enables detailed scenario analysis and decision support, helping to address urban challenges such as congestion and energy consumption. While the project promises significant improvements in urban life, it faces hurdles in data privacy, technological adoption among residents, and coordination between government entities and stakeholders.

In addition to the case studies previously highlighted, several efforts are underway globally to establish standards for the application of Digital Twin technologies, as outlined in Table 6. These initiatives span various countries and sectors, aiming to harmonize approaches, ensure interoperability, and foster innovation in the use of DTs for urban planning, manufacturing, and beyond.

Table 6. Summarize various efforts around the world related to the standardization of digital twin and urban digital twin technologies.

Organization	Country/Region	Focus	Description
Digital Twin Consortium (DTC) [153]	Global	Cross-sector digital twin best practices and standards	Providing technical foundations and standards requirements for the digital twin industry across various sectors.
International Standards Organization (ISO) [154]	Global	Digital twin use cases, concepts, terminology, manufacturing framework	Developing standards including ISO/IEC AWI 30172 (use cases), ISO/IEC AWI 30173 (concepts and terminology), and ISO/FDIS 23-247 (manufacturing framework).
British Standards Institute (BSI) [155]	United Kingdom	Digital Twin Standards Roadmap	Commissioned by the Centre for Digital Built Britain to prioritize digital twin standards development in the UK.
National Digital Twin Programme (NDTP) [150]	United Kingdom	Infrastructure and built environment digital twin integration	Focused on developing standards, processes, and tools to support creating and integrating safe, secure, ethical, and sustainable DTs.
IPC (Association Connecting Electronics Industries) [156]	USA	Digital twin product, manufacturing, and lifecycle frameworks	Released IPC-2551, the first international standard for DTs, enabling interoperability across digital and physical entities.
StandICT.eu 2026 [157]	Europe	ICT standardization in digital twin technologies	Funded by the EU, aiming to streamline digital twin standardization efforts by providing a comprehensive landscape of global work in this area.
Local Digital Twin & Citiverse EDIC [158]	Europe (Estonia, Germany, Slovenia, Czech Republic, Spain)	UDT and virtual worlds	A European Commission initiative to support the deployment of local DTs and develop the Citiverse, emphasizing standardized, interoperable instruments.

5. Discussion

In the discussion, the insights from both bibliometric and content analyses have been integrated to paint a clearer picture of the research landscape surrounding UDTs. These analyses have unveiled key technological trends and methodologies being explored in the field of UDTs, with a growing focus on providing emerging technologies such as IoT, AI, and BD to create dynamic and responsive urban management systems. Despite this technological push, the findings indicate a notable gap between theoretical research and its practical application in real-world urban settings.

A significant gap identified is the limited number of real-world implementations of UDTs, suggesting a need for more empirical studies that demonstrate how UDTs can be effectively used in urban environments. Additionally, the absence of standardized protocols for the development and deployment of UDTs emerges as a major barrier, limiting the ability of different urban systems to work together seamlessly. This challenge is compounded by issues related to system interoperability, computing demands, and data privacy concerns, all of which are critical to advancing UDTs' potential for improving smart city initiatives.

Moreover, the importance of gaining public trust and developing supportive governance frameworks is highlighted, pointing to the necessity for future research to push the envelope in technological advancements and address social and regulatory aspects.

It is vital to address the challenges of system interoperability and the computing infrastructure needed to analyze and process the vast data amounts of urban systems. The analysis calls for innovative solutions that ensure data privacy while leveraging UDT's capabilities for urban management.

The combined insights from the conducted analyses offer a comprehensive view of where UDT research stands today. They emphasize the urgency of bridging the gap between theory and practice, standardizing development protocols, and tackling interoperability, computing, and privacy challenges. Overcoming these hurdles will be crucial for realizing UDT's potential in developing sustainable and intelligently managed urban spaces, necessitating a collaborative approach that spans technological innovation, policymaking, and community engagement.

6. Conclusions

The main findings underscore UDTs' vital role in revolutionizing urban planning and management, thereby contributing significantly to the smart cities' sustainability.

This paper has systematically reviewed the integration challenges, technological advancements, and future directions of UDTs within the framework of smart city development. The research contributed to the existing theory and practice in the main findings, and has addressed the main research questions raised from the literature reviews and the existing gaps in the field, underscoring several critical insights: through the lens of bibliometric and content analyses were identified key technological trends, methodological approaches, and significant research gaps, notably the need for empirical validation, standardization, and a deeper focus on interoperability, computing power, and data privacy concerns.

The research reveals that while UDT technologies promise significant advancements, the transition from theory to practice faces substantial hurdles. These include the need for more real-world implementations, standardized protocols, and effective strategies for system integration and data management. To bridge these gaps, the research emphasizes the necessity of interdisciplinary collaboration among technologists, urban planners, policymakers, and community stakeholders. This collective effort is crucial for developing robust, technologically sophisticated, socially inclusive frameworks. By fostering empirical research and establishing universal standards, we can ensure that UDT systems are innovative but also ethical and privacy conscious. The practical contributions of this research are manifold, especially in explaining the role of the emerging field of UDTs in combination with growing technologies such as the IoT, AI, and BD. The research calls for comprehensive frameworks and guidelines to facilitate consistent and compatible UDT implementations across various applications. These standards will support seamless data exchange, integration of disparate systems, and adoption of new technologies, thus enhancing the adaptability and robustness of UDT platforms.

Additionally, the research analyzed the possibility of merging all the extraordinary challenges that currently grow based on the UDT to create dynamic and responsive urban management systems and support sustainable growth development. The research results highlighted that integrative and holistic models are essential for capturing the interconnected nature of urban systems. By incorporating environmental, social, and economic metrics, UDTs can offer a comprehensive view of urban health and support informed decision making for sustainable development. This approach will aid in predictive analytics and strategic interventions, driving forward the evolution of smart cities. The research advocates for empirical comparisons of UDTs with traditional simulation methodologies. These studies will provide valuable insights into UDTs' performance, accuracy, and cost-effectiveness, helping urban planners and policymakers make informed decisions about adopting UDT technologies. Understanding the practical implications of UDTs compared to other tools will clarify their role in urban planning and management. This research has shed light on the future direction of UDTs in contributing to the development of sustainable smart cities, advocating for a collaborative effort among academia, industry, and governance to fully realize the potential of UDTs in shaping the urban landscapes of tomorrow. The critical role of interdisciplinary research has been highlighted as indispensable in navigating the complex technological, socioeconomic, and governance landscapes that UDT deployment entails. Addressing these multifaceted challenges requires converging technology, urban planning, sociology, and policymaking expertise. Such collaborative efforts are essential for developing UDT frameworks that are not only technologically advanced but also socially inclusive and governed by robust regulatory frameworks.

Creating a priority matrix to understand conceptual linkages between urban management, planning, and governance will guide strategic development, help prioritize actions, allocate resources effectively, and ensure that UDT projects align with broader urban objectives.

Comprehensive cost–benefit and socio-technical analyses will be critical in validating UDTs' strategic importance. These analyses will quantify both their tangible and intangible benefits, helping stakeholders assess their value and address potential barriers to adoption.

Finally, integrating nanosensors into UDT systems presents a groundbreaking opportunity for real-time monitoring and precise data collection. Future research should focus on advancing nanosensor technology, developing frameworks for data integration, and addressing data management and privacy challenges.

While comprehensive, the research presented in this paper is subject to several limitations that necessitate careful consideration. Firstly, the scope of the bibliometric and content analyses, though extensive, may only encompass part of the rapidly evolving field of UDTs. The dynamic nature of technology and urban planning means new developments could emerge beyond the timeframe of this study. Additionally, the focus on published research might overlook significant insights from ongoing UDT projects or gray literature, including reports and white papers from industry and government sources, which could provide valuable practical perspectives on UDT deployment and challenges.

Furthermore, while beneficial, the interdisciplinary approach advocated for addressing UDT challenges presents its own complexities. Integrating diverse fields of study requires overcoming barriers related to terminology, methodologies, and research traditions. This integration is crucial for advancing UDT development but necessitates frameworks that facilitate effective collaboration among stakeholders from different disciplines.

Future research directions should mitigate these limitations by extending the scope of the literature review to include emerging studies and more gray literature, thus capturing a broader spectrum of UDT applications and challenges. Efforts should also be made to develop methodologies for interdisciplinary research that streamline collaboration across technological, socioeconomic, and governance domains. Empirical studies focusing on implementing and evaluating UDTs in real-world urban settings will be particularly valuable, offering insights into the practical challenges and benefits of UDT deployment.

Additionally, future research should explore the development of standardized protocols and frameworks that enhance the interoperability of UDT systems across different urban infrastructures. This includes tackling the computing and data privacy challenges critical for UDTs' scalable and ethical use. Investigating the socioeconomic impacts of UDTs, including their effects on urban equity, privacy, and governance, will also be crucial for ensuring that UDT technologies serve the broader goals of sustainable and inclusive urban development.

In conclusion, advancing UDT technologies requires a multifaceted approach integrating standardized frameworks, holistic models, empirical research, and innovative data collection methods. These efforts will propel the development of smart cities toward more integrated, responsive, and sustainable urban environments. Therefore, the results call upon scholars, urban practitioners, and policymakers to join forces in advancing the implementation of UDTs. This collaborative endeavor should foster empirical research, establish universal standards, and ensure that UDT systems are designed and deployed in an ethical, privacy-preserving manner that benefits all urban stakeholders. As cities continue to evolve towards greater digital integration, UDTs stand as a beacon for sustainable urban development, promising enhanced urban life quality, more efficient city management, and a resilient urban future. The path forward requires concerted efforts to harness this potential fully for the benefit of all global urban communities.

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