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Applications of Augmented/Virtual Reality (AR/VR), Digital Twin, and Edge Computing in Smart Urban Resource Management, Waste Management, and Transportation

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Abstract

The present study aimed to investigate the role of Augmented/Virtual Reality (AR/VR), Digital Twin systems, and Edge Computing in improving smart urban resource management, waste management optimization, intelligent transportation performance, environmental sustainability, and citizen satisfaction in Tehran. This study employed a mixed-methods exploratory-sequential design with qualitative and quantitative phases. In the qualitative stage, semi-structured interviews were conducted with 18 experts in smart city technologies, urban planning, transportation systems, environmental management, and digital infrastructure using purposive sampling until theoretical saturation was achieved. The qualitative findings were used to design a researcher-developed questionnaire containing 52 items distributed across dimensions including AR/VR applications, Digital Twin integration, Edge Computing efficiency, smart waste management, transportation performance, environmental sustainability, operational responsiveness, and citizen satisfaction. In the quantitative phase, 384 managers, urban planners, transportation experts, and municipal technology specialists from Tehran Municipality were selected through stratified random sampling. Content validity was confirmed through expert review, while construct validity was examined using exploratory and confirmatory factor analyses. Reliability coefficients exceeded 0.70 for all variables. Data were analyzed using SPSS-27 and AMOS-26 through descriptive statistics, Pearson correlation analysis, multiple regression, confirmatory factor analysis, and structural equation modeling. The results demonstrated significant positive relationships among all research variables at the 0.01 significance level. Digital Twin Integration had the strongest direct effect on Smart Urban Management Efficiency ($\beta = 0.36$, $p = 0.001$), followed by Edge Computing Efficiency ($\beta = 0.33$, $p = 0.001$) and AR/VR Applications ($\beta = 0.29$, $p = 0.001$). Smart Urban Management Efficiency significantly predicted Environmental Sustainability ($\beta = 0.42$, $p = 0.001$) and Citizen Satisfaction ($\beta = 0.39$, $p = 0.001$). The strongest correlation was observed between Edge Computing Efficiency and Operational Responsiveness ($r = 0.78$, $p < 0.01$). The structural equation model demonstrated acceptable fit indices ($\chi 2/df = 2.11$, RMSEA = 0.054, GFI = 0.93, AGFI = 0.91, CFI = 0.95, TLI = 0.94), confirming the adequacy of the proposed conceptual framework. The findings indicate that the integration of AR/VR technologies, Digital Twin systems, and Edge Computing infrastructures substantially enhances smart urban governance by improving operational efficiency, transportation management, waste management optimization, environmental sustainability, and citizen-centered service delivery. The study highlights the strategic importance of interoperable digital ecosystems and real-time intelligent infrastructures in supporting sustainable and resilient urban development in metropolitan environments.

Keywords: Smart Cities, Augmented Reality, Virtual Reality, Digital Twin, Edge Computing, Urban Resource Management, Smart Transportation, Waste Management, Environmental Sustainability, Citizen Satisfaction

1. Introduction

The accelerated transformation of contemporary cities into data-intensive, service-oriented, and sustainability-driven systems has created a new technological agenda for urban management. Rapid urbanization, climate pressure, infrastructure congestion, resource scarcity, environmental degradation, and the increasing complexity of municipal services have made traditional models of urban governance insufficient for managing the dynamic interactions among citizens, infrastructure, mobility systems, energy flows, waste streams, and environmental risks. In this context, smart city development has shifted from the simple digitization of services toward integrated cyber-physical ecosystems in which physical urban assets are continuously monitored, modeled, simulated, and optimized through advanced digital technologies. Augmented Reality and Virtual Reality (AR/VR), Digital Twin systems, and Edge Computing have become central components of this transformation because they allow urban managers to visualize complex environments, simulate future scenarios, process real-time data near its source, and support faster, more adaptive decision-making (Campo et al., 2024; Gao et al., 2024; Meng et al., 2025; Singh et al., 2025). The convergence of these technologies is particularly important in smart urban resource management, waste management, and transportation, where operational efficiency, environmental sustainability, and citizen-centered service delivery depend on accurate data, predictive analytics, spatial intelligence, and interactive visualization.

Smart cities are increasingly understood as interconnected digital ecosystems rather than isolated technological projects. Foundational discussions on smart cities emphasize that digital transformation contributes to the digital economy by integrating urban infrastructure, governance platforms, data analytics, and service innovation into a coordinated decision-support environment (Pedro, 2023). This view has been extended by research on the Internet of Things (IoT), which shows that emerging IoT applications create new possibilities for sensing, connectivity, automation, and intelligent service delivery across urban domains (Rangarajan & Al-Quraishi, 2023). In parallel, the next generation of smart city development is being shaped by advanced connectivity infrastructures such as 6G, which can support ultra-low latency communication, massive device connectivity, and high-capacity data exchange for real-time urban systems (Murroni et al., 2023). These technological foundations make it possible to move from reactive urban management to proactive, predictive, and adaptive management, particularly when physical infrastructure is linked to digital models, immersive interfaces, and distributed computational architectures.

Digital Twin technology occupies a central position in this emerging paradigm. A digital twin can be understood as a dynamic digital representation of a physical object, infrastructure system, urban process, or entire city environment that is continuously updated through data flows from sensors, IoT devices, operational systems, and analytics platforms. In urban governance, digital twins provide a foundation for monitoring infrastructure status, modeling service flows, predicting system behavior, and evaluating the effects of policy or operational interventions before they are implemented in real space. Studies on digital twin-based smart city platforms demonstrate that such systems can support monitoring and decision-making by integrating urban data into actionable representations of city functions (Dani et al., 2023). Similarly, reviews of digital twins as frameworks for IoT applications indicate that digital twins can connect sensing networks and computational models, allowing urban managers to interpret complex data streams and transform them into operational intelligence (Mudiyanselage & Sellahewa, 2023). Earlier work on digital twins of urban ecosystems also highlights their relevance for improving quality of life by enabling more responsive, evidence-based, and citizen-oriented urban services (Mukhacheva et al., 2022).

The value of Digital Twin technology becomes especially evident when applied to sustainability planning and governance. Combining digital twins with green metrics enables urban decision-makers to evaluate sustainability performance, compare alternative planning scenarios, and integrate environmental indicators into the management of smart buildings and cities (Corrado et al., 2022). Digital twins can also contribute to the transition toward more sustainable and resilient built environments by improving lifecycle monitoring, asset management, and data-based planning. Research on building information modeling (BIM) evolution across lifecycle stages demonstrates that digital modeling tools increasingly function as knowledge infrastructures that support design, construction, operation, maintenance, and eventual transformation of buildings and urban assets (Kuai et al., 2023). Likewise, the synchronization of information flows throughout the building lifecycle is necessary for maintaining continuity between design data, operational data, maintenance processes, and decision-making systems (Raitviir & Lill, 2024). These insights are highly relevant to smart urban resource management because cities require continuous alignment between physical infrastructure, digital information flows, and managerial decisions.

Augmented Reality and Virtual Reality technologies add an immersive and interactive layer to smart city management. AR can overlay digital information onto physical environments, while VR can create fully simulated environments for planning, training, visualization, and stakeholder engagement. In urban management, these technologies allow planners, engineers, decision-makers, and citizens to experience proposed interventions, infrastructure changes, traffic scenarios, environmental risks, or service configurations before they are implemented. Research on immersive technology and BIM for sustainable smart cities emphasizes that AR/VR can enhance spatial understanding, improve collaboration among stakeholders, and support sustainability-oriented design and planning (Liu et al., 2024). Similarly, extended reality has been identified as a catalyst for circular economy transition in the built environment because it can visualize material flows, support adaptive reuse planning, improve stakeholder awareness, and facilitate more sustainable lifecycle decisions (Soman et al., 2024). In this respect, immersive technologies are not merely visualization tools; they are decision-support instruments that can improve the cognitive accessibility of complex urban data and support more participatory forms of smart governance.

The connection between immersive environments and the broader city metaverse further expands the conceptual scope of AR/VR applications. Spatial data intelligence and the city metaverse provide a framework for integrating geospatial information, real-time sensing, virtual environments, and interactive urban simulations into a unified digital experience (Meng et al., 2025). The metaverse and artificial intelligence can also support the Internet of City Things by combining XReality, AIoT, and cost-effective interactive technologies to create new forms of urban experience, service design, and data-driven governance (Bibri & Jagatheesaperumal, 2023). However, the urban implications of the metaverse are not purely technical. Ethical, social, and economic considerations remain central, particularly regarding privacy, exclusion, data ownership, governance accountability, and unequal access to digital urban services (Tiwari, 2024). The metaverse may offer new instruments for urban planning, but its promises must be assessed critically to avoid technological determinism and unfulfilled expectations (Nenković-Riznić, 2023). Therefore, AR/VR and metaverse-based smart city systems should be evaluated not only according to technical feasibility but also according to their contribution to inclusive, sustainable, and equitable urban development.

Edge Computing provides another essential technological layer for smart urban systems. While cloud computing remains important for large-scale storage and analytics, many smart city applications require real-time or near-real-time responses that cannot rely exclusively on centralized processing. Edge Computing processes data closer to the point of generation, thereby reducing latency, lowering bandwidth pressure, improving local responsiveness, and supporting time-sensitive urban operations. This is particularly important for intelligent transportation systems, waste collection routing, energy monitoring, public safety, and infrastructure maintenance. Research on resource-constrained extended reality operated with digital twins in industrial IoT demonstrates that the integration of XR, digital twins, and distributed computing can support real-time interaction even under computational and communication constraints (Kamdjou et al., 2024). In addition, cloud-based digital twin systems have already been used in urban contexts such as intelligent lighting design in historic landscape blocks, showing the potential of computational platforms to manage urban environmental quality and infrastructure performance (Wei et al., 2023). Together, cloud, edge, and digital twin architectures create a layered computational ecosystem in which real-time sensing, simulation, visualization, and operational control can be coordinated.

One of the most important application domains for these technologies is urban waste management. Conventional waste management systems often suffer from inefficient collection routes, delayed monitoring, limited citizen feedback, poor forecasting, and insufficient integration with environmental indicators. Smart waste management aims to address these limitations through sensors, IoT platforms, predictive analytics, automation, and data-based decision-making. Waste Management 2.0 research demonstrates that IoT-enabled systems can support more efficient and eco-friendly smart city solutions by improving waste monitoring, collection optimization, and operational sustainability (Addas et al., 2024). Digital Twin implementation in waste management can further improve production and service systems by creating dynamic models of waste flows, service performance, and operational bottlenecks (Barbosa et al., 2023). These developments are closely connected to circular economy objectives because waste management is no longer treated simply as disposal, but as part of a broader urban resource cycle involving reduction, reuse, recycling, recovery, and environmental accountability. Digital technologies have been identified as key enablers of circular economy practices, providing tools for tracking resources, optimizing processes, and supporting sustainability-oriented business and governance models (Chi et al., 2023). A broader classification of digital technologies also confirms their links to circular economy transitions by showing how different technologies contribute to data collection, traceability, process optimization, resource efficiency, and systemic transformation (Piedra-Muñoz et al., 2025).

Transportation is another major field in which AR/VR, Digital Twin systems, and Edge Computing can transform urban management. Urban transportation systems generate large volumes of real-time data from vehicles, roads, traffic signals, mobile devices, public transport systems, cameras, and environmental sensors. Digital twins can model transportation networks, simulate congestion patterns, evaluate infrastructure interventions, and optimize traffic management strategies. Digital twin-enabled Internet of Vehicles applications show that the integration of digital representations with connected vehicles can improve intelligent mobility, traffic coordination, safety, and transportation efficiency (Gao et al., 2024). AR/VR can also improve transportation planning by visualizing traffic scenarios, infrastructure redesigns, pedestrian flows, and transit-oriented development alternatives. Edge Computing is especially relevant in this domain because transportation systems require low-latency processing for real-time route optimization, incident detection, vehicle communication, and adaptive traffic control. When integrated, these technologies can support a shift from fragmented traffic management toward intelligent, predictive, and multimodal urban mobility governance.

The smart urban resource management dimension extends beyond waste and transportation to include energy, water, infrastructure, public spaces, environmental assets, and municipal service capacities. Digital twin-based platforms can integrate these domains into cross-sectoral decision-support systems. Cross-domain interoperability is crucial because urban challenges rarely remain confined to a single sector; transportation affects air quality, waste collection affects mobility, energy systems affect emissions, and infrastructure maintenance affects public safety. Research on virtual reality and IoT-based digital twins for smart city cross-domain interoperability demonstrates that combined immersive and sensing technologies can improve coordination among urban domains and support more integrated decision-making (Campo et al., 2024). Interoperability is also important for twin-transition strategies in cities, where digital transformation and sustainability transition must be aligned through platforms capable of integrating BIM, urban data, and sustainability planning. A Delphi-based roadmap for Mediterranean cities shows that BIM 6D can function as an interoperable platform for sustainable urban development and twin transition (Jaafari, 2025). Such approaches are directly relevant to metropolitan contexts where infrastructure complexity, environmental constraints, and governance fragmentation require integrated data environments.

Smart city development also requires attention to organizational, social, and human dimensions. Technology alone cannot guarantee urban sustainability or managerial efficiency unless it is embedded in inclusive governance, institutional capacity, and stakeholder collaboration. Innovation intermediaries can contribute to inclusive smart cities by connecting technological innovation with social needs, policy structures, and participatory mechanisms (Lepore et al., 2023). The blending of humanware, software, and hardware in smart city design similarly emphasizes that smart urban systems must combine technical infrastructures with human expertise, institutional learning, and social acceptance (Almusaed & Almssad, 2023). In the built environment, the integration of architecture, engineering, and construction practices into Industry 6.0 further suggests that smart and sustainable future-built environments require collaboration between digital technologies, environmental goals, and human-centered design principles (Almusaed et al., 2023). These perspectives are essential because AR/VR, Digital Twin, and Edge Computing applications will succeed only if urban stakeholders understand them, trust them, and are able to use them effectively in planning, operations, and service delivery.

Recent research on artificial intelligence, data analytics, and visualization further strengthens the case for integrating advanced digital systems into urban management. AI and machine learning can enhance data analytics and visualization in database management with digital twins by enabling more accurate interpretation of complex datasets, predictive modeling, and decision-support processes (Singh et al., 2025). In architecture, engineering, and construction, leading-edge AI, IoT, and big data technologies have been associated with smart and sustainable practices, although challenges remain in interoperability, data quality, technical skills, privacy, and organizational readiness (Rane et al., 2023). A broader review of leading-edge technologies for architectural design similarly indicates that digital innovations are reshaping design, simulation, visualization, and performance evaluation processes across built environment practices (Rane, 2023). These advances are relevant to smart city management because municipal decision-making increasingly depends on the ability to transform large, heterogeneous, and real-time datasets into usable knowledge.

Despite the promise of emerging digital technologies, several challenges remain unresolved. The industrial metaverse literature highlights environmental impacts and implementation challenges, including energy consumption, infrastructure demands, technical complexity, and governance concerns (S. M. Nleya & M. Velempini, 2024). The preprint version of this work similarly emphasizes that the environmental and operational implications of industrial metaverse systems must be examined carefully before large-scale adoption (S. Nleya & M. Velempini, 2024). Business ecosystem research on the metaverse also shows that value creation depends on complex interactions among platforms, users, service providers, data infrastructures, and regulatory frameworks (Kontogianni & Ανθόπουλος, 2024). In addition, thematic analysis of 3D printing and smart cities demonstrates that emerging technologies can contribute to smarter urban development, but their implementation requires attention to infrastructure readiness, governance models, sustainability outcomes, and long-term urban value (Prasittisopin, 2024). Conference and topical-track research in IoT and smart city domains also indicates that technological innovation is fragmented across vertical sectors, making interdisciplinary integration necessary for coherent smart city strategies (Filipovic & Stüttgen, 2023). These challenges show that the application of AR/VR, Digital Twin, and Edge Computing in urban management must be studied through an integrated framework rather than as separate technological interventions.

In metropolitan cities such as Tehran, the need for integrated smart urban technologies is particularly significant. Tehran faces complex challenges related to traffic congestion, air pollution, waste generation, uneven resource distribution, infrastructure pressure, and the need for responsive municipal governance. Technologies such as AR/VR, Digital Twin systems, and Edge Computing can provide new tools for understanding and managing these challenges by improving real-time monitoring, simulation-based planning, predictive decision-making, operational coordination, and stakeholder engagement. However, empirical research is still needed to clarify how these technologies contribute specifically to resource management, waste management, and transportation outcomes in the urban governance context. While existing literature has examined digital twins, immersive environments, IoT, AI, circular economy, metaverse systems, and smart city platforms, fewer studies have integrated these technologies into a unified model of smart urban management efficiency and sustainability. Therefore, the present study was conducted to examine the applications of AR/VR, Digital Twin, and Edge Computing in smart urban resource management, waste management, and transportation in Tehran and to evaluate their contribution to smart urban management efficiency, environmental sustainability, and citizen satisfaction.

2. Methods and Materials

The present study was conducted using a mixed-methods applied research design with an exploratory-sequential approach in the context of smart urban management in Tehran. In the qualitative phase, the study aimed to identify the major dimensions, indicators, and practical applications of Augmented Reality (AR), Virtual Reality (VR), Digital Twin technology, and Edge Computing in urban resource management, waste management systems, and intelligent transportation infrastructures. The statistical population in the qualitative section consisted of university professors in smart city studies, urban planners, transportation engineers, municipal technology experts, environmental management specialists, and information technology professionals working in Tehran Municipality and smart infrastructure companies. Using purposive sampling and the theoretical saturation principle, 18 experts were selected for semi-structured interviews. The inclusion criteria included at least five years of professional or academic experience in smart city technologies, urban digital infrastructure, or intelligent transportation systems. The interviews were conducted until data saturation was achieved and no new conceptual themes emerged. In the quantitative phase, the study employed a descriptive-correlational survey design to validate the proposed conceptual model and investigate the relationships among the identified variables. The statistical population consisted of managers, technical experts, urban planners, transportation analysts, and employees involved in smart city projects across different districts of Tehran Municipality. Based on Cochran's sample size formula and considering the size of the target population, a sample of 384 participants was selected using stratified random sampling proportional to organizational units. The participants were recruited from departments associated with urban services, transportation, environmental management, digital infrastructure, and smart governance systems in Tehran.

Data collection was conducted using both qualitative and quantitative instruments. In the qualitative phase, semi-structured interviews were designed based on previous literature related to AR/VR technologies, Digital Twin systems, Edge Computing, smart transportation, urban sustainability, and intelligent waste management. The interview protocol included open-ended questions regarding technological capabilities, implementation barriers, infrastructure readiness, operational efficiency, environmental sustainability, urban monitoring, citizen engagement, and future development opportunities in smart urban ecosystems. The interviews lasted between 45 and 75 minutes and were recorded with participant consent. After transcription, the interview data were analyzed using thematic analysis and open, axial, and selective coding procedures. In the quantitative phase, a researcher-developed questionnaire was designed according to the findings of the qualitative stage and existing theoretical foundations in smart city research. The questionnaire consisted of 52 items distributed across several dimensions, including AR/VR applications in urban visualization and decision-making, Digital Twin integration in urban simulation and infrastructure monitoring, Edge Computing efficiency in real-time data processing, smart waste management optimization, intelligent transportation performance, urban resource allocation, environmental sustainability, operational responsiveness, and citizen satisfaction. The questionnaire items were scored using a five-point Likert scale ranging from strongly disagree to strongly agree. Content validity was assessed through expert review by 12 specialists in urban technology and smart city governance, and the Content Validity Ratio (CVR) and Content Validity Index (CVI) confirmed the adequacy of the instrument. Construct validity was evaluated through exploratory and confirmatory factor analyses. Reliability was examined using Cronbach's alpha coefficients and composite reliability indices, all of which exceeded the acceptable threshold of 0.70, indicating satisfactory internal consistency.

The collected data were analyzed using both qualitative and quantitative analytical techniques. In the qualitative phase, MAXQDA software was employed for coding, categorization, and extraction of conceptual themes from interview transcripts. In the quantitative phase, SPSS-27 and AMOS-26 software packages were used for statistical analysis and structural modeling. Descriptive statistics including means, standard deviations, skewness, and kurtosis values were calculated to examine the distribution of the variables. Inferential analyses included Pearson correlation analysis, multiple regression analysis, exploratory factor analysis, confirmatory factor analysis, and structural equation modeling to test the proposed conceptual framework and the causal relationships among the variables. Model fit was evaluated using indices such as Chi-square/df ratio, RMSEA, GFI, AGFI, CFI, IFI, and TLI. In addition, mediation and indirect effect analyses were conducted to investigate the intermediary role of intelligent infrastructure integration between emerging digital technologies and urban management efficiency. Statistical significance was considered at the 0.05 level for all inferential analyses.

3. Findings and Results

The demographic analysis indicated that among the 384 participants, 247 individuals (64.3%) were male and 137 individuals (35.7%) were female. Regarding educational level, 72 participants (18.8%) held bachelor's degrees, 221 participants (57.6%) held master's degrees, and 91 participants (23.7%) possessed doctoral qualifications. In terms of organizational affiliation, 34.1% of respondents were employed in transportation management sectors, 27.6% in urban environmental and waste management departments, 21.9% in smart infrastructure and digital governance units, and 16.4% in urban planning and municipal strategic development divisions. The mean professional experience of the respondents was 11.84 years with a standard deviation of 4.92 years, indicating that the majority of participants possessed substantial practical expertise in smart urban systems and technology-oriented municipal operations. Furthermore, approximately 69% of the respondents reported previous experience with smart urban technologies, simulation systems, or data-driven urban management platforms, reflecting an appropriate level of familiarity with the concepts investigated in the present study.

Table 1. Descriptive Statistics of Research Variables

Variables	Mean	Standard Deviation	Skewness	Kurtosis	Minimum	Maximum
AR/VR Applications in Urban Management	4.12	0.71	-0.48	-0.21	1.89	5.00
Digital Twin Integration	4.25	0.68	-0.54	0.16	2.03	5.00
Edge Computing Efficiency	4.07	0.74	-0.39	-0.34	1.76	5.00
Smart Waste Management Optimization	3.98	0.77	-0.27	-0.41	1.62	5.00
Intelligent Transportation Performance	4.19	0.69	-0.45	-0.18	1.94	5.00
Urban Resource Allocation Efficiency	4.10	0.73	-0.31	-0.27	1.87	5.00
Environmental Sustainability	4.16	0.70	-0.52	0.09	2.01	5.00
Operational Responsiveness	4.04	0.75	-0.29	-0.36	1.70	5.00
Citizen Satisfaction	3.91	0.81	-0.18	-0.47	1.55	5.00

The descriptive findings presented in Table 1 demonstrate that the participants generally reported high levels of agreement regarding the effectiveness and applicability of emerging digital technologies in smart urban management systems. Among the studied variables, Digital Twin Integration obtained the highest mean score (M = 4.25, SD = 0.68), indicating that respondents perceived digital twin technologies as highly effective for urban infrastructure monitoring, simulation, predictive maintenance, and real-time decision-making processes. Intelligent Transportation Performance also showed a high mean score (M = 4.19, SD = 0.69), suggesting that advanced digital technologies substantially contribute to traffic optimization, route management, congestion reduction, and transportation efficiency within urban environments. Environmental Sustainability and AR/VR Applications in Urban Management similarly demonstrated elevated mean values, reflecting positive perceptions regarding the contribution of immersive technologies to sustainable urban planning, environmental monitoring, and citizen-centered urban services. Citizen Satisfaction exhibited the lowest mean score among the variables (M = 3.91, SD = 0.81), although the value remained above the midpoint, indicating an overall favorable evaluation of smart city technological integration among urban stakeholders. Additionally, skewness and kurtosis indices for all variables fell within the acceptable range of ±2, confirming the normal distribution of the data and supporting the suitability of parametric statistical analyses.

Table 2. Correlation Matrix among Research Variables

Variables	1	2	3	4	5	6	7	8	9
1. AR/VR Applications	1								
2. Digital Twin Integration	0.71**	1							
3. Edge Computing Efficiency	0.68**	0.75**	1						
4. Smart Waste Management Optimization	0.63**	0.70**	0.72**	1					
5. Intelligent Transportation Performance	0.69**	0.77**	0.74**	0.65**	1				
6. Urban Resource Allocation Efficiency	0.66**	0.73**	0.71**	0.68**	0.76**	1			
7. Environmental Sustainability	0.64**	0.72**	0.69**	0.75**	0.67**	0.70**	1		
8. Operational Responsiveness	0.67**	0.74**	0.78**	0.66**	0.73**	0.75**	0.69**	1	
9. Citizen Satisfaction	0.58**	0.69**	0.65**	0.61**	0.71**	0.72**	0.67**	0.76**	1

**p < 0.01

The results of the Pearson correlation analysis revealed significant positive relationships among all study variables at the 0.01 significance level. The strongest observed correlation was between Edge Computing Efficiency and Operational Responsiveness (r = 0.78, p < 0.01), indicating that real-time decentralized data processing substantially enhances the responsiveness and adaptability of urban management systems. Digital Twin Integration also demonstrated strong positive relationships with Intelligent Transportation Performance (r = 0.77, p < 0.01) and Urban Resource Allocation Efficiency (r = 0.73, p < 0.01), suggesting that simulation-driven urban management platforms improve predictive planning and optimize municipal operational strategies. Furthermore, Smart Waste Management Optimization showed a strong association with Environmental Sustainability (r = 0.75, p < 0.01), emphasizing the role of intelligent waste systems in achieving sustainable urban environmental goals. Citizen Satisfaction exhibited significant correlations with all technological and managerial variables, particularly with Operational Responsiveness (r = 0.76, p < 0.01) and Urban Resource Allocation Efficiency (r = 0.72, p < 0.01), indicating that improvements in smart infrastructure performance and service delivery directly enhance public satisfaction within smart urban ecosystems.

Table 3. Structural Equation Modeling Results for Predicting Smart Urban Management Efficiency

Path	Standardized Beta	Standard Error	Critical Ratio	p-value
AR/VR Applications → Smart Urban Management Efficiency	0.29	0.041	5.84	0.001
Digital Twin Integration → Smart Urban Management Efficiency	0.36	0.038	7.29	0.001
Edge Computing Efficiency → Smart Urban Management Efficiency	0.33	0.044	6.71	0.001
Smart Urban Management Efficiency → Environmental Sustainability	0.42	0.036	8.11	0.001
Smart Urban Management Efficiency → Citizen Satisfaction	0.39	0.040	7.46	0.001

The structural equation modeling analysis demonstrated that all proposed paths in the conceptual framework were statistically significant. Digital Twin Integration exerted the strongest direct effect on Smart Urban Management Efficiency ($\beta = 0.36$, $p = 0.001$), highlighting the critical role of digital simulation technologies in enhancing urban operational intelligence, predictive maintenance capabilities, and infrastructure coordination. Edge Computing Efficiency also significantly predicted Smart Urban Management Efficiency ($\beta = 0.33$, $p = 0.001$), confirming the importance of low-latency decentralized processing systems for real-time urban analytics and decision-making processes. AR/VR Applications similarly showed a meaningful positive effect ($\beta = 0.29$, $p = 0.001$), indicating that immersive visualization technologies improve urban planning accuracy, stakeholder engagement, training simulations, and infrastructure management. In addition, Smart Urban Management Efficiency significantly predicted Environmental Sustainability ($\beta = 0.42$, $p = 0.001$) and Citizen Satisfaction ($\beta = 0.39$, $p = 0.001$), suggesting that technologically integrated smart city systems contribute simultaneously to ecological sustainability and improved public service quality. Overall, the structural model demonstrated strong explanatory power and supported the theoretical assumption that emerging digital technologies substantially enhance urban governance performance and sustainability outcomes.

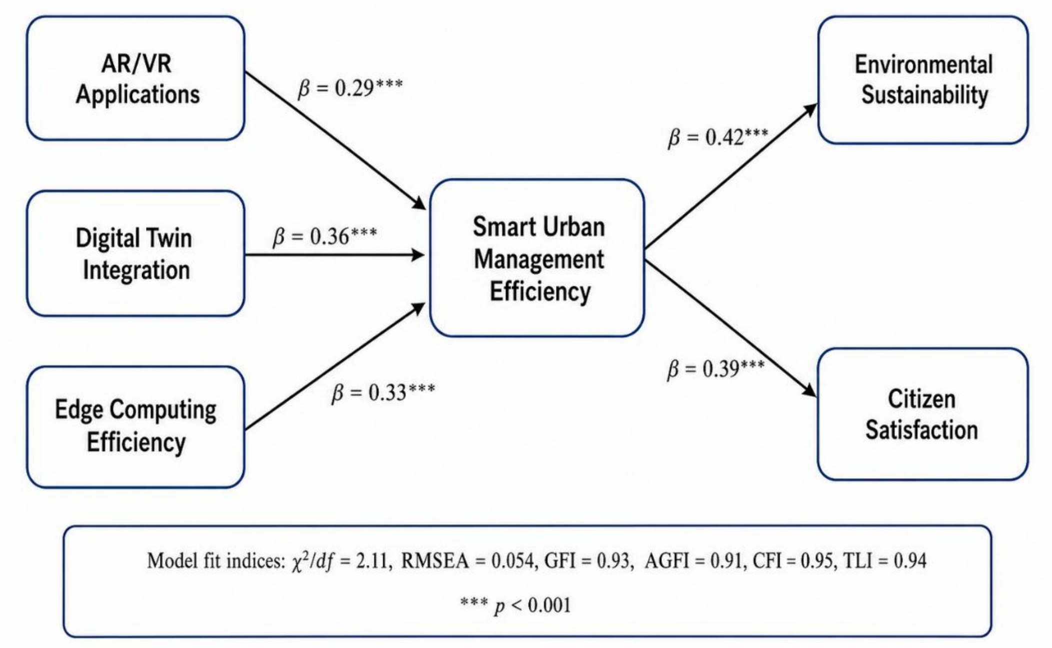

Figure 1. Structural Model of the Relationships among AR/VR Applications, Digital Twin Integration, Edge Computing Efficiency, and Smart Urban Management Outcomes

The structural model illustrated in Figure 1 demonstrates the integrated relationships among immersive technologies, intelligent digital infrastructures, and urban management outcomes within smart city ecosystems. The model indicates that AR/VR applications, Digital Twin systems, and Edge Computing architectures collectively function as interconnected technological enablers that improve urban operational efficiency, environmental sustainability, and citizen-oriented service delivery. The standardized path coefficients revealed that Digital Twin Integration and Edge Computing Efficiency exerted the strongest influences on smart urban management performance, reflecting the importance of predictive simulation systems and decentralized computational infrastructures in modern urban governance. The figure further demonstrates that enhanced smart urban management efficiency directly contributes to environmental sustainability and citizen satisfaction, emphasizing the strategic role of advanced digital ecosystems in achieving sustainable and resilient urban development objectives. The overall model fit indices confirmed the adequacy of the proposed framework, with $\chi2/df = 2.11$, RMSEA = 0.054, GFI = 0.93, AGFI = 0.91, CFI = 0.95, and TLI = 0.94, indicating a satisfactory fit between the conceptual model and the observed data.

Table 4. Model Fit Indices of the Structural Equation Model

Fit Index	Obtained Value	Recommended Value	Model Status
$\chi2/df$	2.11	< 3.00	Acceptable
RMSEA	0.054	< 0.08	Acceptable
GFI	0.93	> 0.90	Good
AGFI	0.91	> 0.90	Good
CFI	0.95	> 0.90	Excellent
IFI	0.95	> 0.90	Excellent
TLI	0.94	> 0.90	Excellent

The goodness-of-fit indices reported in Table 4 confirmed that the proposed structural equation model exhibited satisfactory compatibility with the empirical data collected from smart urban management professionals in Tehran. The $\chi2/df$ ratio of 2.11 was below the recommended threshold of 3.00, indicating an acceptable overall model fit. Similarly, the RMSEA value of 0.054 suggested a low approximation error and confirmed the adequacy of the structural framework. Incremental and comparative fit indices including CFI, IFI, and TLI all exceeded 0.90, reflecting strong explanatory capability and robust structural validity of the proposed model. Furthermore, the GFI and AGFI values demonstrated that the model adequately represented the covariance structure among the observed variables. Collectively, these findings provide substantial empirical support for the theoretical framework suggesting that AR/VR technologies, Digital Twin systems, and Edge Computing infrastructures play a significant role in enhancing urban sustainability, intelligent transportation systems, waste management optimization, and smart resource allocation in modern metropolitan environments.

4. Discussion and Conclusion

The findings of the present study demonstrated that Augmented Reality and Virtual Reality (AR/VR), Digital Twin systems, and Edge Computing technologies significantly contribute to smart urban management efficiency in the domains of urban resource management, waste management, and intelligent transportation. The results revealed that Digital Twin Integration exerted the strongest influence on smart urban management efficiency, followed by Edge Computing Efficiency and AR/VR Applications. Furthermore, smart urban management efficiency significantly predicted environmental sustainability and citizen satisfaction. The correlation analyses also showed strong positive relationships among immersive technologies, digital infrastructure integration, operational responsiveness, transportation optimization, waste management efficiency, and sustainability indicators. These findings collectively indicate that the integration of advanced digital technologies creates a synergistic smart urban ecosystem capable of enhancing operational coordination, predictive governance, environmental performance, and public service quality.

One of the major findings of the study was the strong effect of Digital Twin Integration on smart urban management efficiency. This finding suggests that digital twin systems provide municipal authorities with advanced capabilities for simulation-based decision-making, infrastructure monitoring, predictive maintenance, and urban operational optimization. These results are consistent with previous studies emphasizing the strategic role of digital twins in smart city governance and urban sustainability. Research on smart city platforms based on digital twin technology demonstrated that digital twins improve urban monitoring and support evidence-based decision-making processes through continuous synchronization between physical and digital environments (Dani et al., 2023). Similarly, studies investigating digital twins as frameworks for IoT applications showed that these systems facilitate real-time data interpretation and operational coordination across interconnected urban systems (Mudiyanselage & Sellahewa, 2023). Earlier research on urban ecosystem digital twins also highlighted their importance in improving quality of life and enhancing municipal responsiveness through predictive and adaptive urban management approaches (Mukhacheva et al., 2022). The present findings extend these arguments by empirically confirming that digital twins significantly enhance urban operational efficiency within the context of Tehran's municipal systems.

The significant relationship between Digital Twin Integration and environmental sustainability observed in the present study further supports sustainability-oriented urban governance theories. Digital twins can simulate environmental impacts, optimize resource allocation, reduce energy waste, and support sustainable planning strategies before costly physical implementation occurs. These findings align with studies indicating that combining digital twins with sustainability metrics improves urban environmental governance and long-term planning capacity (Corrado et al., 2022). Likewise, BIM-enabled sustainable urban development frameworks emphasize the importance of interoperable digital systems in supporting twin transitions that integrate digital innovation with environmental sustainability objectives (Jaafari, 2025). Previous research also demonstrated that cloud-based digital twin systems improve environmental quality management and intelligent infrastructure operations in urban contexts (Wei et al., 2023). Therefore, the present study confirms that digital twin ecosystems not only improve technical efficiency but also contribute meaningfully to sustainable urban transformation.

Another important finding of the study was the substantial effect of Edge Computing Efficiency on smart urban management performance and operational responsiveness. This result indicates that decentralized and low-latency data processing architectures improve the responsiveness and adaptability of smart urban systems, especially in transportation management, waste collection logistics, and infrastructure monitoring. Edge Computing enables municipal systems to process real-time information closer to the point of data generation, thereby reducing delays and improving decision-making speed. These findings are consistent with previous studies highlighting the growing importance of distributed computational infrastructures in future smart cities. Research on resource-constrained extended reality operated with digital twins demonstrated that edge-supported XR systems improve operational continuity and real-time interaction under communication limitations (Kamdjou et al., 2024). In addition, studies on 6G-enabled smart city infrastructures emphasized that future urban ecosystems require ultra-low latency communication systems capable of supporting massive real-time urban data flows (Murroni et al., 2023). The findings of the current study support these theoretical assumptions by showing that edge computing infrastructures play a direct role in improving urban service responsiveness and operational coordination.

The results also revealed that AR/VR Applications significantly predicted smart urban management efficiency. This finding highlights the importance of immersive technologies in urban visualization, planning, simulation, citizen engagement, and managerial decision support. AR and VR technologies make complex urban datasets more understandable and interactive, thereby improving collaboration among planners, engineers, administrators, and stakeholders. These findings correspond closely with studies emphasizing the contribution of immersive technologies to sustainable smart city planning and digital urban management. Research on immersive technology and BIM integration showed that AR/VR environments improve spatial cognition, planning accuracy, and stakeholder interaction in smart city systems (Liu et al., 2024). Similarly, studies examining XR technologies in circular economy transitions indicated that immersive technologies support sustainability-oriented decision-making, infrastructure adaptation, and environmental awareness in the built environment (Soman et al., 2024). The present findings therefore confirm that AR/VR technologies function not only as visualization tools but also as strategic governance instruments capable of supporting more intelligent urban management processes.

The positive association between AR/VR technologies and citizen satisfaction is particularly important in the context of participatory urban governance. Immersive technologies can improve transparency, communication, and public understanding of urban projects by allowing citizens to experience infrastructure proposals, transportation scenarios, and urban development plans interactively. Previous literature on the city metaverse and spatial data intelligence suggests that immersive digital environments create new opportunities for interactive urban experiences and collaborative governance (Meng et al., 2025). Likewise, studies on the Internet of City Things emphasize that AI-driven XR environments can improve service accessibility and urban engagement through cost-effective interactive technologies (Bibri & Jagatheesaperumal, 2023). However, previous research also warned that immersive urban systems raise ethical, economic, and social concerns regarding exclusion, privacy, governance accountability, and digital inequality (Tiwari, 2024). The current findings indicate that despite such challenges, immersive technologies can still significantly improve citizen satisfaction when effectively integrated into municipal governance frameworks.

The findings related to intelligent transportation performance also deserve attention. The results demonstrated strong relationships between digital infrastructure integration and transportation efficiency, indicating that smart transportation systems benefit substantially from real-time analytics, simulation technologies, and predictive management systems. These findings align with previous studies on Digital Twin-enabled Internet of Vehicles applications, which showed that digital transportation ecosystems improve mobility coordination, traffic optimization, and transportation safety (Gao et al., 2024). Cross-domain interoperability research similarly demonstrated that IoT-based digital twins support integrated transportation and urban management systems by enabling synchronized communication among urban infrastructures (Campo et al., 2024). The strong relationship between Edge Computing Efficiency and transportation performance observed in this study further confirms the importance of real-time decentralized processing for traffic control, congestion management, and adaptive transportation operations.

The study also demonstrated that smart waste management optimization significantly contributed to environmental sustainability. This finding indicates that digital technologies can improve waste monitoring, collection efficiency, recycling coordination, and resource recovery processes. Previous research on Waste Management 2.0 showed that IoT-enabled waste systems improve environmental performance and operational efficiency in smart cities (Addas et al., 2024). Furthermore, digital twin implementation in waste management systems has been associated with improvements in production efficiency, service optimization, and circular resource management (Barbosa et al., 2023). The present findings support these conclusions and further suggest that waste management systems become more effective when integrated with broader digital urban ecosystems involving immersive visualization, predictive simulation, and distributed data processing.

The strong relationship observed between smart urban management efficiency and environmental sustainability also supports circular economy theories emphasizing the role of digital technologies in sustainable urban transformation. Previous studies indicated that digital technologies support circular economy practices through data transparency, process optimization, intelligent monitoring, and resource efficiency improvements (Chi et al., 2023). Likewise, broader classifications of digital technologies demonstrated their significant contribution to sustainable production systems, lifecycle management, and circular resource flows (Piedra-Muñoz et al., 2025). The findings of the current study extend this perspective by showing that integrated digital urban systems can simultaneously improve operational efficiency and sustainability outcomes in large metropolitan environments.

Another important implication of the study concerns the growing convergence of artificial intelligence, IoT systems, digital twins, immersive environments, and smart infrastructure platforms. Previous literature emphasized that AI, IoT, and big data technologies collectively reshape architecture, engineering, construction, and urban governance practices by enabling predictive analytics, automated monitoring, and intelligent decision support (Rane et al., 2023). Similar conclusions were reached in studies examining leading-edge technologies for architectural and urban design innovation (Rane, 2023). Research on AI-driven analytics in digital twin systems also showed that machine learning enhances urban data interpretation and visualization capacities (Singh et al., 2025). The current study empirically supports these theoretical developments by demonstrating that the integration of multiple digital technologies creates synergistic benefits for urban governance efficiency and sustainability.

The findings additionally highlight the importance of interoperability and integrated information flow management in smart city ecosystems. Effective urban management requires synchronization among sensors, computational systems, infrastructure platforms, and governance processes. Research on information flow synchronization throughout the building lifecycle emphasized the importance of maintaining continuity among digital systems and operational processes (Raitviir & Lill, 2024). Likewise, scientometric analyses of BIM evolution showed that integrated information systems are becoming foundational infrastructures for sustainable built environments (Kuai et al., 2023). The current findings confirm that urban digital ecosystems function more effectively when data flows are integrated and coordinated across sectors.

The present study also supports the argument that successful smart city development depends not only on technological sophistication but also on organizational and human integration. Previous studies emphasized the role of innovation intermediaries in creating inclusive smart cities through collaboration among stakeholders, institutions, and technological actors (Lepore et al., 2023). Similarly, research on blending humanware with software and hardware in smart city design argued that sustainable urban innovation requires integration between technical systems and human-centered governance approaches (Almusaed & Almssad, 2023). Research on Industry 6.0-oriented built environments also stressed the need for strategic integration between digital innovation, sustainability objectives, and human participation (Almusaed et al., 2023). The present findings support these arguments by showing that technological efficiency ultimately contributes to citizen satisfaction only when integrated into broader governance and service systems.

The study findings should also be interpreted in light of the challenges identified in previous research regarding metaverse ecosystems, industrial XR systems, and emerging urban technologies. Studies on the industrial metaverse identified environmental concerns, energy consumption challenges, infrastructure requirements, and governance complexities associated with immersive urban technologies (S. Nleya & M. Velempini, 2024; S. M. Nleya & M. Velempini, 2024). Business ecosystem analyses of metaverse systems further suggested that value creation in digital ecosystems depends on complex interorganizational coordination and platform governance structures (Kontogianni & Ανθόπουλος, 2024). Research on smart city technology implementation also emphasized that emerging technologies may fail to achieve expected outcomes without appropriate institutional readiness, interoperability standards, and strategic planning (Filipovic & Stüttgen, 2023). Therefore, while the findings of the present study confirm the positive effects of AR/VR, Digital Twin systems, and Edge Computing, they also imply that successful implementation requires strong governance capacity, infrastructure readiness, and strategic integration frameworks.

One limitation of the present study was its reliance on cross-sectional data collected from participants within Tehran Municipality and related smart city organizations. Although the sample provided valuable insights into urban technology implementation, the findings may not fully capture long-term technological adaptation processes or causal changes over time. Another limitation concerns the use of self-report questionnaires, which may be influenced by respondent bias, organizational expectations, or subjective perceptions regarding technological efficiency. Additionally, while the study examined several important technological dimensions, other variables such as cybersecurity readiness, financial constraints, governance regulations, and digital literacy were not directly included in the conceptual model.

Future research should employ longitudinal and comparative designs to investigate how digital urban technologies evolve over time and influence sustainability outcomes across different metropolitan contexts. Researchers are encouraged to examine additional technological dimensions such as artificial intelligence governance, blockchain integration, cybersecurity frameworks, digital ethics, and smart energy systems. Comparative studies between different cities and countries may also provide deeper insight into contextual differences in smart city implementation and digital infrastructure readiness. Furthermore, future investigations could explore citizens' behavioral acceptance of immersive technologies and digital urban platforms using mixed-method or experimental approaches.

From a practical perspective, municipal authorities and urban policymakers should prioritize integrated smart city strategies that combine Digital Twin systems, AR/VR technologies, Edge Computing infrastructures, and IoT platforms into unified urban governance ecosystems. Urban managers should invest in interoperable data infrastructures, real-time monitoring systems, and predictive analytics platforms to improve transportation efficiency, waste management operations, and resource allocation processes. In addition, policymakers should develop regulatory frameworks and governance guidelines addressing privacy protection, data security, interoperability standards, and ethical concerns associated with immersive urban technologies. Training programs for municipal employees and public awareness initiatives for citizens may also improve technological adoption and increase public trust in smart urban governance systems.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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References

Addas, A., Khan, M. N., & Naseer, F. (2024). Waste Management 2.0 Leveraging Internet of Things for an Efficient and Eco-Friendly Smart City Solution. *PLoS One*, *19*(7), e0307608. https://doi.org/10.1371/journal.pone.0307608

Almusaed, A., & Almssad, A. (2023). Blending Human Ware With Software and Hardware in the Design of Smart Cities. https://doi.org/10.5772/intechopen.109053

Almusaed, A., Yitmen, İ., & Almssad, A. (2023). Reviewing and Integrating AEC Practices Into Industry 6.0: Strategies for Smart and Sustainable Future-Built Environments. https://doi.org/10.20944/preprints202308.0860.v1

Barbosa, J. M. V., Gómez, Ó. D. C., & García, J. A. G. (2023). A Methodological Approach for Digital Twin Implementation in Waste Management: Improvement of Production and Service Systems. https://doi.org/10.20944/preprints202309.0899.v1

Bibri, S. E., & Jagatheesaperumal, S. K. (2023). Harnessing the Potential of the Metaverse and Artificial Intelligence for the Internet of City Things: Cost-Effective XReality and Synergistic AIoT Technologies. *Smart Cities*, *6*(5), 2397-2429. https://doi.org/10.3390/smartcities6050109

Campo, G. d., Saavedra, E., Piovano, L., Luque, F., & Santamaría, A. (2024). Virtual Reality and Internet of Things Based Digital Twin for Smart City Cross-Domain Interoperability. *Applied Sciences*, *14*(7), 2747. https://doi.org/10.3390/app14072747

Chi, Z., Liu, Z., Wang, F., & Osmani, M. (2023). Driving Circular Economy Through Digital Technologies: Current Research Status and Future Directions. *Sustainability*, *15*(24), 16608. https://doi.org/10.3390/su152416608

Corrado, C., DeLong, S. M., Holt, E., Hua, E. Y., & Tolk, A. (2022). Combining Green Metrics and Digital Twins for Sustainability Planning and Governance of Smart Buildings and Cities. https://doi.org/10.37247/pasus3ed.3.23.19

Dani, A. A. H., Supangkat, S. H., Lubis, F. F., Nugraha, I. G. B. B., Kinanda, R., & Rizkia, I. (2023). Development of a Smart City Platform Based on Digital Twin Technology for Monitoring and Supporting Decision-Making. *Sustainability*, *15*(18), 14002. https://doi.org/10.3390/su151814002

Filipovic, D., & Stüttgen, H. (2023). Vertical and Topical Tracks. https://doi.org/10.1109/wf-iot58464.2023.10539531

Gao, J., Peng, C., Yoshinaga, T., Han, G., Guleng, S., & Wu, C. (2024). Digital Twin-Enabled Internet of Vehicles Applications. *Electronics*, *13*(7), 1263. https://doi.org/10.3390/electronics13071263

Jaafari, Y. E. (2025). BIM 6D as an Interoperable Platform for Twin Transition in Mediterranean Cities : A Delphi-Based Roadmap for Sustainable Urban Development. *Iop Conference Series Earth and Environmental Science*, *1568*(1), 012019. https://doi.org/10.1088/1755-1315/1568/1/012019

Kamdjou, H. M., Baudry, D., Havard, V., & Ouchani, S. (2024). Resource-Constrained EXtended Reality Operated With Digital Twin in Industrial Internet of Things. *Ieee Open Journal of the Communications Society*, *5*, 928-950. https://doi.org/10.1109/ojcoms.2024.3356508

Kontogianni, E., & Ανθόπουλος, Λ. (2024). Exploring the Business Ecosystem and the Value Sources of Metaverse. https://doi.org/10.20944/preprints202403.0027.v1

Kuai, X., Liu, Y., Bi, M., & Luo, Q. (2023). Deciphering Building Information Modeling Evolution: A Comprehensive Scientometric Analysis Across Lifecycle Stages. *Buildings*, *13*(11), 2688. https://doi.org/10.3390/buildings13112688

Lepore, D., Testi, N., & Pásher, E. (2023). Building Inclusive Smart Cities Through Innovation Intermediaries. *Sustainability*, *15*(5), 4024. https://doi.org/10.3390/su15054024

Liu, Z., He, Y., Demian, P., & Osmani, M. (2024). Immersive Technology and Building Information Modeling (BIM) for Sustainable Smart Cities. *Buildings*, *14*(6), 1765. https://doi.org/10.3390/buildings14061765

Meng, X., Li, Y., Liu, K., Liu, Y., Yang, B., Song, X., Liao, G., Wang, S., Yu, Z., Chen, L., Pan, X., & Lin, Y.-M. (2025). Spatial Data Intelligence and City Metaverse: A Review. *Fundamental Research*, *5*(3), 1169-1193. https://doi.org/10.1016/j.fmre.2023.10.014

Mudiyanselage, M. P. D., & Sellahewa, H. (2023). Digital Twins as a Framework for IoT Applications: A Review. 1-6. https://doi.org/10.1109/slaai-icai59257.2023.10365018

Mukhacheva, A. V., Ugryumova, M. N., Morozova, I. S., & Mukhachyev, M. Y. (2022). Digital Twins of the Urban Ecosystem to Ensure the Quality of Life of the Population. *208*. https://doi.org/10.2991/aebmr.k.220208.047

Murroni, M., Anedda, M., Fadda, M., Ruiu, P., Popescu, V., Zaharia, C., & Giusto, D. (2023). 6G—Enabling the New Smart City: A Survey. *Sensors*, *23*(17), 7528. https://doi.org/10.3390/s23177528

Nenković-Riznić, M. (2023). METAVERSE – A Powerful New Instrument for Urban Planning or Yet Another Unfulfilled Tech-Promise? , 92-99. https://doi.org/10.60152/zkhvd3og

Nleya, S., & Velempini, M. (2024). Industrial Metaverse: A Comprehensive Review, Environmental Impact, and Challenges. *Applied Sciences*, *14*(13), 5736. https://doi.org/10.3390/app14135736

Nleya, S. M., & Velempini, M. (2024). Industrial Metaverse: A Comprehensive Review, Environmental Impact and Challenges. https://doi.org/10.20944/preprints202402.1052.v1

Pedro, F. G. (2023). Foundational Aspects of Smart Cities Leading the Digital Economy - An Review. *Journal of Computing and Natural Science*, 35-45. https://doi.org/10.53759/181x/jcns202303004

Piedra-Muñoz, L., García-Granero, E. M., Tarpani, R. R. Z., & Gallego-Schmid, A. (2025). Digital Technologies: Description, Classification, and Links to Circular Economy. *Business Strategy and the Environment*, *34*(6), 6612-6639. https://doi.org/10.1002/bse.4312

Prasittisopin, L. (2024). How 3D Printing Technology Makes Cities Smarter: A Review, Thematic Analysis, and Perspectives. *Smart Cities*, *7*(6), 3458-3488. https://doi.org/10.3390/smartcities7060135

Raitviir, C.-R., & Lill, I. (2024). Conceptual Framework of Information Flow Synchronization Throughout the Building Lifecycle. *Buildings*, *14*(7), 2207. https://doi.org/10.3390/buildings14072207

Rane, N. L. (2023). Integrating Leading-Edge Artificial Intelligence (AI), Internet of Things (IoT), and Big Data Technologies for Smart and Sustainable Architecture, Engineering and Construction (AEC) Industry: Challenges and Future Directions. *International Journal of Data Science and Big Data Analytics*, *3*(2), 73-95. https://doi.org/10.51483/ijdsbda.3.2.2023.73-95

Rane, N. L., Choudhary, S. P., & Rane, J. (2023). Leading-Edge Technologies for Architectural Design: A Comprehensive Review. *International Journal of Architecture and Planning*, *3*(2), 12-48. https://doi.org/10.51483/ijarp.3.2.2023.12-48

Rangarajan, S., & Al-Quraishi, T. (2023). Navigating the Future of the Internet of Things: Emerging Trends and Transformative Applications. *BJIoT*, *2023*, 8-12. https://doi.org/10.58496/bjiot/2023/002

Singh, S. K., Kumar, S., Goyal, S., Arya, V., Attar, R. W., Gupta, B. B., Alhomoud, A., & Chui, K. T. (2025). Leveraging AI and Machine Learning for Enhanced Data Analytics and Visualization in Database Management With Digital Twins. *Journal of Database Management*, *36*(1), 1-29. https://doi.org/10.4018/jdm.388135

Soman, R. K., Nikolić, D., & Sanchez, B. (2024). Extended Reality as a Catalyst for Circular Economy Transition in the Built Environment. 171-193. https://doi.org/10.1007/978-3-031-39675-5_10

Tiwari, A. (2024). A Review of the Metaverse and Its Implications for Urban Environments: Ethical, Social, and Economic Considerations. https://doi.org/10.20944/preprints202406.0845.v1

Wei, Z., Nie, J., & Zhang, W. (2023). Intelligent Lighting Design of Cloud Computing Platform Based on Digital Twin Historic Landscape Blocks—Take Yu Garden Commercial Street in Shanghai as an Example. *Concurrency and Computation Practice and Experience*, *36*(7). https://doi.org/10.1002/cpe.7975