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REVIEW

Artificial Intelligence for Net-Zero and Climate-Resilient Sustainable Cities: Technologies, Challenges, and Future Perspectives

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ABSTRACT

Urbanization, climate change, increasing energy demand, and rapid infrastructure development have created significant challenges for achieving sustainable and resilient cities. Artificial intelligence (AI) has emerged as a transformative technology that enables data-driven decision-making, intelligent automation, and efficient resource management, making it an important enabler of net-zero and climate-resilient urban systems. This narrative review examines AI applications relevant to urban climate mitigation and adaptation, drawing on literature identified through Google Scholar and ScienceDirect. The review examines the role of machine learning, deep learning, Internet of Things (IoT), big data analytics, cloud computing, digital twins, and generative AI in improving urban energy systems, sustainable transportation, environmental monitoring, infrastructure management, and smart governance. The study also discusses how these technologies contribute to carbon emission reduction, renewable energy integration, climate adaptation, disaster preparedness, and efficient urban planning. In addition, major challenges associated with AI implementation are critically analyzed, including data privacy, cybersecurity, algorithmic bias, lack of interoperability, high energy consumption of AI systems, digital inequality, and governance issues. Emerging research trends such as explainable AI, green AI, AI-enabled digital twins, federated learning, and human-centered smart governance are highlighted as important directions for future research. Based on the reviewed literature, the study proposes future research priorities that emphasize interdisciplinary collaboration, responsible AI governance, standardized urban data frameworks, and sustainable policy development. Overall, AI has the potential to accelerate the transition toward intelligent, low-carbon, and climate-resilient cities. The synthesis is qualitative and non-exhaustive, with limitations arising from unavailable original search and screening records and differences between study settings and outcome measures. However, the successful implementation of AI will depend on integrating technological innovation with ethical governance, public participation, and long-term sustainability planning to achieve the United Nations Sustainable Development Goals.

KEYWORDS Artificial Intelligence, Sustainable Cities, Net-Zero Cities, Climate Resilience, Smart Infrastructure, Digital Twins, Smart Urban Systems

1. Introduction

Rapid urbanization and industrial development have created significant challenges for cities across the world. Increasing population growth, high energy demand, greenhouse gas emissions, traffic congestion, waste generation, and climate-related disasters are placing enormous pressure on urban infrastructure and natural resources. According to the United Nations, more than half of the global

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population currently lives in urban areas, and this percentage is expected to increase further in the coming decades. Cities are also responsible for nearly 70% of global carbon dioxide emissions and consume a major share of the world's energy resources. Therefore, developing sustainable, resilient, and low-carbon urban systems has become one of the most important global priorities (El-Agamy *et al.* 2024). Climate change has further intensified urban challenges through rising temperatures, floods, droughts, sea-level rise, and extreme weather events. Many cities are increasingly vulnerable to environmental risks that affect transportation systems, energy infrastructure, water resources, public health, and economic activities. As a result, governments and policymakers worldwide are promoting the development of net-zero and climate-resilient cities to reduce environmental impacts and improve urban sustainability. Net-zero cities aim to balance greenhouse gas emissions through energy efficiency, renewable energy integration, sustainable transportation, and smart resource management, while climate-resilient cities focus on adapting urban systems to withstand climate-related risks and disasters (Mondal *et al.* 2024; Mylonas *et al.* 2021).

In recent years, artificial intelligence (AI) has emerged as a transformative technology with significant potential to support sustainable urban development. AI methods, including machine learning and deep learning, are increasingly integrated with enabling technologies such as the Internet of Things, cloud computing and digital twins to support urban monitoring, prediction and decision-making. AI can process large volumes of urban data in real time and provide intelligent solutions for energy optimization, traffic management, environmental monitoring, infrastructure maintenance, disaster prediction, and urban planning (Olawade *et al.* 2024; Ramu *et al.* 2022). AI-driven technologies are playing an important role in reducing carbon emissions and improving energy efficiency in cities. Smart grids combined with AI can optimize electricity distribution, balance renewable energy supply and demand, and reduce energy waste. AI-based building management systems can improve heating, ventilation, air conditioning, and lighting efficiency, leading to lower energy consumption and reduced operational costs. Similarly, intelligent transportation systems can optimize traffic flow, reduce fuel consumption, support electric vehicle integration, and decrease urban air pollution (Pan 2025; Sacoto-Cabrera *et al.* 2025; Stephen *et al.* 2025). AI is also becoming increasingly important in climate resilience and environmental monitoring. Advanced AI models can predict floods, heat waves, storms, and other extreme weather events using real-time environmental and satellite data. These technologies can support disaster preparedness, emergency response, and risk management in vulnerable urban regions. In addition, AI-enabled environmental monitoring systems can track air quality, water quality, urban heat islands, and carbon emissions, helping governments and urban planners develop effective sustainability strategies (Pan 2025; Yahia *et al.* 2025; Xu *et al.* 2024).

Another rapidly growing area is the use of AI-powered digital twins in smart city development. Digital twins are virtual models of physical urban systems that can simulate city operations, infrastructure performance, and environmental conditions in real time. When integrated with AI and IoT technologies, digital twins can help policymakers analyze urban scenarios, optimize infrastructure management, and improve urban resilience. AI-enabled digital platforms also support data-driven governance, citizen engagement, and efficient public service delivery in modern smart cities (Yahia *et al.* 2025; Sachdeva *et al.* 2021; Gupta and Degbelo 2022; Kyriaki *et al.* 2025; Ma *et al.* 2024). Despite the growing benefits of AI in sustainable urban systems, several important challenges still exist. AI technologies require large volumes of high-quality data, advanced computational infrastructure, and significant energy consumption. Concerns related to data privacy, cybersecurity, algorithmic bias, ethical governance, and social inequality remain major barriers to large-scale AI adoption in cities (Ali *et al.* 2025; O'Dwyer *et al.* 2019; Nikpour 2023). In many developing countries, limited technological infrastructure, lack of skilled professionals, and insufficient policy frameworks further restrict the implementation of AI-driven urban solutions (Olawade *et al.* 2024; Srivastava and Maity 2023).

Previous reviews provide important foundations for understanding the role of digital technologies in sustainable urban development. Bibri et al. (2024b) examined the integration of artificial intelligence, the artificial intelligence of things and urban digital twins for data-driven environmental planning. Mazzetto (2024) reviewed urban digital twin integration, applications, implementation challenges and future directions in smart city development. These contributions address substantial parts of the relationship between digital technologies and urban sustainability. Building on this work, the present review adopts a cross-sector perspective centred on two connected objectives: reducing urban greenhouse gas emissions and strengthening resilience to climate-related hazards. Its guiding question is how the reported performance of AI applications relates to these objectives, and what technical, environmental and institutional conditions influence their practical value.

In this review, net-zero greenhouse gas emissions refers to a balance between human-caused greenhouse gas emissions and removals over a specified period, using a stated metric to express the gases as CO_2 equivalents. Carbon neutrality refers specifically to balancing CO_2 emissions and removals. At the global scale, carbon neutrality is equivalent to net-zero CO_2 emissions; at the city or organizational scale, neutrality claims may include compensation beyond the entity's boundary. The gases covered, accounting boundary, reporting period, and treatment of removals or offsets must therefore be stated. Climate resilience refers to the capacity of urban social, ecological, and infrastructure systems to cope with climate-related disturbances, maintain essential functions, and adapt or reorganize as conditions change (IPCC 2022; IPCC 2023).

The contribution of this review is to bring AI applications in energy, transportation, environmental monitoring, infrastructure and urban governance into a common analytical discussion of climate mitigation and adaptation. The analysis distinguishes improvements in prediction or operational efficiency from evidence of emissions reduction or improved resilience. It also considers how data quality, transferability between cities, computational resource use, cybersecurity and governance affect the interpretation and implementation of reported benefits. Digital twins are examined as platforms that can support AI-enabled monitoring, simulation and decision-making within this wider urban context. Through this approach, the review aims to identify where evidence supports practical applications, where benefits remain conditional, and which research priorities are needed to strengthen future evaluations.

2. Review approach and limitations

2.1. Literature identification and scope

This article adopts a narrative review approach to examine artificial intelligence applications relevant to net-zero and climate-resilient cities. Literature was identified through Google Scholar and ScienceDirect (Elsevier). The review covers AI applications in urban energy systems, transportation, environmental monitoring, infrastructure, digital twins and governance. Its purpose is to discuss these applications in relation to climate mitigation and adaptation, together with the challenges affecting their practical implementation.

2.2. Organisation of the discussion

The literature is organised thematically by urban application area. The discussion considers the AI approaches described in the cited publications, their intended applications, reported benefits and limitations. Technical issues are considered alongside environmental, ethical and governance concerns.

This thematic organisation provides a basis for comparing applications across sectors. Findings from individual publications are considered within their reported settings and methods. Improvements in prediction accuracy or operational performance are not, by themselves, treated as evidence of reduced greenhouse gas emissions or improved climate resilience.

2.3. Methodological limitations

A complete search and screening register was not retained. Consequently, the exact search histories, database-specific retrieval counts, duplicate-removal records and full-text exclusion decisions cannot be reported reliably. The article therefore does not claim a reproducible systematic search or exhaustive coverage of the literature, and no verified study-selection counts are presented.

The narrative approach is subject to selection bias, and relevant publications may have been omitted. Differences in study settings, methods, evaluation metrics and implementation conditions also limit direct comparisons. The conclusions should therefore be interpreted as a qualitative discussion of the cited literature rather than a comprehensive assessment of all available evidence.

3. AI technologies for sustainable cities

Artificial intelligence (AI) technologies are becoming important tools for improving the sustainability, efficiency, and resilience of modern cities. Rapid urbanization, increasing energy demand, traffic congestion, environmental pollution, and climate change have encouraged governments and researchers to adopt intelligent digital technologies for better urban management. AI technologies can analyze large volumes of urban data, support real-time decision-making, automate complex systems, and improve resource efficiency in smart cities (Bibri *et al.* 2024a; Tingzon *et al.* 2025; Varzeshi *et al.* 2026). Several advanced technologies such as machine learning, deep learning, Internet of Things (IoT), big data analytics, cloud computing, and digital twins are widely used in sustainable urban systems. These technologies help cities improve energy management, transportation systems, environmental monitoring, infrastructure maintenance, and urban planning. The integration of AI with smart infrastructure is also supporting the transition toward net-zero and climate-resilient cities (Yessef *et al.* 2025; van Deursen and van Dijk 2018; Sebastian 2024).

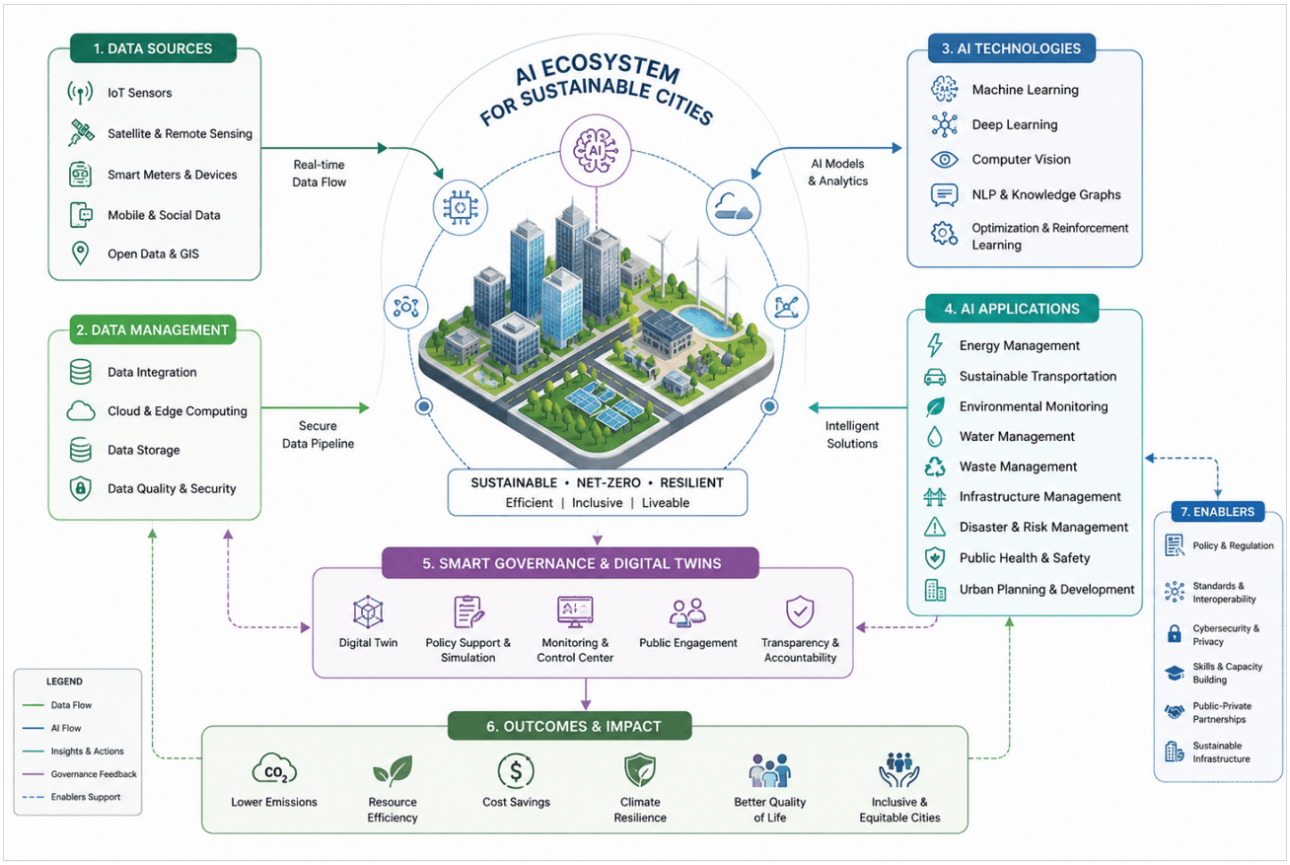

Figure 1. Conceptual framework illustrating the integration of urban data sources, AI technologies, smart governance, and digital twins to support sustainable urban applications. The framework highlights how AI-driven analytics enable efficient resource management, climate resilience, net-zero transitions, and improved quality of life through intelligent urban decision-making.

The overall AI ecosystem for sustainable cities is represented in Figure 1. Urban data generated from IoT sensors, smart meters, satellite observations, geographic information systems (GIS), and other digital platforms are integrated through cloud and edge computing infrastructures. AI technologies, including machine learning, deep learning, computer vision, and natural language processing, analyze these data to support applications such as smart energy management, sustainable transportation, environmental monitoring, infrastructure management, water and waste management, disaster risk reduction, and urban planning. Smart governance and digital twin platforms further enable real-time monitoring, policy evaluation, simulation, and citizen engagement. Together, these components contribute to reduced carbon emissions, improved resource efficiency, enhanced climate resilience, and better quality of life, supporting the development of net-zero and sustainable cities (Seidu *et al.* 2025; Sanusi 2025; Vishwakarma *et al.* 2025).

3.1. Machine learning and deep learning

Machine learning (ML) is one of the most widely used branches of artificial intelligence in sustainable city applications. ML algorithms can learn from historical and real-time data to identify patterns, make predictions, and optimize urban operations. Deep learning, a more advanced form of machine learning based on artificial neural networks, can process large and complex datasets with high accuracy. Smart energy systems combine forecasting, optimization, and control to coordinate energy supply and demand (O'Dwyer *et al.* 2019). In transportation, machine learning can support prediction and decision-making alongside simulation and optimization methods (de la Torre *et al.*

2021). The environmental benefits of these applications depend on their implementation and should be assessed using appropriate operational and emissions indicators. AI-based models can analyze weather conditions, occupancy patterns, and energy consumption behavior to reduce energy waste and improve efficiency. Deep learning models are also applied in traffic management systems to predict traffic congestion, optimize signal timing, and reduce fuel consumption and carbon emissions (Elghaish *et al.* 2024; Stephen *et al.* 2025). In environmental applications, machine learning can support air quality monitoring, flood prediction, climate modeling, and disaster risk analysis. AI-based predictive systems help urban authorities make faster and more accurate decisions during extreme weather events and environmental emergencies. In addition, deep learning techniques are increasingly used in image recognition and remote sensing applications for monitoring urban growth, land-use changes, and infrastructure conditions. ML also plays an important role in predictive maintenance of urban infrastructure. AI systems can continuously monitor bridges, roads, pipelines, and buildings using sensor data to identify faults before major failures occur. This reduces maintenance costs, improves public safety, and extends infrastructure lifespan (Ma *et al.* 2024; He and Prasad 2024).

3.2. Internet of Things (IoT) and smart sensors

The Internet of Things (IoT) refers to interconnected devices and sensors that collect and exchange data through communication networks. IoT is a key component of smart city infrastructure because it enables real-time monitoring and management of urban systems. Smart sensors are widely used in transportation systems, energy grids, water management, waste collection, environmental monitoring, and public safety applications. These sensors continuously collect data related to traffic flow, air quality, temperature, humidity, noise levels, energy consumption, and infrastructure conditions. The collected data are then analyzed using AI algorithms to improve urban efficiency and sustainability (Ramu *et al.* 2022; Huzzat *et al.* 2025). For example, IoT-enabled smart grids can monitor electricity demand and optimize energy distribution in real time. Similarly, smart transportation systems use sensors and AI technologies to manage traffic flow, reduce congestion, and improve public transportation efficiency. IoT-based waste management systems can optimize waste collection routes and reduce fuel consumption. Environmental monitoring is another important application of IoT technologies in sustainable cities. Smart sensors can monitor urban heat islands, water quality, carbon emissions, and air pollution levels continuously. These systems help governments and urban planners develop effective environmental protection and climate adaptation strategies. The combination of AI and IoT is often called Artificial Intelligence of Things (AIoT), where AI technologies analyze sensor data and automate decision-making processes. AIoT systems are becoming increasingly important in the development of intelligent and autonomous urban infrastructure (Sacoto-Cabrera *et al.* 2025; Huzzat *et al.* 2025; Meng and Zhu 2024).

Table 1. AI methods, application areas, and enabling technologies for sustainable urban systems

Category	Method, field, or technology	Main role	Illustrative urban applications
AI methods	Machine learning	Learns patterns for prediction and decision support; examples include random forests, support vector machines, and gradient boosting	Energy-demand forecasting, traffic prediction, predictive maintenance
AI methods	Deep learning	Uses multilayer neural networks; examples include CNNs, LSTMs, and transformers	Remote-sensing analysis, infrastructure inspection, environmental forecasting

Table 1. (continued)

Category	Method, field, or technology	Main role	Illustrative urban applications
AI methods	Generative AI	Generates content or candidate designs using learned patterns; examples include large language models and diffusion models	Planning alternatives, document assistance, synthetic-data generation
AI application areas	Computer vision	Extracts information from images and video, often using machine learning	Traffic observation, damage detection, land-use mapping
AI application areas	Natural language processing	Processes text and language, often using machine learning	Policy-document analysis, citizen-feedback analysis, emergency communication
Analytical and optimization methods	Mathematical optimization and metaheuristics	Supports decisions under objectives and constraints; includes linear programming, genetic algorithms, and particle swarm optimization	Building control, EV charging, logistics, resource allocation
Analytical approaches	Big-data analytics	Analyzes large datasets using statistical, computational, and sometimes AI methods	Mobility analysis, environmental monitoring, urban-service planning
Enabling infrastructure	Internet of Things	Collects and transmits data through connected sensors and devices	Monitoring of buildings, grids, water networks, and environmental conditions
Computing infrastructure	Cloud computing	Provides remote computing and storage resources	Model training, data integration, city-scale analytical platforms
Computing infrastructure	Edge computing	Processes data near its source	Local monitoring, rapid control, reduced communication latency
Modeling and integration platforms	Digital twins	Links digital representations with observations of physical systems; may incorporate simulation and AI	Infrastructure monitoring, scenario evaluation, adaptation planning

Note: The categories distinguish technological roles and are not mutually exclusive. Deep learning is a subset of machine learning, while computer vision and natural language processing can use several AI methods. Big-data analytics and optimization are not exclusively AI-based. IoT, cloud computing, edge computing, and digital twins can support AI applications but are not themselves AI methods. Their use alone does not demonstrate an environmental benefit.

Table 1 summarizes the AI methods, application areas, and enabling technologies that support sustainable urban development, with the main role of each and illustrative urban applications. Together, these technologies provide the foundation for intelligent urban management by enabling data-driven decision-making, efficient resource utilization, climate adaptation, infrastructure optimization, and sustainable public services.

3.3. Big data analytics and cloud computing

Modern cities generate enormous amounts of data from sensors, communication systems, satellites, transportation networks, and public services. Managing and analyzing these large datasets require advanced big data analytics and cloud computing technologies. Big data analytics helps process structured and unstructured urban data to identify trends, optimize operations, and support urban decision-making. AI-based data analytics systems can improve energy efficiency, transportation

planning, healthcare management, public safety, and emergency response systems. Cloud computing provides scalable storage and computing infrastructure for managing smart city data and AI applications. Cloud platforms allow urban authorities to process large datasets efficiently without requiring expensive local computing systems. Cloud-based AI systems also support real-time monitoring and control of urban infrastructure. The integration of AI, big data, and cloud computing enables cities to develop intelligent urban management platforms capable of handling complex urban challenges. These technologies improve operational efficiency, reduce resource waste, and support sustainable development goals (Sacoto-Cabrera *et al.* 2025; Mousavi *et al.* 2024; Sepasgozar 2021).

3.4. Digital twins and intelligent urban platforms

Digital twin technology is rapidly emerging as one of the most important technologies for sustainable cities. A digital twin is a virtual model or digital replica of a physical object, system, or urban environment that continuously receives real-time data from sensors and connected devices. Digital twins can simulate the behavior and performance of urban infrastructure, transportation systems, buildings, and energy networks. When integrated with AI and IoT technologies, digital twins help urban planners and decision-makers analyze different urban scenarios, optimize infrastructure management, and improve climate resilience (El-Agamy *et al.* 2024; Huzzat *et al.* 2025; Dembski *et al.* 2020).

AI-enabled digital twins are increasingly used in:

- smart transportation systems,
- energy management,
- disaster preparedness,
- water resource management,
- environmental monitoring,
- infrastructure maintenance.

For example, digital twins can simulate flooding conditions in urban areas and help authorities prepare emergency response strategies. They can also optimize building energy performance and reduce carbon emissions through real-time monitoring and predictive analysis (Kyriaki *et al.* 2025; Simionescu and Strielkowski 2025). Several cities such as Singapore, Amsterdam, and Dubai are actively adopting digital twin technologies for sustainable urban planning and resilience improvement (Ali *et al.* 2025). The integration of federated learning with digital twins is also gaining attention because it improves data privacy and secure data sharing across urban systems. Federated learning allows AI models to learn from distributed data sources without directly transferring sensitive information, which is important for smart city governance and cybersecurity (Ramu *et al.* 2022; Sadri *et al.* 2023; Dembski *et al.* 2020).

3.5. Generative AI and emerging technologies

Generative AI is an emerging branch of artificial intelligence that can create text, images, simulations, code, and predictive models. Recent developments in large language models and generative AI systems are opening new opportunities for sustainable urban planning and smart governance. Generative AI can support urban planners by automatically generating urban design alternatives, infrastructure layouts, transportation scenarios, and sustainability strategies. These technologies can also assist in citizen communication, policy analysis, and urban data interpretation. In digital twin systems, generative AI can help create synthetic urban datasets, simulate future urban conditions, and improve predictive urban modeling. Researchers are increasingly exploring the integration of generative AI with smart city platforms to support automated urban management and intelligent decision-making (Xu *et al.* 2024; Kyriaki *et al.* 2025; Weber-Lewerenz and Traverso 2023).

Other emerging technologies such as edge computing, blockchain, 5G communication, and autonomous systems are also contributing to the development of next-generation sustainable cities. Edge computing enables faster local data processing, while blockchain technologies improve data security and transparency in urban systems (Meng and Zhu 2024). Although these emerging technologies offer significant benefits, several challenges remain, including high computational costs, data privacy concerns, ethical issues, and the need for standardized urban data frameworks. Therefore, responsible and sustainable implementation of AI technologies is essential for achieving long-term urban sustainability goals.

4. AI for net-zero and climate-resilient urban systems

Artificial intelligence (AI) is becoming a key technology for developing net-zero and climate-resilient urban systems. Rapid urbanization, increasing energy demand, greenhouse gas emissions, environmental degradation, and climate-related disasters have created serious challenges for cities worldwide. To address these challenges, governments and researchers are increasingly adopting AI-based technologies for improving energy efficiency, transportation systems, environmental monitoring, disaster management, and urban infrastructure planning. AI technologies can analyze large volumes of real-time urban data, identify patterns, make predictions, and support intelligent decision-making (Vishwakarma *et al.* 2025; Singh and Goyal 2023). These capabilities help cities reduce carbon emissions, optimize resource utilization, improve infrastructure performance, and strengthen climate resilience. The integration of AI with smart grids, renewable energy systems, digital twins, IoT sensors, and intelligent transportation systems is accelerating the transition toward sustainable and low-carbon cities (Bibri *et al.* 2024a; Jia *et al.* 2019). Figure 2 illustrates the conceptual AI framework for developing net-zero urban systems. Artificial intelligence acts as the central decision-making and intelligence layer that integrates six major technological components: data management, machine learning and analytics, predictive analytics, digital twins, optimization, and simulation. Data management provides reliable and integrated urban datasets for AI models. Machine learning and predictive analytics generate accurate forecasts and intelligent insights from large-scale urban data. Digital twins create virtual representations of physical urban systems to support real-time monitoring and scenario analysis, while optimization algorithms improve the efficiency of energy systems, transportation networks, and urban infrastructure. Simulation models evaluate different planning scenarios and policy interventions before implementation. Together, these interconnected technologies enable intelligent urban decision-making, improve resource efficiency, reduce greenhouse gas emissions, strengthen climate resilience, and accelerate the transition toward sustainable net-zero cities (Ishaq and Farooq 2023; Al-Raeei 2024).

Figure 2. AI framework for net-zero urban systems. Conceptual illustration showing artificial intelligence as the central intelligence layer that integrates data management, machine learning and analytics, predictive analytics, digital twins, optimization, and simulation to support sustainable, low-carbon, and climate-resilient urban systems.

Evidence of climate benefit requires outcome measures beyond AI prediction accuracy. For mitigation, relevant measures include absolute greenhouse gas emissions in tonnes of CO_2 equivalent and changes relative to a defined baseline or comparator. The reporting period, accounting boundary, emission factors, and treatment of electricity use and removals should be specified. Energy savings and improved forecasting accuracy are supporting indicators, but do not independently demonstrate emissions reductions or achievement of net zero. City-level inventories can follow the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (World Resources Institute 2021). For climate resilience, relevant outcome measures depend on the hazard and urban service being evaluated. Examples include the duration of service disruption, time needed to restore essential services, population exposed to hazardous heat or flooding, and hazard-related losses under comparable conditions. Warning lead time and detection accuracy indicate predictive capability, while evidence of reduced harm or improved service continuity is needed to demonstrate practical resilience benefits. This narrative review uses these distinctions to interpret the literature;

it does not calculate a pooled effect or claim that all reviewed studies report comparable outcome measures.

4.1. AI in smart energy systems

Energy systems are one of the most important sectors in achieving net-zero cities. Traditional urban energy systems often face problems such as energy waste, inefficient distribution, high operational costs, and dependence on fossil fuels. AI technologies are increasingly being used to improve the efficiency, reliability, and sustainability of urban energy systems. AI-enabled smart grids can monitor electricity demand and supply in real time and optimize power distribution. Machine learning algorithms can forecast electricity consumption patterns and renewable energy production based on weather conditions, user behavior, and historical energy data. These predictive capabilities help reduce energy losses and improve grid stability (O'Dwyer *et al.* 2019). AI technologies are also supporting the integration of renewable energy sources such as solar and wind power into urban energy networks. Since renewable energy generation depends on weather conditions, AI-based forecasting systems can predict fluctuations in energy production and balance supply and demand more effectively. This helps reduce dependence on fossil fuel-based backup systems and lowers greenhouse gas emissions (Mhlanga 2026; Bhatia *et al.* 2025; Neset *et al.* 2024).

In smart buildings, AI-based energy management systems optimize heating, ventilation, air conditioning (HVAC), lighting, and appliance usage. Sensors and IoT devices continuously collect data related to occupancy, temperature, humidity, and energy consumption. AI algorithms then analyze this data to automatically adjust building operations and reduce unnecessary energy usage (Nikpour 2023). AI is also being used in predictive maintenance of energy infrastructure. Intelligent systems can detect equipment faults, monitor transformer health, and predict failures before they occur. This reduces operational downtime, maintenance costs, and energy losses. Recently, utility companies have started using AI-powered monitoring systems for wind turbines, power transmission networks, and energy storage systems to improve energy reliability and operational efficiency (Rajawat *et al.* 2022; Mensah 2025). Another emerging area is the use of explainable AI in smart energy governance. Explainable AI improves transparency and trust in AI-based decision-making systems by allowing users and operators to understand how AI models generate predictions and recommendations. This is important for energy policy implementation and public acceptance of AI-driven urban energy systems (Alsaigh *et al.* 2022).

The role of AI should also be considered alongside the physical technologies that determine energy-system performance. Reviews of building-integrated photovoltaic/thermal systems and high-temperature heat pumps examine design choices, operating conditions, and integration constraints relevant to energy efficiency and decarbonization (Abdelrazik *et al.* 2022; Elwardany *et al.* 2026). These studies provide engineering context rather than direct evidence of AI effectiveness. Any additional benefit attributed to AI-based forecasting or control should therefore be evaluated against an appropriate conventional-control baseline, rather than attributing the entire benefit of the underlying energy technology to AI.

4.2. AI for sustainable transportation

Transportation systems are major contributors to urban carbon emissions, air pollution, and traffic congestion. AI technologies are increasingly being applied to create sustainable and intelligent transportation systems that improve mobility while reducing environmental impacts. AI-based traffic management systems use real-time data from cameras, sensors, GPS devices, and connected vehicles to optimize traffic flow and reduce congestion. Machine learning algorithms can predict traffic patterns and dynamically control traffic signals to minimize waiting times and fuel consumption (Bharadiya 2023; Abduljabbar *et al.* 2019). These systems help reduce greenhouse gas emissions and improve urban air quality. AI also supports the development of smart public transportation systems. Predictive analytics can optimize bus routes, train schedules, and passenger

flow management. Real-time transportation monitoring systems improve service efficiency and encourage the use of public transportation, which contributes to lower carbon emissions and reduced private vehicle dependence (Kashem *et al.* 2025; Alaba *et al.* 2024; Omefe *et al.* 2021).

Electric vehicles (EVs) are another important component of sustainable urban transportation. AI technologies help optimize EV charging infrastructure, battery management systems, and energy distribution networks. Smart charging systems can schedule charging activities during periods of low electricity demand or high renewable energy generation, reducing stress on urban power grids (Olawade *et al.* 2024). AI technologies are further being used for sustainable urban logistics and supply chain management. Intelligent routing systems can optimize delivery operations, reduce transportation distances, and lower fuel consumption in urban freight systems (Abduljabbar *et al.* 2019; Alaba *et al.* 2024; Bharadiya 2023).

Autonomous urban mobility should be evaluated in relation to its actual deployment conditions. Driverless passenger services are operating in selected cities and defined service areas, but these deployments should not be equated with unrestricted automated driving across all roads and conditions. For example, Waymo reported providing fully autonomous public trips in 14 cities in September 2026, with access being introduced progressively in its newest locations (Waymo 2026). Deployment has also encountered significant safety and regulatory setbacks. In October 2023, the California Department of Motor Vehicles suspended Cruise's driverless testing and deployment permits, citing safety concerns and misrepresentation of safety-related information (California DMV 2023). This example demonstrates the importance of operational validation, transparent reporting, and regulatory oversight. For this review, autonomous operation alone is insufficient evidence of a sustainability benefit. Assessment should consider energy use and emissions per passenger-kilometre, occupancy, empty-vehicle travel, and changes in public-transport use and overall travel demand. Claims of lower congestion or emissions should therefore be supported by deployment-specific evidence rather than inferred from automation capability.

4.3. AI for climate resilience and environmental monitoring

Climate change is increasing the frequency and intensity of floods, heat waves, storms, droughts, and other environmental disasters in urban areas. AI technologies are playing an important role in helping cities improve climate resilience and environmental sustainability. AI-based environmental monitoring systems can continuously analyze data from satellites, drones, sensors, and weather stations to monitor air quality, water quality, urban heat islands, and greenhouse gas emissions (Neset *et al.* 2024; Srivastava and Maity 2023). These systems help governments and urban planners identify environmental risks and develop effective climate adaptation strategies. Flood prediction is one of the major applications of AI in climate resilience. Machine learning models can analyze rainfall patterns, river flow data, topography, and historical flood records to predict flood risks and issue early warning alerts (Mehryar *et al.* 2024; Chen and Dong 2025). AI-powered flood management systems help reduce disaster impacts and improve emergency response planning. AI is also increasingly used in urban heat management. Urban heat islands caused by dense infrastructure and limited green spaces can significantly affect public health and energy consumption. AI systems can monitor temperature patterns, identify heat-vulnerable regions, and support urban cooling strategies such as green infrastructure development and optimized building design (Chauhan *et al.* 2025; Rui *et al.* 2026).

Digital twins and AI-based simulation platforms are becoming important tools for climate-resilient urban planning. Digital twins create virtual models of urban systems using real-time data, allowing planners to simulate climate-related scenarios such as flooding, traffic congestion, and energy demand changes. Cities such as Singapore, Amsterdam, and Houston are already using digital twin technologies to improve climate adaptation and urban resilience planning (Ali *et al.* 2025; Sirmacek and Vinuesa 2022). AI technologies are also helping vulnerable and disaster-prone regions improve resilience through geospatial analysis and satellite image processing. AI-based systems can

identify infrastructure vulnerabilities, assess structural damage risks, and support evidence-based urban planning for disaster preparedness (Tingzon *et al.* 2025; Najafi *et al.* 2026). Despite these benefits, challenges still exist in implementing AI for climate resilience. Reliable climate data, computational infrastructure, data sharing frameworks, and interdisciplinary collaboration are necessary for developing accurate and scalable AI systems. In addition, ethical concerns, algorithmic bias, cybersecurity risks, and energy consumption associated with large AI models must be addressed to ensure sustainable AI deployment in urban systems (Chauhan *et al.* 2025; Islam *et al.* 2024).

4.4. AI in smart infrastructure and resource management

Smart infrastructure management is another important application area of AI in sustainable cities. Urban infrastructure such as roads, bridges, buildings, pipelines, and water systems requires continuous monitoring and maintenance. AI technologies can improve infrastructure reliability, reduce maintenance costs, and enhance operational efficiency. AI-enabled predictive maintenance systems use sensors and machine learning algorithms to monitor infrastructure conditions and detect faults before failures occur. These systems reduce downtime, improve public safety, and extend infrastructure lifespan (Waqas Khan *et al.* 2024). In water management systems, AI technologies help detect leakages, optimize water distribution, and monitor water quality. Smart water networks can reduce water losses and improve resource efficiency in cities facing water scarcity challenges. AI is also supporting intelligent waste management systems. Smart waste collection systems use sensors and AI algorithms to optimize waste collection routes, monitor waste bin levels, and improve recycling operations. These technologies reduce fuel consumption, operational costs, and environmental pollution. Resource-efficient urban management is becoming increasingly important for achieving sustainable development goals (Almulhim 2025; Fortuna and Yetgin 2023). AI-driven urban platforms can integrate data from multiple sectors such as transportation, energy, waste management, and environmental systems to support intelligent urban governance and sustainability planning (Varzeshi *et al.* 2026; Rad *et al.* 2025). Overall, AI technologies offer significant opportunities for developing net-zero and climate-resilient urban systems. However, responsible implementation, transparent governance, data security, and sustainable infrastructure investment are essential for ensuring that AI technologies contribute effectively to long-term urban sustainability (Mahor *et al.* 2022; Shulajkovska *et al.* 2024).

4.5. Qualitative evidence summary

Table 2 provides an illustrative summary of selected publications discussed in this narrative review. It is not an exhaustive inventory of the literature or the output of a documented systematic screening process. This distinction is necessary because a review of potential benefits does not itself demonstrate an improvement in urban performance.

Table 2. Selected publications discussed in the narrative review: scope, evidence type, reported contributions and limitations.

Reference	Urban sector and technologies discussed	Evidence type and setting	Reported contribution	Interpretation and limits for the present review
Bibri et al. (2024a), eco-cities review	Environmental sustainability; AI and artificial intelligence of things (AIoT)	Systematic review and evidence synthesis across eco-city literature	Examines the foundations, enabling technologies, environmental applications and implementation challenges of smarter eco-cities.	Provides an organising perspective on AI-enabled environmental sustainability. Its synthesis should not be presented as a single measured city-wide improvement.
O'Dwyer et al. (2019)	Urban energy systems; forecasting, control and optimization	Review of smart energy techniques and implemented examples	Synthesises developments in smart energy systems, application areas, implementation challenges and future directions.	Supports discussion of energy-system approaches. Specific savings or forecasting improvements must be traced to the original studies reviewed.
Olawade et al. (2024)	Net-zero sustainability; AI applications across sectors	Review of AI opportunities, challenges and implementation considerations	Discusses AI applications for net-zero objectives alongside ethical issues, policy support, capacity building and scalability.	Provides broad context for net-zero applications. Urban outcomes need to be distinguished from findings concerning other sectors.
Mazzetto (2024)	Urban planning and management; urban digital twins	Literature review using bibliometric and thematic analysis	Examines urban digital twin integration, applications, challenges and future development.	Supports discussion of digital twin implementation. Digital twin functionality alone should not be treated as evidence of emissions reduction or improved resilience.
Ramu et al. (2022)	Smart city systems; federated learning and digital twins	Review and conceptual discussion across smart city applications	Discusses the integration of federated learning with digital twins, including developments, benefits, limitations and research directions.	Provides a basis for discussing distributed learning. Privacy protection and operational benefits require evaluation of specific implementations.

Table 2. (continued)

Reference	Urban sector and technologies discussed	Evidence type and setting	Reported contribution	Interpretation and limits for the present review
Alnaser et al. (2024)	Buildings, facilities and urban systems; AI, IoT and digital twins	Systematic literature review with scientometric analysis	Maps research on digital twins in construction and facility management, AI–IoT integration for energy optimization, and sustainable built environments.	Identifies application areas and research directions. It should not be described as an original experiment demonstrating improved building energy performance.
Sacoto-Cabrera et al. (2025)	Smart city development; IoT, AI and urban digital twins	Systematic review with bibliometric and thematic analysis	Maps technological and methodological themes in the integration of IoT, AI and digital twins and proposes a research agenda.	Supports comparison of research themes. Bibliometric patterns do not establish the magnitude of environmental or social benefits.
Xu et al. (2024)	Urban data, design and modeling; generative AI and digital twins	Scoping review; cited version is an arXiv preprint	Reviews data augmentation, synthetic data and scenario generation, automated 3D city modeling, and generative urban design.	Provides an overview of emerging approaches. The cited preprint should be identified clearly and should not be presented as a validated city-wide deployment.
Rui et al. (2026)	Urban extreme heat management; AI-based forecasting, monitoring, mitigation and decision support	Systematic review of urban heat research	Synthesises AI applications across the main stages of urban extreme heat management.	Supports the climate-adaptation discussion. Forecasting or monitoring performance must be distinguished from demonstrated reductions in heat exposure or harm.
Temple et al. (2024)	Urban governance; digital twin-based decision and policy support	Systematic literature review published as a conference paper	Establishes a literature-based foundation for developing digital twin decision-support frameworks in the public sector.	Provides conceptual support for governance applications. The paper describes further framework development as future work, rather than a completed deployment evaluation.

Table 2. (continued)

Reference	Urban sector and technologies discussed	Evidence type and setting	Reported contribution	Interpretation and limits for the present review
Yigitcanlar et al. (2019)	Smart city development and urban sustainability; broader digital urbanism	Systematic review of smart and sustainable city literature	Examines the relationship between smart city initiatives and sustainability, questioning whether technological advancement ensures sustainable outcomes.	Provides a conceptual basis for evaluating sustainability claims. It is not a direct performance evaluation of a particular AI intervention.
Rad et al. (2025)	Urban planning, procurement and supply chains; AI-supported decision-making	Scoping literature review published as a conference chapter	Synthesises AI applications in urban design and the evaluation and selection of contractors and suppliers.	Relevant to planning and procurement. It should not be classified as a study measuring the environmental footprint of AI computing.

Note: The table provides an illustrative summary of publications discussed in this narrative review and is not an exhaustive evidence inventory. The final column presents the interpretation of the present review's authors, rather than limitations necessarily stated by the cited publications. The entries primarily synthesise existing literature; specific quantitative outcomes and deployment claims should be traced to the underlying primary studies. AI denotes artificial intelligence; AIoT, artificial intelligence of things; and IoT, Internet of Things.

The table identifies each publication's scope, evidence type, reported contribution and limitations. The final column presents the present authors' interpretation of the relevance and evidential limitations of each publication. The table is intended to support qualitative comparison; it does not establish the distribution of research across countries, technologies or implementation levels.

The evidence summarized in Table 2 should be interpreted according to its type and evaluation setting. Review articles identify applications and research directions, but do not themselves establish the effectiveness of a particular intervention. Similarly, improvements in prediction accuracy do not necessarily produce lower emissions or greater resilience. Such claims require evidence connecting model outputs to operational decisions and measurable outcomes against a suitable comparator. For the present review, important assessment questions are whether an application was evaluated in simulation or actual operation, whether its benefits persisted over time, and whether the evaluation included implementation costs, computational demands, and local infrastructure constraints. Where these details are unavailable, conclusions about effectiveness and transferability remain limited.

5. Smart governance and digital twins

Rapid urbanization, climate change, increasing energy demand, and infrastructure complexity have created major challenges for city management and governance. Traditional urban management approaches are often unable to efficiently handle large-scale urban data, real-time decision-making, and sustainability planning. As a result, smart governance and digital twin technologies are becoming important tools for developing sustainable, resilient, and intelligent cities. Smart governance refers to the use of digital technologies, artificial intelligence (AI), big data, Internet of Things (IoT), and communication systems to improve urban management, public services, citizen participation, and policy decision-making. Smart governance aims to make cities more efficient, transparent, sustainable, and citizen-centered through data-driven urban management systems

(Mazzetto 2024; Shulajkovska *et al.* 2024). Digital twins are virtual replicas of physical systems, infrastructure, or entire cities that continuously receive real-time data from sensors, satellites, IoT devices, and communication networks. When integrated with AI technologies, digital twins can simulate urban operations, predict future scenarios, optimize infrastructure management, and support evidence-based urban planning. These technologies are increasingly being adopted in sustainable city development and climate-resilient urban governance (Yessef *et al.* 2025).

5.1. Urban digital twins

Urban digital twins are among the most important emerging technologies in smart city development. An urban digital twin is a real-time digital representation of urban systems such as transportation networks, buildings, energy systems, water infrastructure, environmental conditions, and public services. These digital platforms combine data from sensors, IoT devices, satellite imagery, drones, and geographic information systems to create dynamic urban simulation models. Digital twins help city authorities monitor urban infrastructure performance, identify risks, predict system failures, and optimize resource management. Unlike conventional urban planning tools, digital twins provide real-time monitoring and predictive capabilities, enabling more efficient urban governance and sustainability management (Deren *et al.* 2021; Thuraka 2021; Dembski *et al.* 2020). AI technologies significantly improve the functionality of digital twins by enabling intelligent data analysis, prediction, automation, and decision support. Machine learning algorithms can analyze large volumes of urban data to identify patterns related to traffic congestion, energy demand, environmental pollution, flood risks, and infrastructure degradation. These predictive capabilities help governments make faster and more accurate decisions (Tandon and Shaheen 2024; Vergara-Perucich 2025).

Urban digital twins are widely applied in:

- transportation planning,
- energy optimization,
- environmental monitoring,
- disaster management,
- infrastructure maintenance,
- and climate resilience planning.

For example, digital twins can simulate flooding conditions in vulnerable urban regions and help authorities design emergency response strategies. They can also support traffic management by predicting congestion and optimizing transportation routes in real time (Mazzetto 2024). Several cities around the world have already started implementing digital twin technologies. Singapore uses its “Virtual Singapore” platform for urban planning and environmental management, while Amsterdam and Houston use digital twins for climate resilience, water management, and infrastructure monitoring (Ali *et al.* 2025). The integration of AI, IoT, and digital twins is also supporting the development of smart and sustainable building environments. AI-driven digital twins can continuously monitor building energy performance, occupancy patterns, and environmental conditions to improve energy efficiency and reduce carbon emissions (Alnaser *et al.* 2024).

5.2. AI-based decision support systems

AI-based decision support systems are becoming increasingly important in smart governance and urban planning. These systems analyze large and complex urban datasets to support policymakers, city administrators, and infrastructure managers in making informed decisions. Traditional urban governance often depends on static data and delayed reporting systems, which limit the ability of authorities to respond quickly to urban challenges. In contrast, AI-based systems provide real-time

analysis and predictive insights that improve operational efficiency and urban resilience (Yigitcanlar *et al.* 2025).

Machine learning and deep learning models can analyze data related to:

- transportation,
- energy consumption,
- public health,
- environmental quality,
- crime patterns,
- infrastructure conditions.

These systems help authorities identify emerging urban risks and optimize resource allocation. AI-based decision systems are especially useful in climate adaptation and disaster management. For example, AI models can predict flood risks, heat waves, air pollution levels, and energy demand fluctuations based on historical and real-time environmental data. This enables urban planners to implement preventive measures and improve emergency preparedness (Temple *et al.* 2024; Mahor *et al.* 2022). Digital twins further strengthen urban decision-making by allowing policymakers to simulate multiple urban scenarios before implementing policies or infrastructure projects. Urban authorities can evaluate the environmental, social, and economic impacts of proposed urban developments using simulation-based planning systems.

Generative AI technologies are also emerging as powerful tools in urban governance. Large language models and generative AI systems can support urban planning, citizen communication, automated reporting, and policy analysis. Generative AI can create predictive urban scenarios, infrastructure layouts, and sustainability strategies that assist decision-makers in complex planning processes (Xu *et al.* 2024; Mkhitaryan *et al.* 2026). In addition, AI-based governance systems improve transparency and efficiency in public administration. Smart governance platforms can automate routine administrative processes, monitor public service performance, and improve communication between governments and citizens.

5.3. Citizen-centric smart governance

Citizen participation is an important component of sustainable and inclusive urban governance. Smart governance systems aim not only to improve urban efficiency but also to strengthen citizen engagement, transparency, and public trust. AI-powered digital platforms enable governments to collect citizen feedback, monitor public concerns, and improve service delivery. Smart city applications allow residents to report infrastructure problems, monitor environmental conditions, access public transportation information, and participate in urban planning processes. Citizen-centric digital twin systems are also being developed to support participatory governance (Aboh and Chuka 2025; Bhatia *et al.* 2025). These platforms allow citizens to visualize proposed urban projects, understand infrastructure impacts, and contribute to policy discussions. Public participation helps ensure that smart city initiatives address local community needs and social sustainability goals (Mensah 2025; Mhlanga 2026).

Smart governance systems can also improve accessibility and inclusiveness in urban services. AI-based technologies support intelligent healthcare systems, smart mobility services, emergency response systems, and personalized public services for vulnerable populations. However, the implementation of citizen-centered smart governance also raises important ethical and social concerns. Large-scale urban data collection may create privacy and surveillance risks if not managed responsibly. Issues related to cybersecurity, algorithmic bias, data ownership, and digital inequality remain major challenges in AI-driven urban governance systems (Bibri *et al.* 2024b). The digital divide is another critical issue, especially in developing countries where access to digital

infrastructure and technical skills may be limited. Therefore, inclusive policies and responsible governance frameworks are necessary to ensure that AI technologies benefit all citizens equally.

6. Challenges and limitations

Artificial intelligence (AI) offers significant opportunities for developing sustainable, net-zero, and climate-resilient cities. AI technologies can improve energy efficiency, transportation systems, infrastructure management, environmental monitoring, and urban governance. However, despite these advantages, several technical, environmental, economic, ethical, and social challenges still limit the large-scale implementation of AI in sustainable urban systems (Vergara-Perucich 2025). The successful development of AI-enabled sustainable cities requires not only advanced technologies but also reliable infrastructure, responsible governance, public trust, and long-term policy support. Many cities, especially in developing countries, still face difficulties in integrating AI systems into existing urban infrastructure due to limited resources, insufficient technical expertise, and fragmented governance systems (Bibri *et al.* 2024a).

6.1. Data privacy, cybersecurity, and operational resilience

Cybersecurity risks in connected urban infrastructure extend beyond unauthorized disclosure of personal data. Compromised credentials, exposed controllers, malicious software, or manipulated sensor inputs can undermine operational decisions and interrupt essential services. AI adds further attack surfaces, including poisoning of training data and inputs designed to evade or mislead a model (NIST 2025). These risks should be evaluated across the sensing, communication, model, and control layers. A documented example is the exploitation of Unitronics programmable logic controllers at a United States water facility in 2023. CISA reported that the affected authority took the system offline and switched to manual operation, with no known risk to drinking water or water supply (CISA 2023). This was an operational-technology incident, not evidence of an attack on an AI model, but it demonstrates the infrastructure dependencies that AI-enabled urban services can inherit. A layered protection strategy should include restricted remote access, strong authentication, separation of operational networks, removal of unnecessary internet exposure, tested software updates, and recoverable controller configurations. AI-specific evaluation should additionally examine data integrity and robustness to manipulated inputs. Manual fallback procedures and recovery exercises remain necessary because automated detection cannot guarantee prevention. Security evaluation should therefore consider service continuity and recovery time, as well as attack-detection performance.

AI systems in smart cities depend heavily on large volumes of real-time data collected from sensors, surveillance cameras, smartphones, connected vehicles, smart meters, social media, and IoT devices. These datasets often include sensitive personal information related to citizen activities, transportation patterns, healthcare, energy consumption, and communication systems. The large-scale collection and storage of urban data create serious concerns regarding privacy and cybersecurity. Unauthorized access, cyberattacks, data breaches, and misuse of personal information can threaten both public safety and citizen trust. AI-driven smart city platforms may also increase surveillance activities if appropriate data governance policies are not implemented (Kitchin 2016). Another challenge is data ownership and transparency. In many smart city systems, citizens may not clearly understand how their personal data are collected, analyzed, shared, or stored. Lack of transparency in AI algorithms may further reduce public trust in smart governance systems. To address these challenges, strong cybersecurity frameworks, data protection regulations, encryption technologies, and transparent data governance policies are necessary. Privacy-preserving AI approaches such as federated learning and secure multi-party computation are also gaining attention because they allow AI systems to analyze data without directly sharing sensitive information (Ramu *et al.* 2022).

6.2. Ethical and responsible AI

Ethical concerns are among the most important challenges in AI-enabled urban systems. AI algorithms can unintentionally produce biased or unfair outcomes if they are trained using incomplete, inaccurate, or unbalanced datasets. Bias in AI systems may affect urban governance, public services, law enforcement, healthcare, transportation, and infrastructure planning. For example, AI-based surveillance or predictive policing systems may disproportionately affect certain communities due to biased training data. Similarly, AI systems used for public service allocation may unintentionally create inequality in access to urban resources and opportunities. The "black-box" nature of many AI models is another major concern. In some advanced deep learning systems, it is difficult to understand how the AI model generates predictions or decisions. Lack of explainability reduces transparency and accountability in public decision-making systems (Alsaigh *et al.* 2022).

Responsible AI governance requires:

- transparency,
- fairness,
- accountability,
- explainability,
- and human oversight.

Governments and urban authorities must establish ethical guidelines and regulatory frameworks to ensure that AI technologies are used responsibly and inclusively in sustainable cities.

6.3. Environmental footprint of AI and assessment of net climate benefits

AI introduces environmental costs that must be considered alongside its potential contribution to urban decarbonization. These costs arise from model development, training, repeated inference, data storage, and supporting computing infrastructure. Strubell et al. (2019) demonstrated the importance of accounting for the computational costs of developing deep-learning systems. Such estimates are specific to the workloads and assumptions examined and should not be treated as a universal footprint for every AI model. The International Energy Agency estimated that data centres consumed approximately 415 TWh of electricity in 2024, equivalent to about 1.5% of global electricity consumption (IEA 2025). This estimate covers data centres generally and must not be attributed entirely to AI. It nevertheless illustrates why growing computational demand matters when assessing digitally enabled climate strategies. For urban applications, the relevant question is whether the intervention produces a net environmental improvement compared with an appropriate alternative. Assessment should include the additional electricity required for training and operation, associated emissions, hardware production where relevant, and cooling-related resource use. Potential rebound effects should also be considered: lower operating costs or improved service availability may increase total demand and partly offset efficiency gains. We recommend that evaluations report computational energy use alongside service performance and estimated avoided emissions, using a consistent boundary and assessment period. Smaller task-specific models, less frequent retraining where performance permits, efficient hardware, and appropriate workload scheduling should be evaluated as possible mitigation options. Neither edge processing nor cloud deployment should automatically be assumed to have the lower footprint; the comparison depends on utilization, communication requirements, equipment, and electricity supply.

6.4. Lack of standardization and interoperability

Smart city systems often involve multiple technologies, platforms, communication protocols, and infrastructure networks developed by different organizations and vendors. Lack of standardization creates interoperability problems between urban systems such as transportation, energy, healthcare, environmental monitoring, and governance platforms. Many cities still operate fragmented digital

infrastructures where data exchange between different departments and systems is limited. This reduces the efficiency of AI-based decision-making and prevents the development of integrated urban management platforms (Mazzetto 2024). Digital twin systems also require standardized data models and communication frameworks to integrate data from multiple urban sectors. Without interoperability standards, cities may face difficulties in scaling AI solutions across large urban regions. International collaboration and common technological standards are therefore important for enabling efficient smart city development and data sharing.

6.5. Economic and infrastructure constraints

The implementation of AI technologies in sustainable cities often requires significant financial investment, advanced infrastructure, high-speed communication networks, cloud computing systems, and skilled technical professionals. Many developing countries and smaller cities face economic limitations that restrict the adoption of advanced AI systems. Limited access to digital infrastructure, insufficient funding, lack of technical expertise, and weak policy support can delay smart city development (Olawade *et al.* 2024). In addition, maintaining AI systems and updating digital infrastructure require long-term operational costs and continuous technological upgrades. Urban authorities must therefore carefully evaluate economic feasibility and sustainability before implementing large-scale AI projects. Public-private partnerships, government funding programs, and international collaboration may help support AI adoption in resource-limited urban regions.

6.6. Social inclusion and digital divide

The digital divide is another major challenge in AI-enabled smart city development. Unequal access to digital technologies, internet connectivity, education, and technical skills can create social inequality and limit citizen participation in smart governance systems. Vulnerable populations, low-income communities, elderly citizens, and rural migrants may face difficulties accessing digital public services or participating in AI-driven urban systems. If smart city technologies are not designed inclusively, they may increase social and economic inequality rather than reduce it (van Deursen and van Dijk 2018). AI-based urban services should therefore prioritize accessibility, affordability, and inclusiveness. Governments must also invest in digital literacy programs, public awareness campaigns, and equitable digital infrastructure development to ensure that all citizens benefit from AI technologies. Citizen participation and community engagement are essential for developing socially sustainable smart cities.

6.7. Governance and regulatory challenges

AI technologies are evolving much faster than existing legal and policy frameworks. Many countries still lack comprehensive regulations related to AI ethics, urban data governance, cybersecurity, liability, and automated decision-making systems. Unclear regulatory frameworks may create uncertainty regarding accountability, transparency, and legal responsibility in AI-driven urban systems. For example, questions remain regarding who is responsible if AI systems fail or produce harmful outcomes in transportation, healthcare, or infrastructure management. Smart governance systems also require coordination between multiple stakeholders including governments, private companies, researchers, infrastructure providers, and citizens. Weak institutional coordination may slow down smart city implementation and policy integration (Yigitcanlar *et al.* 2019). Future urban governance frameworks must therefore combine technological innovation with ethical regulations, sustainability policies, and human-centered planning approaches.

Urban AI deployment is also shaped by specific regulatory and governance instruments. The European Union's AI Act, Regulation (EU) 2024/1689, establishes a risk-based framework. Certain uses involving safety components in critical infrastructure can fall within its high-risk provisions. Relevant requirements address risk management, data governance, documentation, logging, human oversight, accuracy, robustness, and cybersecurity. Classification depends on the intended use and

applicable legal provisions; not every urban AI application is automatically high-risk (European Parliament and Council 2024). The United States National Institute of Standards and Technology's AI Risk Management Framework provides voluntary guidance for managing AI risks through governance, contextual assessment, measurement, and risk management (Tabassi 2023). It should be distinguished from binding legislation. For urban authorities, these instruments highlight the need to establish responsibilities between suppliers and public agencies, document system limitations, provide appropriate human oversight, and plan monitoring and incident response. Procurement decisions should therefore assess accountability and operational safeguards alongside predictive performance.

Table 3. Challenges, impacts, and mitigation strategies for AI-enabled sustainable cities.

Challenge	Potential Impact on Sustainable Cities	Possible Mitigation Strategies	Future Research Needs
Data privacy and security	Risk of unauthorized access, cyberattacks, loss of public trust, and misuse of sensitive urban data	Strong cybersecurity frameworks, data encryption, privacy-preserving AI, federated learning, secure data governance	Privacy-aware AI models, secure data-sharing protocols, trustworthy AI frameworks
Algorithmic bias and fairness	Unfair decision-making, social inequality, discrimination in public services and urban planning	Diverse and representative datasets, bias detection algorithms, fairness-aware AI, regular model auditing	Explainable and unbiased AI models for public decision-making
Lack of explainability	Reduced transparency and limited public acceptance of AI-based decisions	Explainable AI (XAI), interpretable machine learning models, human oversight	Transparent AI models for critical urban applications
High energy consumption of AI systems	Increased electricity demand, higher operational costs, additional carbon emissions	Green AI, energy-efficient algorithms, renewable energy-powered data centres, edge computing	Low-carbon AI computing, energy-aware model optimization
Poor data quality and availability	Inaccurate predictions, unreliable urban planning, poor system performance	Standardized data collection, real-time sensor calibration, data validation techniques	Urban benchmark datasets and data quality assessment frameworks
Lack of interoperability	Difficulty integrating different smart city platforms and infrastructure systems	Open standards, interoperable communication protocols, common data models	Unified architectures for AI-enabled smart city platforms
High implementation cost	Limited AI adoption, especially in developing cities and small municipalities	Public-private partnerships, phased implementation, cloud-based AI services, government funding	Cost-effective AI deployment models and scalable infrastructure
Limited digital infrastructure	Poor connectivity, reduced system reliability, restricted real-time monitoring	Expansion of broadband, 5G networks, cloud and edge computing infrastructure	AI solutions for low-resource and developing urban environments
Digital divide and social exclusion	Unequal access to digital services, reduced citizen participation, social inequality	Digital literacy programmes, inclusive policies, affordable digital technologies	Human-centred and inclusive AI systems for sustainable cities

Table 3. (continued)

Challenge	Potential Impact on Sustainable Cities	Possible Mitigation Strategies	Future Research Needs
Regulatory and governance gaps	Unclear legal responsibilities, inconsistent AI implementation, weak policy coordination	AI governance frameworks, ethical guidelines, national and international standards	Adaptive regulatory frameworks for AI-enabled urban governance
Climate uncertainty and dynamic urban environments	Reduced prediction accuracy and planning reliability under changing climate conditions	Continuous model updating, real-time monitoring, adaptive AI systems	AI models capable of handling uncertain and dynamic urban scenarios
Public trust and acceptance	Resistance to AI adoption and reduced participation in smart city initiatives	Transparent governance, citizen engagement, explainable AI, public awareness campaigns	Citizen-centred governance models and trust evaluation frameworks

Table 3 summarizes the major technical, environmental, economic, governance, and social challenges associated with the implementation of artificial intelligence in sustainable cities. For each challenge, the corresponding impacts on urban sustainability, practical mitigation strategies, and future research needs are presented. The table highlights that achieving net-zero and climate-resilient cities requires not only technological innovation but also responsible governance, secure digital infrastructure, ethical AI practices, inclusive policies, and interdisciplinary collaboration. Addressing these challenges will improve the reliability, transparency, scalability, and long-term sustainability of AI-enabled urban systems.

7. Future perspectives and research directions

The following research directions represent the authors' interpretation of the issues discussed in this narrative review. They are proposed priorities for future investigation, rather than established findings or predictions of inevitable technological progress. The emphasis is on evaluating AI applications under practical urban conditions, assessing their environmental costs and benefits, and establishing accountable and inclusive implementation practices.

7.1. Explainable and responsible AI

One of the major future research directions in smart city development is explainable artificial intelligence (XAI). Many current AI systems operate as "black-box" models where decision-making processes are difficult to understand. In urban governance and critical infrastructure systems, lack of transparency may reduce public trust and create ethical concerns. Explainable AI aims to improve the transparency, interpretability, and accountability of AI systems. XAI models can help urban authorities, policymakers, and citizens understand how AI systems generate predictions, recommendations, and decisions. This is especially important in sectors such as transportation, healthcare, public safety, energy management, and disaster response where AI-driven decisions may directly affect human lives (Alsaigh *et al.* 2022; Thuraka 2021).

Future research should focus on:

- transparent AI models,
- ethical AI governance,
- fairness and bias reduction,
- human-centered AI systems,
- regulatory frameworks for responsible AI deployment.

Responsible AI development will be essential for ensuring that smart city technologies remain socially inclusive, secure, and sustainable.

7.2. Integration of AI and digital twins

The integration of AI with digital twin technology is expected to become one of the most transformative developments in future sustainable cities. Digital twins provide virtual replicas of urban systems, while AI enables intelligent data analysis, prediction, optimization, and automation.

Future AI-powered digital twins may support:

- real-time urban monitoring,
- climate adaptation planning,
- infrastructure optimization,
- disaster prediction,
- traffic management,
- energy system control.

These systems can continuously simulate urban scenarios and help authorities evaluate policy decisions before real-world implementation. For example, digital twins may predict flooding impacts, optimize renewable energy integration, or simulate transportation changes to reduce congestion and carbon emissions (Mazzetto 2024).

Future research should focus on improving:

- scalability of urban digital twins,
- interoperability between systems,
- real-time data integration,
- cybersecurity,
- energy-efficient simulation models.

The integration of digital twins with geospatial technologies, satellite data, drones, and AI analytics will further improve urban resilience and sustainability planning.

7.3. AI for circular economy and resource efficiency

Future sustainable cities will increasingly adopt circular economy principles to reduce waste generation, improve recycling, and optimize resource utilization. AI technologies can significantly support circular economy systems through intelligent waste management, material tracking, predictive maintenance, and resource optimization. AI-based systems can monitor resource consumption patterns and improve recycling operations using automated waste sorting and predictive collection systems. Machine learning models may also optimize industrial processes to minimize energy use and material waste.

Future research is expected to explore AI applications in:

- smart recycling systems,
- sustainable manufacturing,
- circular supply chains,
- water reuse systems,
- low-carbon construction materials.

The combination of AI, IoT, and blockchain technologies may also improve transparency and traceability in urban resource management systems (Bibri *et al.* 2024a; Subramanian *et al.* 2023).

7.4. Autonomous and intelligent urban infrastructure

Autonomous infrastructure systems are likely to become an important component of future studies. AI-enabled autonomous systems can continuously monitor infrastructure performance, detect faults, optimize operations, and perform predictive maintenance with minimal human intervention (Mehan 2026).

Future urban infrastructure may include:

- self-optimizing smart grids,
- autonomous transportation systems,
- AI-managed water distribution networks,
- intelligent waste management systems,
- automated environmental monitoring platforms.

AI combined with robotics and autonomous systems may also improve disaster response and emergency management in climate-vulnerable urban regions.

Research in this area should focus on:

- infrastructure reliability,
- human-AI collaboration,
- resilient communication systems,
- autonomous urban operations,
- energy-efficient AI hardware.

Future research should compare edge and cloud deployment under equivalent workloads, considering response time, communication requirements, energy use, and emissions (Xu *et al.* 2024).

7.5. Human-centered and inclusive smart cities

Future studies should prioritize human well-being, social inclusion, and citizen participation rather than focusing only on technological advancement. Human-centered AI systems aim to improve quality of life, accessibility, healthcare, safety, and public engagement. AI technologies can support personalized public services, intelligent healthcare systems, accessible transportation, and inclusive governance platforms. Citizen-centric urban planning approaches will become increasingly important for ensuring that smart city initiatives address local community needs and social sustainability goals (Mahor *et al.* 2022; Mensah 2025).

Future research should focus on:

- reducing the digital divide,
- improving digital literacy,
- increasing accessibility of urban services,
- strengthening citizen participation,
- ensuring equitable access to AI technologies.

Inclusive governance frameworks are necessary to prevent social inequality and ensure that the benefits of AI technologies are shared across all sections of society (Yigitcanlar *et al.* 2019).

7.6. Green AI and sustainable computing

As AI systems become more complex and computationally intensive, future research must also focus on reducing the environmental impacts of AI technologies themselves. Large-scale AI models and cloud computing systems consume substantial amounts of energy and may contribute to carbon

emissions (Vergara-Perucich 2025). Green AI aims to develop energy-efficient AI algorithms, low-power hardware systems, and sustainable data center operations. Future research may include:

- renewable energy-powered data centers,
- energy-efficient machine learning algorithms,
- lightweight AI models,
- carbon-aware computing systems.

The development of sustainable AI infrastructure will be critical for ensuring that AI contributes positively to climate goals and net-zero urban development.

8. Cross-sector interpretation

The authors interpret the applications discussed in this review through three questions: what task the AI system performs, what urban outcome is evaluated, and under what conditions the reported result is obtained. This distinction is important because prediction accuracy, operational efficiency and climate-related outcomes represent different levels of evidence. An improvement in forecasting, for example, does not by itself establish a reduction in emissions or an improvement in disaster preparedness. A second consideration is the suitability of an approach for a particular urban setting. Results should be interpreted alongside the study's data, comparison method, evaluation period and implementation conditions. A result obtained in a simulation or an individual facility should not be assumed to apply across an entire city. Similarly, the availability of a digital platform does not establish that institutions have the resources or authority needed to act on its outputs. The central interpretation of this review is therefore that AI should be assessed as part of an urban decision-making process. Its value depends on whether its outputs inform effective actions and whether the resulting benefits justify the resources and risks involved. This interpretation provides a basis for the research priorities proposed in Section 7. It is not a quantitative finding about the prevalence or effectiveness of AI across the wider literature.

9. Conclusion

This narrative review examines AI applications relevant to urban climate mitigation and adaptation across energy, transportation, environmental monitoring, infrastructure and governance. It brings together discussions of their intended benefits and the technical, environmental and institutional conditions affecting implementation. The central conclusion is that technical performance should be distinguished from demonstrated sustainability outcomes. Claims about emissions reduction or climate resilience require evidence connecting model outputs to practical actions and measured consequences. Data quality, cybersecurity, accountability, accessibility and the environmental costs of computing also need to be considered when interpreting the value of an application. Because the review does not use a reproducible systematic selection process, its conclusions are limited to a qualitative interpretation of the cited literature. The proposed research priorities emphasise transparent evaluation, testing under practical urban conditions and explicit measurement of environmental and social outcomes.

Declarations

Author contributions. Rakesh A. Afre: Conceptualisation: Developed the overarching themes and objectives of the review. Methodology: Designed the review framework and criteria for literature selection. Writing – Original Draft: Wrote the initial manuscript draft, including key sections. Supervision: Supervised the study. Bhavana B. Thakre: Literature Review: Conducted a comprehensive search and analysis of relevant literature. Writing – Review & Editing: Contributed to the revision of the manuscript, focusing on clarity and coherence. Radha Panchal and Sandhyatai Kadam: Literature Review: Conducted a comprehensive search and analysis of relevant literature.

Writing – Review & Editing: Assisted in editing and refining the final manuscript, ensuring accuracy and completeness. All authors have read and approved the final version of the manuscript.

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