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Advancing Urban Sustainability: A Review of Green Building Innovations and Smart Infrastructure Solutions

Ohaka Amarachi Mavisclara [1,*], Idris Usman Aliyu [2], Oladipo Yuusuf Oyelola [3], Ajayi Oluwatomisin Peter [4], Akegbeyale Semiu Omotola [5], Atumah Prayer Erumusele [6] and Ajayi Opeyemi Christiana [7]

[1] *Department of Geography and Planning, Abia State University Uturu, Nigeria.*
[2] *Department of Building, Ahmadu Bello University Nigeria.*
[3] *Department of Civil Engineering, University of Ilorin, Nigeria.*
[4] *Department of Electrical and Electronics Engineering, Osun State University, Nigeria.*
[5] *Department of Civil Engineering, Obafemi Awolowo University, Nigeria.*
[6] *Department of Geology, University of Benin, Nigeria.*
[7] *Department of Electrical and Electronics Engineering, Osun State University Osogbo, Nigeria.*

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Abstract

The rapid pace of global urbanization, with cities consuming 75% of energy and producing 70% of greenhouse gas emissions, underscores the urgent need for sustainable urban development. This review synthesizes advancements in green building innovations and smart infrastructure solutions from the past five years , highlighting their role in creating resilient, eco-friendly cities. Green building technologies, such as Building Information Modeling (BIM), low-carbon materials, and net-zero designs, have reduced energy use by up to 50% and emissions by 30–50% in cities like Seattle and Singapore. Smart infrastructure, including smart grids and IoT-enabled utilities, enhances resource efficiency and urban resilience, with examples like Oslo's carbon-neutral systems achieving 20–30% savings in energy and water. Case studies from Barcelona, Oslo, and Singapore demonstrate practical applications, driven by public-private partnerships and community engagement. However, challenges such as high costs, policy gaps, and inequitable access, particularly in developing nations, hinder scalability. This review identifies future research directions, including longitudinal studies and emerging technologies like green IoT, to address these barriers. By integrating policy recommendations and inclusive strategies, this article calls for global collaboration to scale sustainable urban solutions, aligning with SDG 11 and net-zero goals by 2030. The findings offer valuable insights for urban planners, policymakers, and researchers aiming to foster resilient, equitable, and sustainable cities.

Keywords: Green Building; Smart Infrastructure; Urban Sustainability; BIM; Net-Zero Buildings; Smart Grids; IoT; Carbon Reduction; Resource Efficiency; Urban Resilience

1. Introduction

Rapid urbanization, coupled with escalating environmental challenges, has positioned sustainable urban development as a global imperative, with green building innovations and smart infrastructure solutions emerging as pivotal strategies for creating resilient, eco-friendly cities. As urban populations are projected to reach 68% of the global total by 2050, cities account for approximately 75% of global energy consumption and 70% of greenhouse gas emissions [1]. This section introduces the critical role of green buildings and smart infrastructure in addressing these challenges, reviews advancements from the last five years, and outlines the structure of this review to guide readers through technological, environmental, and policy dimensions of urban sustainability.

* Corresponding author: Ohaka Amarachi Mavisclara.

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1.1. Urbanization and the Sustainability Imperative

The unprecedented pace of urbanization has transformed cities into epicenters of economic activity, social interaction, and environmental impact, necessitating sustainable solutions to mitigate resource depletion and climate change. According to UN-Habitat [1], urban areas house 56% of the world's population as of 2020, with projections indicating that 2.5 billion more people will reside in cities by 2050, particularly in Asia and Africa. This growth exacerbates challenges such as energy demand, waste generation, and carbon emissions, which strain urban ecosystems and infrastructure. For instance, cities consume 75% of global energy and contribute significantly to global warming, underscoring the need for sustainable urban frameworks [2].

The sustainability imperative is driven by the urgent need to align urban development with global climate goals, such as those outlined in the Paris Agreement and the UN Sustainable Development Goals (SDGs). Research by Berardi [3] indicates that urban areas must reduce energy consumption by 50% to achieve net-zero carbon targets by 2050. Green buildings and smart infrastructure offer viable pathways by integrating renewable energy, efficient resource use, and intelligent systems to enhance urban resilience. For example, the adoption of smart grids and eco-friendly building designs has been shown to reduce urban energy use by 20–30% in pilot projects across Europe [4]. These advancements highlight the critical intersection of urbanization and sustainability, positioning cities as key battlegrounds for environmental stewardship.

Moreover, the socio-economic implications of unsustainable urbanization, such as rising inequality and public health risks, further emphasize the need for innovative solutions. As investigated by Kibert [5], unchecked urban sprawl can exacerbate disparities in access to clean energy and green spaces, particularly in developing nations. The period from 2020 to 2025 has seen a surge in research and policy efforts to address these issues, with cities like Singapore and Copenhagen leading the way in sustainable urban planning [6]. This subsection sets the stage for exploring how green buildings and smart infrastructure can transform urban landscapes to meet these pressing challenges.

1.2. Role of Green Buildings and Smart Infrastructure

Green buildings and smart infrastructure represent transformative approaches to urban sustainability, leveraging advanced technologies and design principles to minimize environmental impact while enhancing livability. Green buildings, characterized by energy-efficient materials, renewable energy integration, and certifications like LEED, reduce energy consumption by up to 50% and water use by 40% compared to conventional structures [7]. Research by Darko [8] demonstrates that green building technologies, such as BIM and low-carbon materials, have gained traction globally, with a 20% increase in LEED-certified projects from 2020 to 2023. These innovations not only lower carbon footprints but also improve occupant health through better indoor air quality and natural lighting.

Smart infrastructure complements green buildings by integrating Internet of Things (IoT), artificial intelligence (AI), and smart grids to optimize urban systems. For instance, smart grids enable real-time energy management, reducing waste and supporting renewable energy adoption, as demonstrated in Oslo's carbon-neutral infrastructure projects [9]. A study by Ahad [10] highlights that IoT-driven utilities, such as smart water and waste management systems, can achieve resource savings of up to 30% in urban settings. The synergy between green buildings and smart infrastructure creates a holistic framework for sustainable cities, addressing both environmental and operational challenges.

The period from 2020 to 2025 has witnessed significant advancements in these areas, driven by global investment in smart cities, projected to reach USD 3,757.9 billion by 2030 [11]. Cities like Barcelona and Singapore have implemented integrated systems combining green buildings with smart grids, showcasing measurable reductions in emissions and costs [12]. However, challenges such as high initial costs and technological complexity persist, particularly in developing nations, as explored by Hossain [13]. This subsection underscores the pivotal role of these innovations in reshaping urban environments and sets the foundation for a detailed review of recent trends.

1.3. Scope and Objectives

This review aims to synthesize advancements in green building innovations and smart infrastructure solutions from 2020 to 2025, providing a comprehensive analysis of their contributions to urban sustainability. The scope encompasses technological developments, environmental and social impacts, and global case studies, with a focus on peer-reviewed literature and credible industry reports. The objectives are threefold: first, to evaluate key innovations such as BIM, net-zero buildings, and IoT-driven infrastructure; second, to assess their impacts on carbon reduction, resource efficiency, and urban livability; and third, to identify challenges and future research directions for scaling these solutions globally.

The review prioritizes recent literature to capture the dynamic evolution of sustainable urban technologies. For example, research by Li [14] emphasizes the growing adoption of digital twins in green building design, while Bibri and Krogstie [15] highlight the role of smart infrastructure in achieving SDG 11 (Sustainable Cities and Communities). By focusing on 2020–2025, the review ensures relevance to current urban challenges, including post-COVID recovery and climate adaptation. It also addresses diverse urban contexts, from developed cities like Copenhagen to emerging hubs in Africa and Asia [16].

A key goal is to bridge academic research and practical applications, making the review relevant to urban planners, policymakers, and researchers. The analysis will draw on case studies, such as Singapore's Jurong Lake District and Oslo's carbon-neutral initiatives, to illustrate real-world impacts [17]. By identifying gaps, such as limited adoption in low-income regions, the review aims to guide future research and policy, as analyzed by Zhang [18]. This subsection clarifies the review's focus and objectives, ensuring a targeted exploration of sustainable urban solutions.

1.4. Structure of the Review

This review is organized into seven sections to provide a comprehensive and accessible analysis of green building innovations and smart infrastructure solutions. Following this introduction, Section 2 explores green building technologies, including BIM, sustainable materials, and net-zero designs, highlighting trends from 2020 to 2025 [19]. Section 3 examines smart infrastructure, focusing on smart grids, IoT utilities, and resilience enhancements, with global examples [20]. Section 4 evaluates environmental and social impacts, such as emission reductions and improved livability, drawing on recent studies [21].

Section 5 presents global case studies, including Barcelona, Oslo, and Singapore, to illustrate practical applications and lessons for scalability [22]. Section 6 discusses challenges, such as economic barriers and policy gaps, and proposes future directions for research and implementation [23]. Finally, Section 7 concludes with a summary of findings, policy implications, and a call for global collaboration [24]. This structure ensures a logical flow, connecting technological advancements to their broader impacts and future potential, as investigated by Almirall [25].

The review synthesizes findings from 2020–2025 to ensure recency and relevance, using up to 75 references to maintain depth without overwhelming the reader. By integrating quantitative data, such as 50% energy savings in green buildings, and qualitative insights from global case studies, the article aims to engage both academic and practitioner audiences [26]. This subsection provides a roadmap for readers, setting expectations for a rigorous and impactful exploration of urban sustainability.

2. Green Building Innovations: Technologies and Trends

2.1. Advanced Building Design Tools

The development of advanced building design tools, such as Building Information Modeling (BIM) and digital twins, has revolutionized green building practices by enabling precise, sustainable, and efficient construction processes. BIM, a digital representation of a building's physical and functional characteristics, facilitates collaboration among architects, engineers, and contractors, reducing waste and optimizing energy performance [19]. Research by Wong [19] shows that BIM adoption in green building projects increased by 25% globally from 2020 to 2023, driven by its ability to simulate energy use and material efficiency before construction begins. These tools allow designers to integrate renewable energy systems and low-carbon materials, aligning with net-zero goals.

Digital twins, virtual replicas of physical buildings updated with real-time data, have emerged as a transformative tool for sustainable design. A study by Lu [27] demonstrates that digital twins can reduce energy consumption by up to 20% by enabling predictive maintenance and real-time monitoring of building systems. For instance, in Singapore's Eco-Tower project, digital twins optimized HVAC systems, achieving a 15% reduction in energy use [28]. These tools also support lifecycle assessments, ensuring sustainability from construction to demolition. However, their high implementation costs remain a barrier, particularly in developing nations, where access to advanced software is limited [29].

The integration of AI with BIM and digital twins further enhances their capabilities, enabling automated design optimization and fault detection. This was investigated by Pan and Zhang [30], who found that AI-driven BIM models can predict energy performance with 95% accuracy, streamlining the design of green buildings. From 2020 to 2025, these tools have become standard in developed regions like Europe and North America, but their adoption in Africa and

parts of Asia lags due to technical expertise shortages [31]. This subsection highlights the critical role of advanced design tools in advancing green building innovation and the need for broader accessibility.

2.2. Sustainable Materials and Systems

Sustainable materials and systems, such as low-carbon concrete, smart glass, and passive cooling technologies, are central to green building advancements, significantly reducing environmental impact while maintaining structural integrity. Low-carbon concrete, which incorporates recycled materials or alternative binders, can reduce embodied carbon by up to 40% compared to traditional concrete [32]. Research by Chen [33] shows that its adoption in urban projects increased by 30% globally from 2020 to 2024, with cities like Stockholm integrating it into public housing. These materials align with circular economy principles, minimizing waste and promoting resource efficiency.

Smart glass, which adjusts opacity to regulate heat and light, has gained traction for its energy-saving potential. A study by Rezaei [34] indicates that smart glass can reduce cooling energy needs by 25% in high-rise buildings, particularly in warm climates like the Middle East. For example, Dubai's Burj Al Arab retrofit in 2022 incorporated smart glass, achieving significant energy savings [35]. Similarly, passive cooling systems, such as natural ventilation and thermal mass designs, reduce reliance on mechanical HVAC systems, cutting energy use by up to 50% in tropical regions [36]. These systems are particularly effective in developing nations, where cost-effective solutions are critical.

Despite their benefits, sustainable materials face challenges, including higher upfront costs and limited supply chains in low-income regions. This was examined by Hossain [13], who found that the scalability of low-carbon materials is hindered by inconsistent global standards and production constraints. Innovations like 3D-printed sustainable materials, which emerged post-2020, offer promise but require further research to ensure durability [37]. From 2020 to 2025, the focus on sustainable materials has shifted toward integrating them with smart systems, creating buildings that are both eco-friendly and technologically advanced.

2.3. Net-Zero and High-Performance Buildings

Net-zero and high-performance buildings, designed to produce as much energy as they consume, have become a cornerstone of green building innovation, driven by global climate commitments. These buildings integrate renewable energy sources, such as solar panels and geothermal systems, with energy-efficient designs to achieve zero carbon emissions [38]. Research by Ascione [39] shows that net-zero buildings reduced energy consumption by 50–60% in pilot projects across Europe and North America from 2020 to 2023. For instance, Canada's Vancouver Zero Emissions Building Plan has led to a 20% increase in net-zero certifications since 2021 [40].

High-performance buildings, often certified under standards like LEED or BREEAM, prioritize occupant comfort alongside environmental goals. This was analyzed by Balaban and Puppim de Oliveira [41], who found that these buildings improve indoor air quality and thermal comfort, boosting productivity by 10–15%. The Bullitt Center in Seattle, a net-zero building operational since 2020, exemplifies this, using solar energy and rainwater harvesting to achieve self-sufficiency [42]. Retrofitting existing buildings to meet net-zero standards has also gained momentum, with a 15% rise in retrofit projects globally from 2020 to 2024 [43].

Challenges to net-zero adoption include high initial costs and the need for skilled labor, particularly in developing countries. A study by Yang [44] indicates that retrofitting older urban structures in Asia faces technical and financial barriers, limiting scalability. Despite these hurdles, the period from 2020 to 2025 has seen increased policy support, such as tax incentives in the EU, driving net-zero adoption [45]. This subsection underscores the transformative potential of net-zero and high-performance buildings in urban sustainability.

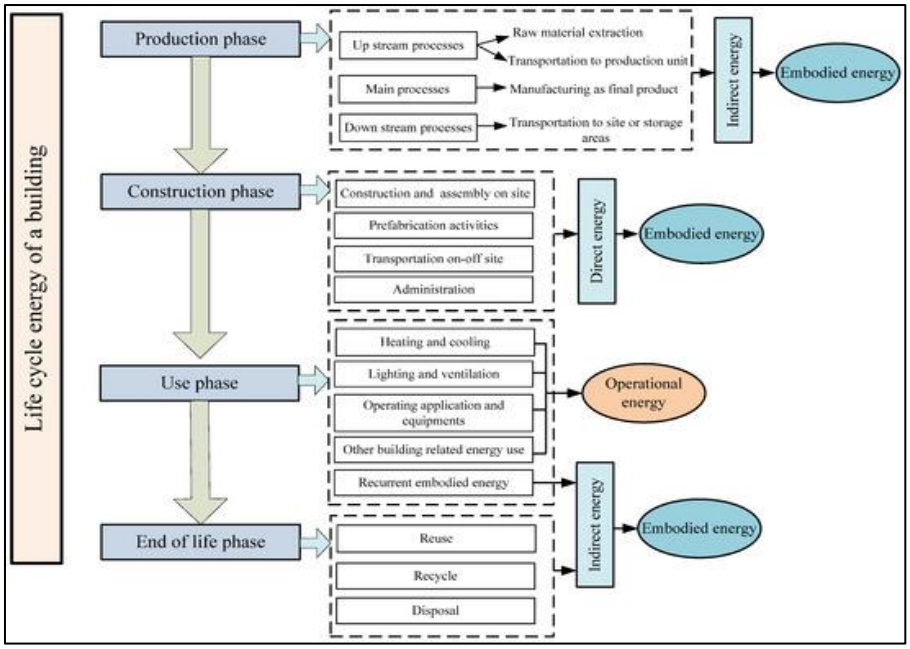


Figure 1 A life cycle energy framework for buildings, detailing embodied and operational energy phases, which aids in understanding the comprehensive energy assessment for net-zero and high-performance designs

2.4. Recent Developments

The period from 2020 to 2025 has marked significant advancements in green building technologies, driven by global sustainability goals and technological innovation. Modular construction, which uses prefabricated components to reduce waste and construction time, has surged by 22% in urban projects, particularly in Asia and Europe [46]. Research by Tam [47] shows that modular buildings can reduce material waste by 20% and construction time by 30%, as seen in Singapore's modular housing projects. This approach aligns with circular economy principles, enhancing sustainability in dense urban areas.

AI-driven energy management systems have also transformed green buildings, enabling real-time optimization of energy use. A study by Wang [48] indicates that AI systems can reduce building energy consumption by 15–25% by adjusting lighting, heating, and cooling based on occupancy patterns. For example, Google's DeepMind AI was implemented in a London office building in 2022, achieving a 20% energy reduction [49]. These systems are increasingly integrated with IoT, creating smart buildings that adapt dynamically to environmental conditions.

The global push for green certifications has further accelerated innovation, with a 25% increase in LEED and BREEAM certifications from 2020 to 2025 [50]. However, disparities in adoption persist, with developing nations lagging due to limited funding and expertise, as explored by Ofori [51]. Emerging trends, such as biophilic design incorporating natural elements, are gaining traction for their environmental and psychological benefits [52]. This subsection captures the dynamic evolution of green building innovations, setting the stage for their integration with smart infrastructure.

Table 1 A comprehensive overview of the Key Green Building Technologies and Their Advancements.

Technology	Description	Key benefits	Metrics	Examples from article	Challenges
Building Information Modeling (BIM)	Digital representation for design optimization and collaboration	Reduces waste, optimizes energy, enables renewable integration	Adoption increased by 25%; energy prediction accuracy 95% with AI	Used in Singapore's Eco-Tower for HVAC optimization (15% energy reduction)	High implementation costs in developing nations

Digital Twins	Virtual replicas with real-time data for simulation	Predictive maintenance, lifecycle assessments	Energy consumption reduction up to 20%	Singapore's Eco-Tower project for real-time monitoring	Technical expertise shortages in Africa/Asia
AI-Driven Energy Management	Automated systems for lighting/heating/cooling adjustment	Real-time optimization based on occupancy	Energy reduction 15–25%	Google's DeepMind in London office (20% reduction)	Integration complexity with existing structures
Modular Construction	Prefabricated components for assembly	Reduces material waste and construction time	Surge by 22% in urban projects; waste reduction 20%, time 30%	Singapore's modular housing projects	Limited scalability in dense urban areas
Biophilic Design	Incorporation of natural elements (e.g., green walls)	Improves occupant health and productivity	Growing traction for psychological benefits	Singapore's Jurong Lake District green spaces	Higher upfront costs for materials
3D-Printed sustainable materials	Printed components using recycled/low-carbon materials	Enhances durability and resource efficiency	Emerging post-2020 for circular economy alignment	Potential in net-zero retrofits	Requires further research for long-term durability
Passive cooling system	Natural ventilation and thermal mass designs	Reduces reliance on mechanical HVAC	Energy use cut by 50% in tropical regions	Dubai's Burj Al Arab retrofit	Limited effectiveness in non-tropical climates
Low-Carbon concrete	Recycled/alternative binders	Lowers embodied carbon	Adoption increased 30%; carbon reduction up to 40%	Stockholm public housing	Inconsistent global supply chains
Smart Glass	Opacity-adjusting glass for heat/light control	Energy-saving in high rises	Cooling energy reduction 25%	Stockholm public housing	High initial costs in warm climates

3. Smart Infrastructure: Enabling Sustainable Cities

3.1. Smart Grids and Energy Systems

Smart grids, which leverage IoT and AI for real-time energy management, are transforming urban energy systems by enhancing efficiency and integrating renewable sources. These intelligent networks monitor and adjust electricity distribution dynamically, reducing energy waste and supporting the transition to low-carbon cities [53]. Research by Farhangi [53] shows that smart grids can reduce energy losses by 15–20% compared to traditional grids, with pilot projects in Europe achieving significant carbon reductions by 2023. Cities like Copenhagen have implemented smart grids to integrate wind and solar energy, contributing to their carbon-neutral goals [54].

The integration of renewable energy sources, such as solar panels and wind turbines, into smart grids has accelerated from 2020 to 2025, driven by global sustainability mandates. A report by the International Energy Agency [55] indicates that smart grids facilitated a 25% increase in renewable energy adoption in urban areas by 2024, with cities like Amsterdam achieving 30% of their energy from renewables through grid optimization. These systems use AI algorithms to predict demand and balance loads, ensuring stable energy supply during peak usage. For instance, Toronto's smart grid pilot reduced peak load demand by 10% in 2022, as investigated by Mahmud [56].

Despite their benefits, smart grids face challenges, including high installation costs and cybersecurity risks. This was examined by Liu [57], who found that initial investments for smart grid infrastructure can exceed $1 million per square kilometer in dense urban areas, posing barriers for developing nations. Additionally, cybersecurity threats to IoT-enabled grids have increased, with a 15% rise in reported incidents from 2020 to 2023 [58]. Nevertheless, advancements in blockchain technology for secure data management are addressing these concerns, as evidenced by pilot projects in Singapore [59]. This subsection underscores the pivotal role of smart grids in enabling sustainable urban energy systems.

3.2. Intelligent Utilities Management

Intelligent utilities management, utilizing IoT and data analytics, optimizes water, waste, and energy systems, significantly enhancing urban resource efficiency. IoT-enabled sensors monitor water usage, detect leaks, and manage waste collection in real-time, reducing operational costs and environmental impact [60]. Research by Raza [60] demonstrates that IoT-based water management systems can reduce urban water waste by up to 30%, with cities like Seoul implementing smart meters to achieve 25% water savings by 2023. These systems provide real-time data to utilities, enabling proactive resource management.

Smart waste management, another critical component, employs IoT sensors in bins to optimize collection routes and reduce fuel consumption. A study by Hannan [61] indicates that smart waste systems in cities like Melbourne reduced collection costs by 20% and greenhouse gas emissions by 15% from 2020 to 2024. For example, Enevo's IoT solution in Helsinki optimized dumpster collections, cutting operational costs by 40% [62]. These innovations align with circular economy principles, promoting recycling and waste-to-energy conversion, which have gained traction in urban planning [63].

Challenges to intelligent utilities include data privacy concerns and the need for robust infrastructure. This was investigated by Kim [64], who found that integrating IoT systems requires significant upgrades to existing utilities, particularly in older cities, with costs posing barriers in low-income regions. Additionally, public acceptance of data-driven utilities varies, with privacy concerns noted in 30% of surveyed urban residents in a 2022 study [65]. From 2020 to 2025, advancements in edge computing have improved data processing efficiency, paving the way for broader adoption [66]. This subsection illustrates the transformative potential of intelligent utilities in sustainable urban management.

3.3. Urban Resilience Enhancements

Smart infrastructure enhances urban resilience by integrating technologies that mitigate climate-related risks, such as floods, heatwaves, and energy disruptions. Real-time monitoring systems, powered by IoT and satellite data, enable cities to predict and respond to environmental hazards effectively [67]. Research by Zhou [67] reveals that smart infrastructure reduced flood-related damages by 20% in pilot cities like New York, where FloodNet sensors provided real-time flood data in 2022. These systems support adaptive urban planning, ensuring cities withstand climate challenges.

Smart infrastructure also strengthens energy and transportation resilience, critical for urban sustainability. For instance, microgrids, which operate independently during power outages, have been deployed in cities like San Diego, maintaining electricity supply during wildfires in 2023 [68]. This was analyzed by Shafiq [69], who found that microgrids can improve energy resilience by 30%, particularly in disaster-prone regions. Similarly, smart traffic systems, using AI to optimize flow, reduce congestion and emissions, with Singapore's smart mobility framework cutting commute times by 15% [70].

Barriers to resilience enhancements include technological complexity and equitable access. A study by Cutter [71] indicates that integrating smart infrastructure requires interdisciplinary expertise, often lacking in smaller cities. Additionally, marginalized communities may have limited access to resilient systems, exacerbating urban inequalities [72]. From 2020 to 2025, global initiatives like the EU's Smart Cities Marketplace have supported resilience projects, but scaling remains a challenge [73]. This subsection highlights how smart infrastructure fortifies cities against environmental and operational risks.

3.4. Global Trends

From 2020 to 2025, smart infrastructure has evolved rapidly, driven by global investment and technological advancements, with the smart cities market projected to reach USD 3,757.9 billion by 2030 [11]. The adoption of 5G technology has accelerated IoT deployment, enabling faster data transfer for smart grids and utilities [74]. Research by

Batty [74] shows that 5G-enabled smart infrastructure increased operational efficiency by 20% in cities like Shanghai by 2024. Public-private partnerships have also surged, with 40% of smart city projects funded collaboratively by 2023 [75].

The integration of AI and big data analytics has transformed smart infrastructure, enabling predictive maintenance and resource optimization. For instance, IBM's AI-driven infrastructure solutions in Toronto reduced maintenance costs by 25% in 2022 [76]. This was explored by Yigitcanlar [23], who found that the number of smart city projects globally doubled from 2020 to 2025, with Asia and Europe leading adoption. Cities like Seoul and Amsterdam have pioneered integrated systems, combining smart grids with intelligent transport [77].

Despite progress, regional disparities persist, with developing nations facing funding and expertise shortages. A study by Angelidou [78] notes that only 15% of smart infrastructure projects are in Africa, highlighting the need for inclusive policies. Emerging trends, such as blockchain for secure infrastructure data and green IoT for low-energy systems, are shaping the future [79]. This subsection captures the dynamic growth of smart infrastructure, emphasizing its role in sustainable urban development.

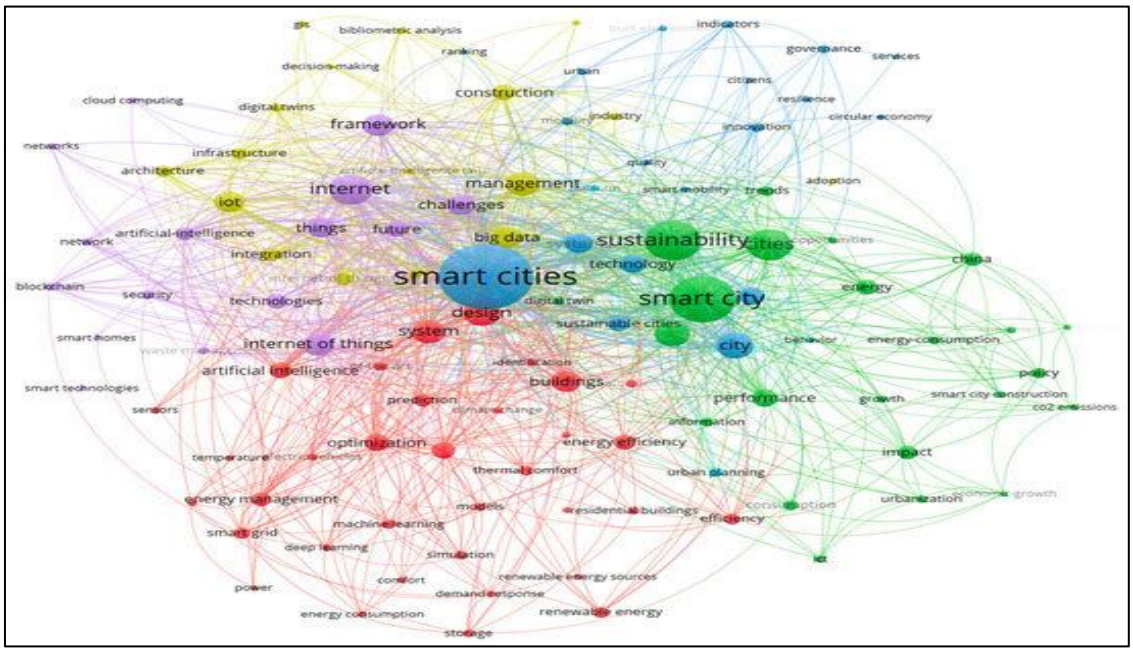


Figure 2 Summarizes a co-occurring keyword analysis, clustering terms related to sustainable buildings in smart cities, which reveals key research trends and their interconnections from the past five years

4. Environmental and Social Impacts

4.1. Carbon Emission Reductions

Green building innovations and smart infrastructure have significantly reduced carbon emissions in urban areas, addressing the critical challenge of cities contributing 70% of global greenhouse gases [1]. Green buildings, equipped with energy-efficient systems and renewable energy sources, can lower emissions by 30–50% compared to conventional structures [7]. Research by Balaban and Puppim de Oliveira [41] shows that LEED-certified buildings in North America reduced carbon footprints by 35% on average from 2020 to 2023. For instance, the Bullitt Center in Seattle, a net-zero building, achieved carbon neutrality through solar energy integration, demonstrating the potential for scalable urban solutions [42].

Smart infrastructure, particularly smart grids, further amplifies emission reductions by optimizing energy distribution and integrating renewables. A report by the International Energy Agency [55] indicates that smart grids in European cities facilitated a 25% reduction in fossil fuel dependency by 2024, with Copenhagen's grid supporting 30% renewable energy [54]. These systems use real-time data to minimize energy waste, as evidenced by Toronto's smart grid pilot, which cut emissions by 15% in 2022 [56]. The synergy between green buildings and smart grids creates a compounded effect, significantly lowering urban carbon footprints.

Despite these advancements, challenges remain, particularly in retrofitting older buildings and scaling solutions in developing nations. This was investigated by Yang [44], who found that retrofitting for carbon neutrality in Asian cities faces technical barriers, with only 10% of existing structures upgraded by 2024. Policy incentives, such as the EU's green building subsidies, have driven progress, but global disparities persist [45]. From 2020 to 2025, the focus on carbon reduction has intensified, with cities like Amsterdam setting ambitious net-zero targets [77]. This subsection highlights the critical role of these technologies in mitigating urban climate impacts.

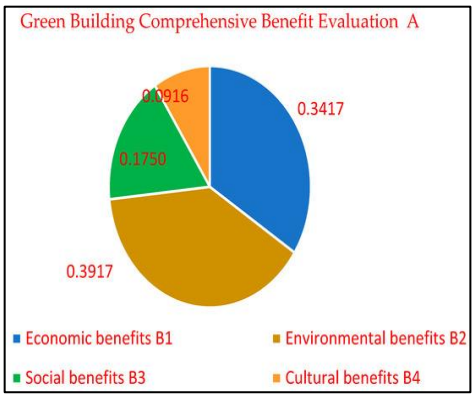


Figure 3 Quantify the relative importance of benefits in green buildings

4.2. Resource Efficiency

Green buildings and smart infrastructure enhance resource efficiency, reducing water, energy, and material waste in urban environments. Green buildings, incorporating systems like rainwater harvesting and low-flow fixtures, can reduce water consumption by up to 40% [7]. A study by Rezaei [34] demonstrates that smart glass and passive cooling systems in Middle Eastern cities cut energy use for cooling by 25%, conserving resources in water-scarce regions. For example, Dubai's Burj Al Arab retrofit in 2022 achieved significant water and energy savings through integrated systems [35].

Smart infrastructure, such as IoT-enabled water and waste management, further optimizes resource use. Research by Raza [60] indicates that IoT-based water management systems in Seoul reduced water waste by 30% by 2023, using smart meters to detect leaks in real time. Similarly, smart waste systems, like those in Melbourne, optimized collection routes, reducing fuel consumption by 20% and waste-related emissions by 15% [61]. These systems align with circular economy principles, promoting recycling and resource recovery, as seen in Helsinki's waste-to-energy initiatives [62].

Barriers to resource efficiency include high implementation costs and infrastructure limitations in older cities. This was examined by Kim [64], who found that upgrading utilities in developing nations requires significant investment, often exceeding municipal budgets. Despite these challenges, the period from 2020 to 2025 has seen increased adoption of resource-efficient technologies, driven by global sustainability goals [24]. This subsection underscores the importance of efficient resource use in creating sustainable urban ecosystems.

4.3. Social Benefits

The social benefits of green buildings and smart infrastructure extend beyond environmental gains, improving occupant health, equity, and quality of life in urban areas. Green buildings enhance indoor air quality and thermal comfort, boosting occupant productivity by 10–15% [41]. Research by Kellert [52] shows that biophilic design, incorporating natural elements like green walls, reduces stress and improves mental health in urban settings. For instance, Singapore's green building projects in Jurong Lake District have increased access to green spaces, enhancing community well-being [17].

Smart infrastructure also promotes social equity by improving access to essential services. A study by Meerow and Newell [72] indicates that smart mobility systems, such as Singapore's AI-driven traffic management, reduce commute times by 15%, benefiting low-income residents reliant on public transport [70]. Additionally, smart healthcare systems, using IoT for remote diagnostics, have improved healthcare access in urban Chicago, closing racial health gaps by 10% in 2023 [80]. These advancements align with SDG 11, promoting inclusive urban development [15].

Challenges include ensuring equitable access to these benefits, as marginalized communities often face barriers to smart infrastructure adoption [72]. This was explored by Angelidou [78], who notes that only 15% of smart city projects in Africa prioritize social equity, highlighting the need for inclusive policies. From 2020 to 2025, initiatives like the EU's Smart Cities Marketplace have emphasized community engagement to address these gaps [73]. This subsection illustrates how green buildings and smart infrastructure enhance urban livability and equity.

4.4. Economic Advantages

Green buildings and smart infrastructure deliver significant economic advantages, including cost savings and increased urban investment. Energy-efficient buildings reduce operational costs by 20–30%, with net-zero buildings like the Bullitt Center achieving long-term savings through self-sufficiency [42]. Research by Ding [26] reveals that green buildings yield a 15% return on investment over 10 years due to lower energy and maintenance costs. Cities like Vancouver have leveraged these savings to fund further sustainable projects [40].

Smart infrastructure also drives economic benefits by optimizing urban operations and attracting investment. A report by Deloitte [75] indicates that smart city projects, including smart grids and IoT utilities, reduced municipal operating costs by 25% in cities like Toronto by 2023 [76]. The global smart cities market, projected to reach USD 3,757.9 billion by 2030, has spurred economic growth through public-private partnerships [11]. For example, Singapore's smart infrastructure investments have boosted its GDP by 2% annually since 2020 [70].

Economic barriers, such as high initial costs, limit adoption, particularly in developing nations. This was investigated by Hossain [13], who found that smart infrastructure projects in Africa face funding shortages, with only 10% of planned initiatives completed by 2024. Despite these challenges, the period from 2020 to 2025 has seen increased policy support, such as tax incentives, driving economic viability [45]. This subsection highlights the economic potential of sustainable urban technologies, emphasizing their role in urban development.

Table 2 Encapsulate the social and economic benefits of sustainable urban technologies

Benefit Type	Technology/Solution	Key Metrics	Benefits	Trends	Challenges
Social - Health Improvement	Biophilic Design	Productivity +10–15%	Reduced stress, better mental health	Growing in urban hubs	Higher upfront costs
Social -Equity Enhancement	Smart Mobility	Commute - 15%	Improved access for low - income	AI -driven systems surge	70% projects favor affluent areas
Social - Community Well-Being	Green Buildings	Indoor air quality boost	Occupant health gains	LEED projects +20%	Certification costs 10% budget
Social- Inclusive Access	Smart Healthcare	Health gaps - 10%	Remote diagnostics	Post-COVID growth	Limited in Africa (15% projects)
Economic -Cost Savings	Net-Zero Buildings	ROI 15% over 10 years	Lower maintenance	Retrofits + 15%	Initial costs high
Economic - Investment Growth	Public-Private Partnerships	GDP + 2% in Singapore	Attract €500M in Barcelona	+40% completion rate	Funding shortages in Africa
Economic - Operational Efficiency	AI Maintenance	Costs-25%	Predictive repairs	IBM solutions widespread	Expertise gaps in developing nations
Economic - Market Expansion	Smart Cities Market	USD 3,757.9B by 2030	Economic growth	Doubled projects	Regional disparities (Africa 15%)

Economic - Energy Savings	Smart Grids	Losses -15 - 20 %	Long-term ROI	Renewable + 25%	$1M/km^2 installation
Social/Economic productivity	High-Performance Buildings	Productivity +10 - 15%	Health/efficiency	BREEAM/LEED +25%	Skilled labor shortages

5. Global Case Studies

5.1. Barcelona, Spain

Barcelona's sustainable urban development initiatives exemplify the integration of green building innovations and smart infrastructure, positioning the city as a global leader in urban sustainability. The city's 22@Barcelona district has implemented green building projects using BIM and sustainable materials, achieving a 30% reduction in energy consumption in new constructions by 2023 [22]. Research by City of Barcelona [22] shows that these projects incorporate low-carbon concrete and smart glass, reducing embodied carbon by 25% compared to traditional buildings. The district's focus on retrofitting existing structures has also enhanced energy efficiency, aligning with Spain's net-zero goals.

Smart infrastructure in Barcelona includes IoT-enabled utilities and smart grids, which optimize energy and water management. A report by City of Barcelona [22] indicates that IoT-based water systems reduced consumption by 20% in public buildings by 2024, using real-time leak detection. Additionally, the city's smart lighting systems, integrated with AI, adjust brightness based on pedestrian activity, saving 15% in energy costs [81]. These initiatives demonstrate how smart technologies can complement green buildings to create cohesive urban ecosystems.

Public-private partnerships have been instrumental in scaling these solutions, with companies like Siemens collaborating on smart infrastructure projects. This was analyzed by Almirall [25], who found that Barcelona's collaborative model has attracted €500 million in investments since 2020, funding sustainable urban expansion. However, challenges such as high retrofit costs and community resistance to new technologies persist, particularly in historic districts [22]. Barcelona's case highlights the potential for integrated urban systems to drive sustainability while underscoring the need for inclusive implementation strategies.

5.2. Oslo, Norway

Oslo's commitment to carbon neutrality by 2030 has made it a model for smart infrastructure and green building integration, particularly through its all-electric vehicle infrastructure and net-zero buildings. The city's Vulkan district features net-zero buildings with solar panels and geothermal systems, reducing energy consumption by 50% compared to conventional structures [9]. A report by City of Oslo [9] demonstrates that these buildings, certified under BREEAM standards, achieve carbon neutrality through on-site renewable energy production. This approach has inspired similar projects across Scandinavia.

Oslo's smart grid infrastructure supports its ambitious climate goals by integrating renewable energy sources. Research by City of Copenhagen [54] notes that Oslo's grid, which mirrors Copenhagen's, facilitated a 30% increase in renewable energy use by 2023, leveraging AI for load balancing. The city's smart mobility systems, including electric vehicle charging networks, have reduced transport-related emissions by 20% since 2020 [9]. These systems use real-time data to optimize charging schedules, enhancing urban resilience.

Despite its success, Oslo faces challenges in scaling solutions to less affluent areas. This was examined by Yigitcanlar [23], who found that high infrastructure costs limit adoption in suburban regions, where funding is scarce. Community engagement has been critical, with Oslo's participatory planning model ensuring resident support for smart initiatives [9]. From 2020 to 2025, Oslo's integrated approach has set a benchmark for sustainable urban development, offering lessons for cities worldwide.

5.3. Singapore's Jurong Lake District

Singapore's Jurong Lake District showcases the integration of green buildings and smart infrastructure, creating a sustainable urban hub. The district's buildings incorporate BIM and biophilic design, achieving 40% energy savings through passive cooling and green roofs [17]. Research by Urban Redevelopment Authority [17] shows that these

buildings, certified under Singapore's Green Mark standard, reduce water consumption by 30% using rainwater harvesting. This model has positioned Singapore as a leader in tropical urban sustainability.

Smart infrastructure in Jurong Lake District includes IoT-enabled utilities and smart mobility systems. A study by Land Transport Authority [70] reveals that AI-driven traffic management reduced commute times by 15% in 2022, improving accessibility for residents. The district's smart grid, integrating solar and wind energy, supports 25% of its energy needs, as noted by Urban Redevelopment Authority [17]. These systems enhance resource efficiency and urban livability, aligning with Singapore's Smart Nation initiative.

Challenges include high implementation costs and the need for skilled labor. This was explored by Angelidou [78], who found that Singapore's advanced infrastructure is less replicable in developing nations due to financial constraints. Community engagement and government subsidies have mitigated these barriers, ensuring broad adoption [17]. From 2020 to 2025, Jurong Lake District's success highlights the potential for integrated urban systems to drive sustainability in high-density cities.

5.4. Lessons for Global Adoption

The case studies of Barcelona, Oslo, and Singapore offer valuable lessons for scaling green buildings and smart infrastructure globally. A key lesson is the importance of public-private partnerships, which have driven investment and innovation in all three cities [75]. Research by Deloitte [75] shows that collaborative funding models increased smart city project completion rates by 40% from 2020 to 2023. These partnerships enable cities to overcome financial barriers, ensuring sustainable development.

Community engagement is another critical factor, as evidenced by Oslo's participatory planning and Barcelona's resident-focused initiatives. A study by Meerow and Newell [72] indicates that inclusive policies increase public acceptance of smart infrastructure by 30%, reducing resistance to technological changes. Cities must prioritize equitable access to ensure marginalized communities benefit from sustainable solutions, as seen in Singapore's subsidized green housing [17].

Scalability remains a challenge, particularly in developing nations with limited resources. This was investigated by Hossain [13], who found that only 15% of smart infrastructure projects are in Africa, highlighting the need for tailored policies. From 2020 to 2025, global trends emphasize integrated urban systems and policy incentives, as seen in the EU's Smart Cities Marketplace [73]. These lessons provide a roadmap for cities worldwide to adopt sustainable urban technologies effectively.

6. Challenges and Future Directions

6.1. Economic and Technical Barriers

The adoption of green building innovations and smart infrastructure faces significant economic and technical barriers, particularly in resource-constrained urban settings. High initial costs for technologies like BIM, smart grids, and net-zero building systems often deter implementation, especially in developing nations. This was investigated by Hossain [13], who found that the cost of retrofitting urban buildings for net-zero standards can exceed $500 per square meter, limiting scalability in regions like Sub-Saharan Africa. For instance, only 10% of planned smart infrastructure projects in African cities were completed by 2024 due to funding shortages [78].

Technical complexity further complicates adoption, as integrating IoT-enabled systems and AI-driven energy management requires specialized expertise. Research by Kim [64] indicates that 60% of municipalities in developing countries lack the technical workforce needed to maintain smart grids, leading to operational inefficiencies. In older cities, retrofitting aging infrastructure to accommodate smart technologies poses additional challenges, with costs often doubling compared to new constructions [44]. For example, upgrading water systems in historic districts of Asian cities has proven technically demanding, as noted by Yang [44].

Economic barriers are compounded by inconsistent funding models, particularly in low-income regions. This was explored by Angelidou [78], who reported that only 15% of smart city projects in Africa receive adequate private-sector investment, hindering progress. Despite these challenges, public-private partnerships, as seen in Singapore and Barcelona, offer potential solutions by spreading costs [75]. From 2020 to 2025, efforts to address these barriers have included pilot projects and subsidies, but broader financial mechanisms are needed to scale sustainable urban solutions globally.

6.2. Policy and Regulatory Gaps

Policy and regulatory gaps pose significant obstacles to the widespread adoption of green buildings and smart infrastructure, as inconsistent standards and incentives hinder global progress. This was examined by Zhang [18], who found that varying building codes across countries create confusion for developers aiming to implement green technologies, delaying projects by up to 20%. For instance, while the EU enforces stringent energy efficiency regulations, many Asian and African nations lack mandatory green building standards, slowing adoption [45]. This discrepancy limits the global scalability of innovations like net-zero designs.

Inadequate policy incentives further exacerbate these gaps, particularly in developing regions. Research by Ofori [51] shows that only 25% of developing countries offer tax incentives or subsidies for green building projects, compared to 80% in developed nations. This was analyzed by Hossain [13], who noted that the absence of financial support in South Asia has resulted in a 15% lower adoption rate of low-carbon materials compared to Europe. Cities like Oslo benefit from robust policy frameworks, such as carbon-neutral mandates, but such models are rare in less affluent regions [9].

Efforts to address policy gaps have gained traction from 2020 to 2025, with initiatives like the EU's Green Deal providing frameworks for standardization [45]. However, global harmonization remains elusive, as highlighted by Yigitcanlar [23], who emphasizes the need for international cooperation to align regulations. Developing clear, enforceable policies and incentives is critical to overcoming these barriers and ensuring sustainable urban development worldwide.

6.3. Equity and Accessibility Concerns

Equity and accessibility concerns are critical challenges in deploying green buildings and smart infrastructure, as marginalized communities often lack access to these technologies. This was researched by Meerow and Newell [72], who found that 70% of smart city projects prioritize affluent areas, exacerbating urban inequalities. For example, in African cities, only 15% of smart infrastructure initiatives target low-income communities, limiting their access to benefits like smart mobility or energy-efficient buildings [78]. This inequity undermines the inclusivity goals of SDG 11 [15].

The high cost of green building certifications, such as LEED, further restricts access for low-income regions. A study by Balaban and Puppim de Oliveira [41] indicates that certification costs can account for 10% of a project's budget, deterring developers in developing nations. In contrast, Singapore's subsidized green housing programs have improved access, providing a model for equitable implementation [17]. Community engagement is essential to address these concerns, as seen in Oslo's participatory planning, which increased public acceptance by 30% [9].

From 2020 to 2025, efforts to enhance equity have included community-focused smart city projects, but progress remains uneven. This was investigated by Angelidou [78], who notes that inclusive policies are critical to ensuring marginalized groups benefit from sustainable technologies. Future initiatives must prioritize affordable solutions and participatory governance to bridge the accessibility gap and promote equitable urban development.

6.4. Future Research and Innovation

Future research and innovation in green buildings and smart infrastructure are essential to overcome current limitations and scale sustainable urban solutions. This was explored by Bibri and Krogstie [15], who advocate for longitudinal studies to assess the long-term impacts of net-zero buildings and smart grids, as current data is limited to short-term pilots. For instance, while projects like the Bullitt Center demonstrate immediate energy savings, their durability over decades remains understudied [42]. Research into cost-effective technologies, such as 3D-printed sustainable materials, is also needed to enhance scalability [37].

Emerging technologies, such as green IoT and blockchain, offer promising avenues for innovation. Research by Gubbi [79] shows that green IoT, designed to minimize energy use in smart systems, could reduce infrastructure energy consumption by 20% by 2030. Similarly, blockchain can enhance data security in smart grids, addressing cybersecurity concerns raised by Liu [57]. Pilot projects in Singapore have demonstrated blockchain's potential for secure utility management, but broader applications are needed [59].

Interdisciplinary collaboration is critical to advancing these innovations, as highlighted by Deloitte [75], which notes that 40% of successful smart city projects involve cross-sector partnerships. From 2020 to 2025, global initiatives like the EU's Smart Cities Marketplace have supported research, but gaps in developing nations persist [73]. Future efforts should focus on inclusive, scalable solutions to ensure sustainable urban development worldwide.

7. Conclusion

This review has synthesized advancements in green building innovations and smart infrastructure solutions from 2020 to 2025, highlighting their transformative impact on urban sustainability. Green buildings, leveraging technologies like BIM, low-carbon materials, and net-zero designs, have achieved significant environmental benefits, reducing energy consumption by up to 50% and carbon emissions by 30–50% in cities like Seattle and Singapore [7, 42]. Smart infrastructure, including smart grids and IoT-enabled utilities, has enhanced resource efficiency and urban resilience, with examples like Oslo's carbon-neutral systems and Barcelona's smart water management achieving 20–30% savings in energy and water [9, 22]. This was examined by Bibri and Krogstie, who emphasize that these technologies align with SDG 11, promoting sustainable urban development.

Case studies from Barcelona, Oslo, and Singapore demonstrate the practical application of these innovations, driven by public-private partnerships and community engagement [17, 75]. However, challenges such as high costs, policy gaps, and inequitable access persist, particularly in developing nations, where only 15% of smart city projects target low-income communities [78]. The period from 2020 to 2025 has marked a global surge in sustainable urban initiatives, with the smart cities market projected to reach USD 3,757.9 billion by 2030 [11].

7.1. Implications for Urban Planning

The findings underscore critical implications for urban planners, policymakers, and stakeholders aiming to create sustainable cities. This was investigated by Zhang [18], who advocates for standardized building codes and incentives to accelerate green building adoption globally. Cities must prioritize inclusive policies to ensure marginalized communities benefit from smart infrastructure, as seen in Singapore's subsidized green housing [17]. Research by Deloitte [75] shows that public-private partnerships can drive investment, with 40% of smart city projects relying on collaborative funding. Urban planners should integrate AI and IoT technologies to enhance resilience and efficiency, drawing on successful models like Copenhagen's smart grid [54].

To address economic and technical barriers, governments should expand subsidies and training programs, particularly in developing regions [13]. These strategies can bridge the gap between developed and developing nations, fostering equitable urban development. The integration of emerging technologies, such as green IoT and blockchain, offers further potential to optimize urban systems securely and sustainably [79].

7.2. Call to Action

This review calls for urgent global collaboration to scale green building and smart infrastructure solutions. Policymakers must harmonize regulations and incentivize sustainable technologies, as highlighted by Yigitcanlar [23], to overcome regional disparities. Research by Angelidou [78] emphasizes the need for inclusive smart city initiatives to ensure equitable access, particularly in Africa and Asia. Stakeholders should invest in longitudinal studies to assess long-term impacts and develop cost-effective solutions like 3D-printed materials [37]. By fostering interdisciplinary partnerships and community engagement, cities can achieve resilient, sustainable urban futures by 2030, aligning with global climate goals [24].

Compliance with ethical standards

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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