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Systematic Review

How Extended Reality Is Shaping Smart Cities: A Systematic Literature Review

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Abstract

XR technologies enhance the sustainable development of urban areas by merging digital and physical worlds. In smart city contexts, XR has been applied in miscellaneous ways, from supporting urban planning and design through immersive visualization, to improving traffic and navigation services via real-time overlays, and to enhancing public safety and emergency response through simulation and situational support. However, the literature does not clearly categorize XR application domains in smart cities, interaction methods, and types of sensory feedback. This study presents an SLR reported in accordance with the PRISMA 2020 guidelines. We included 92 studies published between 2009 and 2024, proposing a classification of application domains, interaction modalities, and sensory feedback. We searched Scopus, Web of Science, and IEEE Xplore using predefined search terms and eligibility criteria. This review offers a comprehensive overview of nearly 20 years of XR research in smart cities, highlighting established practices and guiding future application development and research directions.

Keywords: extended reality; interaction design; perception; sensory feedback; smart city; urban intelligence

1. Introduction

The term smart city refers to the use of digital technologies and ICTs to enhance citizens' quality of life, optimize urban services, and support sustainable development [1]. In this light, smart cities are technologically advanced environments that are also pivotal in promoting environmentally responsible, socially inclusive, and economically viable urban development. Smart cities integrate technologies and resources intelligently to create connected, livable, and sustainable urban environments [2]. The concept emerged over the past decade, highlighting the potential of ICTs to improve efficiency, competitiveness, and address challenges such as poverty, social exclusion, and environmental degradation [3].

Smart cities fall within the transdisciplinary field of urban informatics, which involves applying data and digital technologies in urban contexts at the intersection of people, place, and technology [4]. Experts in urban informatics collect and analyze data using a range of scientific, engineering, and computational methods, such as in situ, remote, or mobile sensing, image processing, natural language processing, statistical modeling, network analysis, machine learning, and GISs [5].

The term urban intelligence is often used interchangeably with smart city, but with a nuanced distinction: while smart city emphasizes technological applications, urban

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intelligence focuses on data-driven analysis and decision support. Kitchin [6] defines it as a city's ability to monitor, manage, and regulate flows and processes—often in real-time—using large-scale data to model, predict, and simulate urban dynamics. Thus, smart cities are not merely sensor-rich environments; they are shaped by human interactions, social relationships, and a sense of place. From a sustainability perspective, urban intelligence provides a data-driven foundation for creating resilient, resource-efficient cities. It enables the continuous monitoring of environmental and socio-economic indicators, the early detection of risks, and the evaluation of alternative policy scenarios.

XR technologies have demonstrated significant potential in advancing smart city development by supporting strategic decision-making [7] and transforming how we plan, design, construct, and operate built environment assets [8]. XR serves as an umbrella term for immersive and spatial computing technologies, encompassing VR, AR, and MR. These technologies facilitate interactions between users and digital systems—whether through computers or wearable devices—within real, virtual, or blended environments, stimulating users' senses [9]. XR applications hold immense potential in smart cities [10], particularly in enhancing training through realistic simulations, providing valuable feedback, enabling safe exploration of risky or expensive procedures, and promoting the understanding of complex concepts.

XR technology has gained significant attention in urban development due to its potential to merge the digital and physical worlds [11]. Numerous studies have explored XR's role in enhancing urban planning, design, and management [12,13]. For instance, AR has been employed to visualize architectural designs within real-world settings, thereby improving stakeholder engagement and facilitating more informed decision-making processes [14]. Similarly, VR environments have been utilized to simulate urban spaces, allowing planners to test and optimize designs prior to actual implementation [15]. Furthermore, the integration of MR has shown promise in collaborative planning sessions, where multiple users can interact simultaneously with both physical models and digital overlays [16].

From a sustainable urban development perspective, XR applications can facilitate interaction between complex urban data and human decision-makers. In planning and design, for example, immersive simulations can be used to explore alternative layouts and assess environmental and social impacts before implementation, thus avoiding resource-intensive trial and error on site [7,8,12]. In maintenance, operation, and monitoring, AR overlays facilitate condition-based interventions on buildings and infrastructure, thereby improving energy efficiency and reducing material waste [7]. XR-enabled visualizations of real-time flows can help planners and drivers reduce congestion and emissions in mobility and traffic management, while XR-based training environments can improve safety in high-risk situations. Finally, participatory and citizen-facing XR applications facilitate communication of complex information and support more inclusive decision-making processes, thereby aligning smart city initiatives with broader sustainability objectives [10].

Despite growing interest, the literature on XR in smart cities remains fragmented. Most studies focus on specific applications, lacking an overarching framework. To date, no systematic classification exists regarding XR application domains, user interaction mechanisms, or the types of sensory feedback involved.

To address these gaps, we conducted an SLR to investigate the applications of XR in smart cities. This SLR is reported in accordance with the PRISMA 2020 guidelines to ensure transparency and reproducibility of the search and study selection process. Our goal is to provide a comprehensive classification to support researchers and developers in designing effective XR solutions for urban environments. Specifically, we address the following research questions:

- RQ1. What are the key application domains of XR in smart cities?
- RQ2. How do users interact with objects in these applications?
- RQ3. What types of sensory feedback are provided?

The paper is structured as follows: Section 2 outlines the SLR methodology reported in accordance with the PRISMA 2020 guidelines. Section 3 presents the findings, including the classification of application domains, interaction types, and sensory feedback. Section 4 discusses the results, and Section 5 concludes the study.

2. Methods

This review followed an SLR methodology booth [17], conducted in two main phases in accordance with the PRISMA 2020 guidelines: paper selection and paper analysis.

2.1. Paper Selection

The paper selection process involved five key steps:

1. Planning the search strategy.
2. Defining the research questions.
3. Identifying keywords and search criteria.
4. Searching for relevant papers.
5. Defining and applying exclusion criteria.

In the search planning, we used three bibliographic databases: Scopus (www.scopus.com, accessed on 2 December 2024), IEEE Explore Digital Library (www.ieeexplore.ieee.org, accessed on 5 December 2024), and Web of Science (www.webofknowledge.com, accessed on 9 December 2024). The search was carried out in December 2024. To address our research questions, we identified three sets of keywords.

In this review, “smart city” is used as an overarching concept, while “urban intelligence” denotes data-driven monitoring, modeling, and decision support capabilities. Both terms were included in the search query to account for terminological variation across publications. However, they are not considered interchangeable in the synthesis. Throughout the paper, “smart city” is used as the primary framing, and “urban intelligence” is only used when a study explicitly adopts a data-centric perspective.

The first set pertains to the relevant XR technologies, including “Virtual Reality”, “Augmented Reality”, “Mixed Reality”—which combines VR and AR [18], and “Extended Reality”, a broader term encompassing all immersive reality formats [9].

The second set of keywords was designed to limit the search to the domains of urban intelligence and smart cities, which are the primary focus of this review.

The third set of keywords aimed to refine further the search to papers that referenced “perception,” “interaction,” “manipulation,” or “handling,” reflecting the interactive and perceptual dimensions of XR experiences that are the focus of our investigation. Thus, the search terms used were:

(“augmented reality” OR “virtual reality” OR “mixed reality” OR “extended reality”)

AND

(“urban intelligence” OR “smart city”)

AND

(“perception” OR “interaction” OR “manipulation” OR “handling”)

The search was performed within the title, abstract, and keywords fields for Scopus, and across all metadata fields for IEEE Xplore and Web of Science. This initial search using the defined keywords yielded a total of 771 papers (see Table 1).

Table 1. Outcome of the Searching Phase.

Database	Search Fields	Documents Returned	
		Before Refinement	After Refinement
Scopus	Title-Abs-Key	246	168
IEEE Xplore	All metadata	235	127
Web of Science	All fields	290	205
Total		771	500

To refine the search, we applied additional inclusion criteria, where applicable, to include only scientific papers that met the following conditions:

- Written in the English language.
- Published in journals or conference proceedings (i.e., conference papers and book chapters).
- Published between 2009 and 2024.
- Relevant to the fields of urban design and management, engineering, and computer science.

Although the concept of a "smart city" was introduced as early as 1998 and 2000 [19,20], the bulk of relevant literature begins around 2012 [21]. Similarly, the literature on urban intelligence dates to 2009 [22,23], which marked the starting point for our review period.

The study selection process is summarized in the PRISMA flow diagram (Figure 1). After applying these initial criteria, we reduced the total number of articles to 500. Since this process was conducted separately for each database, this total included duplicate. Once duplicates were removed, the number of unique articles was reduced to 378. At this stage, it is important to note that neither the titles nor the abstracts of the articles have been read.

No formal quality assessment or scoring procedure was applied to the selected studies. This choice is consistent with the aim of this work, which is to provide a systematic mapping and classification of XR applications in smart city contexts rather than to evaluate the effectiveness of individual solutions. To ensure baseline methodological relevance, eligibility was addressed through the inclusion and exclusion criteria (EC1 and EC2).

We then assessed the content of the remaining 378 articles by defining and applying two sets of exclusion criteria: EC1 and EC2. The exclusion criteria were applied sequentially and served different purposes in refining the dataset. EC1 was used as a first-level screening. This step significantly reduced the dataset by eliminating papers that were thematically adjacent but not directly aligned with the scope of this review. The first set (EC1) was applied after reading the title and abstract of each article. The criteria were as follows:

- The article does not mention VR, AR, XR, or MR technologies.
- The technologies discussed are not applied to the context of urban intelligence or smart cities.
- The article presents a literature review rather than a user study.
- The result of applying the EC1 was a list of 153 papers.

We excluded 112 articles because they did not refer to VR/AR/XR/MR technologies, 118 articles as the technologies were not applied to the urban intelligence or smart city context, and 4 articles because they presented literature reviews instead of user studies. Next, we conducted a full-text assessment of the remaining articles to apply the second exclusion criterion (EC2), excluding studies that, despite addressing VR, AR, XR, or MR technologies, did not consider interaction or perception in the context of the target environment.

After applying the EC2, we excluded 50 articles, leaving a final set of 92 articles that we formally reviewed. EC2 was applied through full-text screening and aimed to ensure conceptual relevance to the research questions. This second filtering step ensured that the final dataset was not only technologically relevant but also aligned with the focus on interaction modalities and sensory feedback. Disagreements, when applicable, were resolved through discussion among the authors. No automation tools were used in the data collection process.

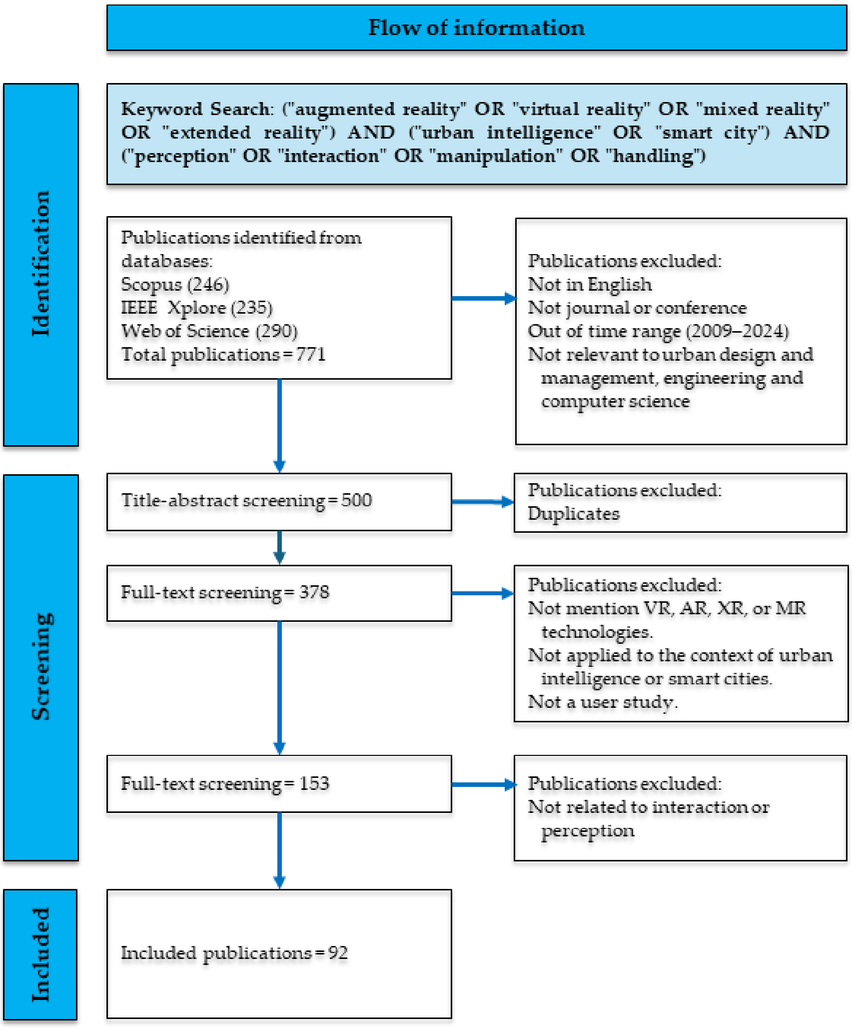

Figure 1. PRISMA flow diagram illustrating the identification and selection process leading to the final sample of 92 papers.

2.2. Paper Analysis

The final dataset included 92 publications, consisting of 19 journal articles, 69 conference papers, and 4 book chapters (see Figure 2). The dataset is dominated by conference papers (n = 69), and this aspect is considered in the Discussion when interpreting the maturity of the evidence base and the typical depth of validation reported in the included studies. Notably, over 75% of the papers were published between 2018 and October 2023, reflecting the growing adoption of XR technologies in smart city research. More than one-third of the developments appeared between 2021 and 2023, indicating an accelerated interest and development in the field.

We extracted bibliographic information, application domain, XR technology, interaction modality, input/output devices, tracking approach, and sensory feedback. A coding scheme was developed iteratively based on the research questions and refined during pilot coding.

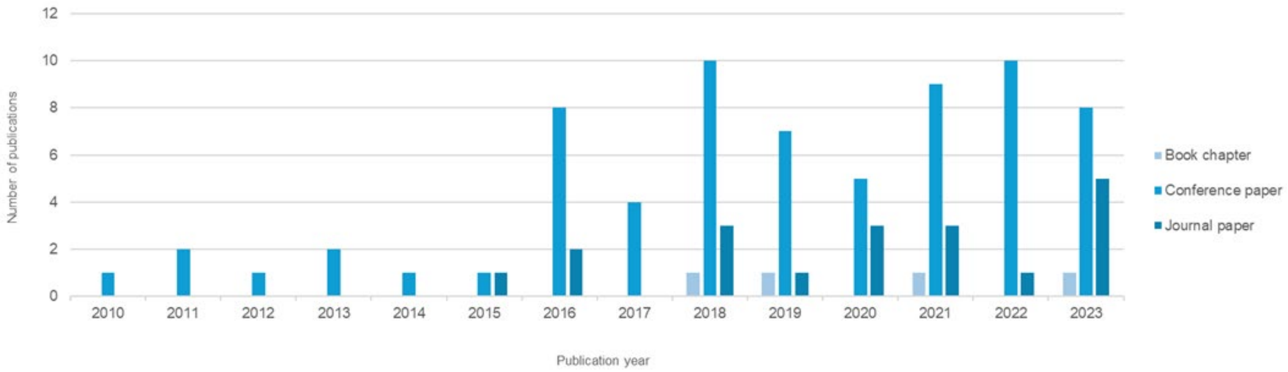

Figure 2. Temporal distribution of selected papers, according to publication type.

3. Results

We now present the results from coding the 92 selected papers. These results are organized according to three key areas: (I) application domains, (II) technology adoption and interaction modalities (including output/input devices and tracking technologies), and (III) sensory feedback.

3.1. Application Domains

To address RQ1, we categorized the papers based on the smart city domains where XR technologies have been implemented. This analysis revealed six distinct domains (see Figure 3 and Table 2), each with unique applications and features.

Figure 3. XR Application Domains in Smart Cities.

3.1.1. Planning and Design

XR has proven to be a valuable tool in the domains of urban planning and design. For instance, this technology allows urban planners and architects to create immersive simulations of urban environments, enabling them to visualize and test different designs and layouts before implementation [24–27]. By providing realistic representations of urban spaces, XR enhances decision-making processes and optimizes spatial planning. AR is frequently used to overlay digital models onto physical sites, giving designers a clear and realistic preview of how future structures will integrate with existing environments [28].

Likewise, VR enables users to take virtual tours through urban areas, improving visualization and facilitating the refinement of architectural designs [29–32]. This immersive approach also facilitates the assessment of potential environmental and community impacts of new developments, providing a more comprehensive evaluation process. While planning and design primarily targets envisioning and evaluating future interventions, XR is also increasingly used once infrastructure is deployed, supporting day-to-day operation, monitoring, and maintenance tasks.

3.1.2. Maintenance, Management, and Monitoring

AR has emerged as a valuable tool in the maintenance, management, and monitoring of urban infrastructure. AR systems allow maintenance teams to visualize and manage infrastructure more efficiently [33]. For instance, AR can be used to monitor sea levels [34], water systems [35,36], and energy infrastructure [37], reducing the risk of accidental damage and improving the efficiency of repairs. Real-time data overlays provide critical information about infrastructure status [38], enabling workers to navigate repair processes with greater accuracy. Moreover, AR can provide real-time data on environmental conditions and urban services [39,40], such as traffic and parking systems [41], thereby supporting the effective monitoring and management of urban ecosystems. VR environments further contribute to remote monitoring and control of infrastructure, such as monitoring polluted gas concentrations [42] or managing street lighting systems [43]. These systems allow real-time data visualization, facilitating more efficient management processes [44]. Beyond infrastructure-centric use cases, XR applications extend to citizen-facing services, where real-time information and guidance become central—particularly in mobility, navigation, and traffic-related scenarios.

Table 2. XR Application Domains in Smart Cities.

XR Application Domains	Use Cases
Planning and Design (n = 9)	Cities [24–27,30] Authoring tools [28] Viewscape [31,32] Underground commercial streets [29]
Maintenance, Management and Monitoring (n = 25)	Gas pollution [42] Geo-infographics [38] Green and smart buildings [44] Water Management Systems [35,36] Pedestrian routes [45] Energy management system [37] Urban data [46–51] Sea level [34] Housing registry information [40] Air b&b [52] Business localization [53] Smart parking system [41,54,55] Urban objects [56] Street lighting management [43]
Navigation, Transportation and Traffic Management (n = 18)	Campus [39] Cities [57–61] Archaeological parks [62] Cyclist / pedestrian behavior [63,64] Inclusion: Visually Impaired [65], Mobility-Impaired [66], Deaf [67], Elderly [68] Driving experience [69–73]

Table 2. *Cont.*

XR Application Domains	Use Cases
Entertainment, Tourism and Cultural Heritage (n = 26)	Tourism system [74–80] Digital Reconstruction of Historical Site [81] Urban games [82–87] Urban art [88,89] Authoring tools [90] Cultural experiences [91–94]
Public Safety, Emergency Response and Healthcare (n = 8)	Site safety [33,95] Traffic system: General [96], Emergency services [97,98] Cityscape Protection [99] Healthcare services: Cognitive assistance [100] Caregivers assistance [101]
Public Engagement and Participation (n = 10)	Housing complex [102] Participative practices [103,104] Community interaction [105,106] Civic participation [37,70,107,108] Fab-living-lab [109]

3.1.3. Navigation, Transportation, and Traffic Management

Both AR and VR applications provide real-time navigation assistance, hazard detection, and traffic updates, improving safety and efficiency for drivers [69–73]. These technologies also deliver real-time traffic information to pedestrians, contributing to smoother urban mobility [63,64]. VR simulations are particularly useful in modeling traffic scenarios, enabling planners to analyze and optimize traffic flow and better manage congestion. Through simulated transportation conditions, AR supports the strategic planning of transportation networks, enhancing the adaptability and efficiency of urban transit systems. Additionally, AR integration has been valuable for providing navigation support to visually impaired individuals [65], mobility-impaired users [66], the deaf [67], and the elderly [68]. In addition to functional mobility support, XR also shapes how people experience the city, enabling richer place-based engagement through tourism, entertainment, and cultural heritage applications.

3.1.4. Entertainment, Tourism, and Cultural Heritage

Both VR and AR have significantly transformed the fields of entertainment, tourism, and cultural heritage [110]. AR enriches tourist experiences by overlaying interactive content on historical sites and landmarks, allowing visitors to access detailed historical information in real-time [81]. VR has expanded access to cultural heritage by enabling virtual tours of historical and cultural sites, making them accessible to a global audience and promoting both tourism and education [74–78]. Moreover, AR has been used to reconstruct historical events and environments, offering deeper and more immersive experiences that foster a better understanding of cultural heritage [91,93,94]. XR technologies, particularly AR, have also contributed to the development of urban games, creating immersive, interactive environments that blend physical and digital spaces. These games transform city landscapes into dynamic gaming experiences using handheld displays [82–87]. Moving from experiential and cultural use cases to higher-stakes contexts, XR is also adopted to enhance public safety and healthcare-related services, where training, situational awareness, and risk reduction are key drivers.

3.1.5. Public Safety, Emergency Response, and Healthcare

XR technologies play a significant role in enhancing emergency responder training by simulating various disaster scenarios. AR can provide real-time information and navigation support during emergencies, helping responders quickly and safely reach affected areas, thereby improving situational awareness and response efficiency [97,98]. This capability also enables the simulation of emergency scenarios, improving the knowledge and skills of personnel through practical, immersive training experiences. VR platforms for smart cities have been developed to enhance public safety by integrating XR, sensor networks, and communication systems [33,95]. Additionally, there is a growing integration of advanced technologies in healthcare, focusing on cognitive assistance [100] and caregiver support [101]. These innovations are revolutionizing patient care by streamlining processes, enhancing precision, and improving the overall quality of life for citizens. Finally, XR is not only used to support professionals and services, but also to involve citizens directly in urban decision-making, enabling participatory planning and public engagement.

3.1.6. Public Engagement and Participation

In urban planning, AR and MR technologies have proven effective in increasing public engagement by offering immersive visualizations of proposed projects [109]. These technologies allow residents to experience potential urban changes firsthand, enabling them to provide more informed and meaningful feedback on development initiatives. AR platforms have been used to visualize proposed plans, facilitating greater citizen participation in the planning process [102,107]. Some applications have even created virtual public forums, where community members can interact with urban planners and contribute to discussions on decision-making [103]. AR has also been employed in participatory planning workshops, allowing stakeholders to collaboratively explore and modify urban plans in real-time [104–106]. These technologies promote transparency and inclusivity in urban development, fostering more engaged and informed communities.

3.2. Technology Adoption and Interaction

The adoption of XR technologies in smart cities is closely linked to the development and integration of diverse interaction modalities that cater to the varying needs and preferences of users. As these technologies become more widespread, the success of XR applications hinges on how intuitively users can interact with virtual environments. The choice of input and output devices, as well as the tracking technologies employed, plays a critical role in shaping the user experience and determining the overall effectiveness of XR systems within smart city contexts. This section systematically analyzes the types of output and input devices, as well as the tracking technologies essential for facilitating effective interaction in XR environments.

3.2.1. Output Devices

Figure 4 presents the five main types of vision-based XR systems—Head-Mounted Displays (HMDs), hand-held displays (HHDs), monitors, projectors, and Cave Automatic Virtual Environments (CAVEs)—which are commonly featured in the current literature.

Since the advent of the current XR trend, HMDs have become the most prominent and widely recognized technology associated with XR experience. In the existing body of literature, approximately half of the studies focus on HMDs in some capacity (see Table 3). Devices such as the HTC Vive (n = 4), Microsoft HoloLens (n = 5), Oculus Rift/Quest (n = 7), and AR Glasses (n = 6) are frequently used.

Figure 4. HMD | HHD | Monitor | Projector | CAVE–XR system.

Table 3. Output Devices in XR Smart Cities Integration.

Type		Source
Head-mounted display (n = 42)	HTC Vive	[27,42,46,57,64]
	Oculus	Rift [29,31,44,61,71,109,111]; Quest [61]
	Microsoft HoloLens	[24,25,34,51,100]
	AR Glasses	[27,45,104,107,112]
	Others	Smartphone-based [56]; VR Box Virtual Reality Head Mounted Display [39]; Google Glass [53]; Not specified [43,45,47,49,50,52,60,63,67,74,92,95,96,99,112–114]
Hand-held display (n = 48)	Smartphone	[27,34,36,37,43,45,48,52,53,55,59,60,63,66–68,75–77,79–81,84–86,88–90,98–102,108,115]
	Tablet	[27,38,40,45,52,59,66,68,75,85,86,90]
CAVE (n = 5)		[24–26,45,109]
Monitors (n = 5)		[27,42,72,104,109]
Projectors (n = 10)		[31,45,70,71,79,86,87,95,96,102]

However, VR does not always require an HMD. Any display technology capable of creating an immersive experience by sufficiently covering the user's FOV can be employed. Accordingly, studies in the existing literature also explore the use of monitors (n = 5), projectors (n = 10), CAVE systems (n = 5), and other display setups (n = 20) as VR technologies. Additionally, AR is being increasingly integrated into smart city applications.

Most studies (n = 36) focus on developing smartphone-based AR solutions, while a smaller subset (n = 12) investigates tablet-based implementations. While smartphones offer widespread accessibility and portability, tablets may provide enhanced visualization due to their larger screen sizes. However, finding the right balance between user convenience and immersive experience remains critical when selecting AR platforms for smart city applications.

3.2.2. Input Devices and Tracking Technologies

To enable natural and effective interaction in XR environments, there is a significant need for precise and multimodal input devices that allow users to engage with various objects. These input devices range from standard pointing tools, such as a mouse, to more specialized VR controllers.

Current research categorizes movement-based input modalities into three main types: devices controlled primarily by hand, head/eye, or full-body motion (see Table 4).

Table 4. Input Devices and Tracking Technologies in XR Smart Cities Integration.

Type		Source
Hand movement-based input (n = 62)	VR controller	[27,29,31,32,45,46,57,61,92,96,99,112]
	Mouse and keyboard	[27,42,109]
	Hand/finger/arm movement tracking (e.g., leap motion and Kinect)	[23,49,71,104,106,112,114]
	Touchscreen	[27,31,32,36–38,40,43,48,52,53,55,57,59,60,63,66,68,75,76,78,79,81,82,84,86–89,91,100,103,104,109,110,113,115]
	Other	Steering wheel and pedals [71]
Eye/head movement —based input (n = 18)	Head tracking	[23,26,30,47,104,106,112–114]
	Eye tracking	[23,26,30,47,58,71,99,104,112]
General body movement (n = 14)	Camera, sensors or other tracking device	compass, accelerometer, optical flow, filtering [65]; geo-location, RFID [28]; IoT [56]; vibration, optical sensor [68]; position tracking system, tactile sensor [44]; water-quality sensor [35]; standard body sensor [82]; particulate matter, temperature, and humidity [45]; LoRa, NB-IoT, and 6LoWPAN [43]; motion sensor and the FAAST [109]; proximity sensors [98]; EEG [113]; AV sensors [72]; temperature, humidity, smoke, harmful gas sensors [112]
Voice input (n = 2)	Speaker/speech	sound system [44]; speech-based input [72]

A critical aspect of navigation and interaction in XR environments is the ability to track the user's gaze and attention. In XR systems, both head movement and orientation (n = 9) and eye-tracking (n = 9) are essential modalities for human–computer interaction.

These technologies are used to interact with the virtual environment and assess where the user's attention is directed. Head movement and orientation capture macro-level attention, tracking broader shifts in focus, while eye-tracking devices—either integrated into the HMD or mounted on a monitor—capture micro-level attention, focusing on specific virtual or urban objects. Additionally, voice control input (n = 2), enabled through sound-based devices, allows users to interact using vocal commands.

All reviewed studies primarily focused on single-user interactions, where individuals engage with XR systems independently, without collaboration or shared environments. Only two papers [25,106] addressed multi-user interactions in XR contexts. Cirulis [106] proposed an AR environment enabling multiple users to interact with shared virtual elements—such as 3D models and intelligent avatars—within large indoor or outdoor spaces, including smart city infrastructures.

In contrast, Davis et al. [25] developed a collaborative application within a CAVE system, allowing users to co-create 3D urban models and simulate large-scale cityscapes. This approach supports various domains, including intelligent transportation, smart city planning, and infrastructure development.

3.2.3. Sensory Feedback

Interactions between humans and XR environments rely on timely and consistent sensory feedback, incorporating stimuli from multiple senses, including the haptic sense.

Multimodal interaction—which engages multiple sensory inputs such as vision, sound, and touch—enables users to interact with XR environments more naturally and effectively. The effectiveness of these sensory modalities in smart city applications, such as urban navigation, public service interaction, and entertainment, plays a critical role in influencing the adoption rate and overall impact of XR technologies.

Visual Feedback

In smart city applications, XR experiences are primarily driven by visual feedback, utilizing immersive technologies to provide interactive, real-time representations of urban environments. A critical factor in the effectiveness of these experiences is visual comfort [29], as prolonged exposure to virtual or augmented environments may lead to eye strain, discomfort, and reduced task performance. Key technical parameters—such as resolution, frame rate, FOV, and the alignment between virtual and real-world elements—substantially influence visual comfort.

Sun et al. [29] emphasize the importance of minimizing disruptive visual factors during the design of virtual environments and 3D models. Their study shows that in virtual commercial streets, high-gloss materials can enhance visual comfort. Similarly, Noland et al. [45], using eye-tracking, demonstrate that object arrangement, depth cues, and lighting significantly affect user perception, with optimized spatial features reducing visual fatigue.

The perception of urban form in 3D city models is shaped by how users interpret depth, shape, and distance within VR environments [27]. Vigier et al. [27] identify rendering features—such as stereoscopy, viewpoint, FOV, and overall realism—as key influences on spatial perception. Depth perception, in particular, depends on a combination of physiological and psychological cues [45]:

- Physiological cues:
    - ○ Binocular: accommodation, vergence, stereopsis.
    - ○ Monocular: motion parallax.
- Psychological cues (monocular):
    - ○ Retinal image size, linear/aerial perspective, shading.

3D models also enable users to alternate between egocentric (first-person) and allocentric (map-like) spatial perspectives, which substantially affect spatial cognition [116]. Notably, egocentric views often result in distance underestimation, known as distance compression [117]. While the exact mechanisms remain uncertain, contributing factors may include limited FOV, inadequate realism, or distortions from the virtual camera [118,119].

Vigier et al. [27] further argue that visual immersion and interface design play a pivotal role in how users interpret urban morphology. When urban indicators or datasets are integrated into 3D city models, the chosen viewing mode (e.g., first-person vs. bird's-eye) can significantly alter the user's understanding of urban form. They recommend either adapting visualizations based on the selected view or promoting multi-perspective exploration to enhance urban analysis.

Although visual feedback remains dominant, there is a growing interest in multisensory integration—notably auditory and haptic feedback—to increase immersion and enrich user interaction in XR-based smart city systems.

Auditory Feedback

The integration of sound, voice, and auditory cues in XR systems is playing an increasingly significant role in the development of smart cities. Auditory feedback enhances immersion, supports hands-free interaction, improves accessibility, and strengthens the connection between physical and virtual environments.

One emerging application involves motion-triggered audio in public spaces. For example, statues equipped with sensors and speakers can "speak" to passersby, offering historical or contextual information via AR overlays [82]. These systems create interactive, informative urban experiences by combining physical structures with digital storytelling.

Audio-based AR platforms are also transforming urban tourism. Applications like AudioNear use GPS-triggered audio tracks to deliver location-specific content as users approach landmarks [76]. Through mobile devices and headphones, users receive hands-free auditory guidance, merging physical exploration with digital narratives.

Beyond engagement, auditory feedback enhances accessibility. For instance, XR systems designed for driving instruction offer real-time audio cues tailored to individuals with hearing impairments [70,73]. In education, AR platforms combining visual and auditory channels support communication for deaf and hard-of-hearing users, promoting inclusive learning environments [71].

Auditory cues also improve navigation and situational awareness in urban spaces. In XR-based driving simulators, audio guides help users maintain speed or respond to road conditions, ensuring realism and reducing cognitive load. Similarly, auditory AR supports orientation in unfamiliar urban areas by delivering environmental information while maintaining spatial awareness [71].

In urban planning, VR sound simulations enable the testing and optimization of urban soundscapes. Using acoustic engineering principles, planners can model how sound interacts with various materials (e.g., glass, stone, vegetation) [7,65]. These simulations help improve acoustic comfort in public spaces, ensuring that sound contributes positively to urban quality of life.

Ultimately, XR platforms enable citizens to engage in auditory assessments of urban environments. Users can record ambient sounds (e.g., traffic noise) and provide contextual notes, generating valuable input for planners and decision-makers [26]. This participatory approach ensures that the acoustic dimension of smart cities evolves based on real-time, user-driven feedback.

Tactile Feedback

The integration of haptic and tactile feedback in XR is reshaping how users engage with digital and physical elements in smart city environments. These technologies bridge the virtual-physical divide by enabling users to perceive and interact with virtual objects, thereby expanding interaction beyond visual and auditory stimuli.

Recent innovations enable experiences involving force and motion perception, and experimental research even explores the future inclusion of taste and smell as sensory inputs [44]. Despite technological advances, current limitations in sensing still make tactile interaction largely dependent on the integration of computer graphics and VR. As sensor systems evolve, XR designers are increasingly able to embed virtual objects into real-world contexts, enabling users to interact with both tangible and intangible elements simultaneously [110].

In urban planning and design, haptic devices support the manipulation of 3D models, allowing users to rotate, inspect, and modify virtual structures [83]. This tactile interaction enhances spatial understanding and supports early-stage decision-making prior to physical construction. Force feedback interfaces provide users with simulated sensations of weight and texture, improving comprehension of complex architectural forms [51].

Beyond planning, tactile feedback is applied in public interfaces, particularly touchscreens. However, hygiene, especially in shared spaces, has prompted the development of contactless haptic technologies, which maintain the benefits of touch interaction without physical contact, improving both safety and user comfort [105].

Safety applications are another critical area for haptic integration. In XR-assisted driving scenarios, multisensory interfaces combining haptic and auditory cues help reduce cognitive load, enabling drivers to remain focused while receiving real-time data from urban infrastructure [99]. These systems enhance decision-making in complex traffic situations.

Haptic feedback also enriches AR-based urban interactions. Users can "touch" virtual buildings or infrastructure using devices that simulate force and surface properties [51], providing a realistic, immersive experience. This tactile immersion strengthens the connection between the digital cityscape and its physical counterpart, contributing to more intuitive and embodied interactions in smart city contexts.

4. Discussion

The proposed classification and findings from our SLR offer valuable insights to address the research questions and inform future XR application development in smart city contexts. To answer RQ1, we clustered the 92 reviewed studies into six application domains, based on shared themes and keywords:

- Planning and Design;
- Maintenance, Operation, and Monitoring;
- Navigation, Transportation, and Traffic Management;
- Entertainment, Tourism, and Cultural Heritage;
- Public Safety, Emergency Response, and Healthcare;
- Public Engagement and Participation.

Although research on XR in smart cities is still emerging, the diversity across these domains is notable. For example, in the Healthcare domain, only two studies were identified [101,102], revealing a significant gap [120] and highlighting the need for further investigation in this area. Despite this limited representation, smart city ecosystems offer several plausible pathways for XR-enabled healthcare services [121,122]. Potential applications include XR-assisted remote triage and guidance for community-based interventions, augmented support for caregivers and assisted living in smart regions, and immersive training and simulation platforms for emergency response coordination across urban infrastructures. In data-rich urban environments, XR may also function as an interface to urban intelligence capabilities by visualizing context-aware information—such as the availability of nearby services, environmental risk factors, or real-time incident data—to support decision-making by practitioners and citizens.

In Entertainment, Tourism, and Cultural Heritage, some studies explored virtual environments based on real-world scans [123]. Only one paper [31] employed LiDAR technology to reconstruct environments via 3D scanning, while the majority relied on fully computer-generated assets, indicating limited adoption of real-world point cloud data in current XR applications.

Understanding these application areas is essential for optimizing XR implementation in smart cities. Each domain poses unique challenges and opportunities, requiring tailored XR solutions. Identifying and targeting these domains can help cities deliver citizen-centric services, drive innovation, and promote sustainable urban development.

To address RQ2, concerning XR technologies and interaction types, we observed a nearly equal split between VR-based studies (n = 52) and AR-based studies (n = 48). Usage patterns varied by domain. In Entertainment, Tourism, and Navigation, most studies implemented AR via smartphones or tablets, offering intuitive, location-based guidance and real-time environmental overlays [124]. The portability and accessibility of these devices enhance usability and user satisfaction in mobile urban contexts [125].

In contrast, Planning, Design, and Maintenance applications often leveraged VR to support immersive visualization, modeling, and monitoring through HMDs or CAVE systems. These platforms enhance spatial understanding, support collaborative decision-making, and offer realistic representations of urban infrastructure [126]. Immersive environments improve both the accuracy of design assessments and the efficiency of planning processes [127].

To further enhance the analytical depth of this review, a comparative analysis of XR approaches across application domains is presented. While VR, AR, and MR are often discussed collectively under the XR umbrella, our findings highlight clear domain-dependent differences in their effectiveness, scalability, and contextual suitability.

VR-based solutions are predominantly adopted in Planning and Design and Maintenance domains, where immersive visualization and spatial understanding are critical. These applications benefit from high levels of realism and controlled environments; however, they are less scalable at city-wide levels due to hardware requirements and limited mobility.

Conversely, AR-based approaches are more prevalent in Navigation, Transportation, Tourism, and Public Engagement domains. Their effectiveness lies in the seamless integration of digital information within real-world contexts, enabling real-time, location-based interaction. AR systems—especially smartphone-based solutions—exhibit higher scalability and accessibility, making them particularly suitable for large, heterogeneous urban populations.

MR applications, although less represented, emerge as promising solutions in collaborative and participatory scenarios, such as public engagement and co-design processes. By enabling simultaneous interaction with physical and virtual elements, MR supports shared understanding and collaborative decision-making. However, current technological constraints and deployment costs limit widespread adoption.

Overall, the comparative analysis suggests that no single XR approach is universally optimal. Instead, the suitability of VR, AR, or MR depends strongly on task requirements, user mobility, interaction complexity, and infrastructural constraints within each smart city domain.

Regarding RQ3 on sensory feedback, consistent with prior research [128–130], we found that visual and auditory cues remain dominant in XR systems, while haptic feedback is used less frequently. In applications such as tourism and navigation, simultaneous perception of real and virtual audio supports situational awareness [70,76]. As smart city systems become increasingly interactive, auditory feedback will continue to play a crucial role in reinforcing environmental awareness and enhancing multisensory immersion. Currently, haptic feedback is limited, primarily appearing in basic touchscreen interfaces [65,67]. Vibrotactile cues and force-feedback technologies could provide enhanced spatial awareness, accessibility, and realism.

The reviewed literature is dominated by conference papers (n = 69 out of 92). While conference venues are often the primary venue for rapidly emerging XR technologies, this imbalance suggests that XR research in smart city contexts is still in a relatively early-to-intermediate maturity stage. In many cases, conference contributions emphasize feasibility demonstrations and prototype development rather than fully validated deployments. As a result, the evidence base frequently reflects short evaluation periods, small sample sizes, and limited ecological validity. Several studies report controlled or laboratory-based assessments, proof-of-concept user tests, or single-session experiments, which can constrain the generalizability of findings to real-world urban settings. Moreover, longitudinal validation is rare, making it difficult to assess sustained adoption, learning effects, habituation, or longer-term impacts on decision-making and urban service outcomes.

Beyond interaction design, XR supports urban intelligence functions (e.g., monitoring and decision support) through virtual simulations and real-time data visualization, contributing to sustainable urban development. For instance, in traffic management, XR can display live data to improve vehicle flow and reduce emissions. By enabling informed decisions and minimizing trial-and-error, XR contributes to enhanced energy efficiency and reduced waste in areas such as infrastructure design and construction.

As XR technologies evolve, their integration with IoT, AI, and other emerging systems will be crucial for scaling efficiency, sustainability, and citizen well-being. The continued development of multisensory interfaces, particularly haptic ones, will be crucial to delivering deeply immersive and accessible urban experiences. Overall, our findings highlight XR's potential as a driver of innovation, inclusivity, and sustainability in future smart cities.

4.1. Implications for Sustainable Urban Development and Urban Intelligence

The six application domains identified in this review have direct implications for sustainable urban development. Firstly, XR-based planning and design environments allow for the virtual prototyping of buildings, infrastructure, and public spaces before physical implementation. These tools allow stakeholders to explore multiple scenarios, assess environmental and social impacts, and detect design flaws at an early stage. This reduces material waste, avoids costly rework, and supports more climate-resilient and resource-efficient interventions.

Secondly, XR applications for maintenance, operation, and monitoring contribute to the efficient management of existing assets. AR-guided inspection and repair procedures, as well as VR-based control rooms linked to sensor networks and digital twins, can optimize energy use, extend the lifetime of infrastructure, and improve the reliability of critical services such as water, energy, and mobility. These capabilities are closely aligned with the goals of sustainable urban development, which emphasize the adaptive reuse and optimization of existing urban systems rather than continuous expansion.

Thirdly, navigation, transportation, and public safety applications demonstrate how XR can facilitate safer, more environmentally friendly mobility systems. Real-time, context-aware XR interfaces can improve traffic flow, reduce congestion, and encourage eco-friendly driving behaviors. Meanwhile, inclusive navigation solutions for vulnerable groups, such as older adults and people with disabilities, can enhance the social sustainability of mobility services.

Fourthly, entertainment, tourism, and cultural heritage applications demonstrate that XR can promote sustainable access to urban experiences by supplementing or partially replacing physical travel and extending the reach of cultural assets to remote audiences. XR-based public engagement and participation tools can also increase transparency and trust in planning processes, helping to align urban development strategies with the needs of citizens and long-term sustainability goals.

Finally, our findings suggest that, across all domains, XR can operate as a human-centered interface to urban intelligence. By visually and multimodally coupling real-time data, predictive models, and simulation outputs with situated experiences in the city, XR reduces the cognitive barriers to exploiting complex urban data in practice. This may facilitate more informed decision-making by planners, operators, and citizens alike, supporting the development of adaptive, data-driven, and sustainable smart city ecosystems.

4.2. Future Research Directions

The findings of this systematic review highlight several research gaps that warrant further investigation and that are currently fragmented across application domains and technological approaches. First, the limited integration of haptic feedback in XR-based smart city applications represents a significant opportunity for advancing embodied and multisensory interaction. Future studies should explore scalable haptic and vibrotactile solutions, particularly for navigation, urban planning, and accessibility-focused applications, where non-visual cues could significantly enhance usability and inclusivity.

Second, healthcare-related XR applications in smart city contexts remain underrepresented in the reviewed literature. Existing contributions primarily focus on cognitive assistance or caregiver support, suggesting the need for broader investigations into urban healthcare services, public health monitoring, and community-based interventions supported by XR technologies.

Third, multi-user and collaborative XR systems remain rare, despite their clear relevance for participatory planning, public engagement, and collective decision-making. Future research should address technical and interactional challenges related to synchronization, shared awareness, and scalability in real-world urban environments.

Finally, many studies report short-term evaluations with small samples and limited ecological validity. Longitudinal, in situ, and large-scale evaluations are needed to assess sustained adoption, learning effects, and long-term impacts of XR systems on urban processes and citizen behavior. Addressing these directions would contribute to increasing the maturity, robustness, and practical relevance of XR research in smart city contexts.

5. Conclusions

Smart cities leverage the integration of ICTs to enhance urban services, reduce operational costs, and optimize resource use. Within this context, XR technologies have emerged as key enablers in achieving these goals. By offering innovative, immersive solutions across various domains, XR technologies significantly improve citizens' quality of life. However, the literature lacks a comprehensive understanding of the primary application domains in smart cities, the technologies employed, the mechanisms by which interactions with urban objects occur, and the types of sensory feedback provided to users.

Findings from this SLR highlight the central role of XR in facilitating smarter urban environments and enabling new forms of interaction with urban systems, contributing to more sustainable and responsive urban ecosystems. The existing literature underscores XR's transformative potential across several smart city domains, which continues to expand. This review categorizes these applications and highlights the sensory interactions and feedback involved, offering a comprehensive understanding of XR's current and future role in urban design and development.

Looking ahead, the evolution of XR in smart city contexts is likely to be increasingly shaped by tighter integration with IoT and AI. IoT infrastructures can provide real-time, context-aware data streams to XR interfaces (e.g., environmental sensing, mobility status, infrastructure condition), enabling more responsive and adaptive user experiences. In parallel, AI can support intelligent content generation, predictive analytics, and personalized interaction, improving decision support and scalability across heterogeneous urban scenarios. These developments also raise important challenges—such as privacy, security, and reliability in high-stakes settings—which should be addressed through rigorous in situ and longitudinal evaluations.

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Abbreviations

The following abbreviations are used in this manuscript:

AR	Augmented Reality
EC	Exclusion Criteria
FOV	Field-of-View
GISs	Geographical Information Systems
ICTs	Information and Communication Technologies
MR	Mixed Reality
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
SLR	Systematic Literature Review
VR	Virtual Reality
XR	eXtended Reality

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