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Review Article

Shaping resilient buildings and cities: Climate change impacts, metrics, and strategies for mitigation and adaptation

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ABSTRACT: In an era characterized by unprecedented urbanization and escalating concerns about climate change, the resilience of buildings and cities has emerged as a paramount global imperative. This review article embarks on a comprehensive exploration of the intricate relationship between climate change and the built environment, delving into multi-faceted dimensions that encompass climate change impacts, quantification methodologies, adaptive strategies, disaster management, eco-centric design paradigms, and assessment metrics. As the world grapples with the challenges posed by shifting climate patterns, understanding the intricate interplay between these elements becomes pivotal to fostering sustainable urban development. From the far-reaching implications of climate change on buildings and cities to the intricate tools and strategies that assess, mitigate, and adapt to these shifts, this article offers a comprehensive roadmap for creating resilient urban landscapes that thrive amidst environmental uncertainties. By amalgamating diverse insights and approaches, it envisions a future where eco-design, climate resilience, and pragmatic strategies converge to shape buildings and cities that stand as bastions of sustainability and fortitude.

KEYWORDS: buildings and cities; climate change impacts; climate resilience; eco-design; metrics; strategies for mitigation and adaptation

1. Introduction

In an era characterized by rapid urbanization and escalating climate concerns, the resilience of buildings and cities stands as a pivotal challenge of our time. As the impacts of climate change[1,2] become increasingly pronounced, understanding and addressing their implications for urban environments have gained paramount importance[3,4]. This comprehensive review article embarks on a multifaceted exploration of the intricate relationship between climate change and the built environment, shedding light on key dimensions that encompass climate change impacts, measurement methodologies, adaptive strategies, disaster management, eco-centric design paradigms, and assessment metrics.

The pressing need to comprehend the interplay between climate change and urban infrastructure underpins the significance of this review. With urban populations rapidly swelling, the vulnerability of buildings and cities to climate-induced stresses has profound socio-economic implications. This article seeks to illuminate the intricate mechanisms through which climate change impacts manifest within urban settings and, subsequently, to provide an array of strategies and metrics that empower stakeholders to forge resilient and sustainable urban landscapes.

While previous research[5–8] has delved into specific facets of climate change impacts and resilience strategies, a comprehensive review that synthesizes the entirety of this multidimensional subject remains a critical knowledge gap. This review aims to bridge this gap by addressing the following pivotal research questions:

1) How do climate change impacts manifest in buildings and cities, and what are the innovative methods and metrics for quantifying these effects on factors such as energy demand, structural integrity, and urban functionality?
2) What strategies effectively mitigate and adapt to climate change impacts in buildings and urban environments, and how do smart disaster management systems enhance resilience against climate-induced hazards?
3) What is the transformative role of eco-design and climate resilience in shaping buildings and cities, and which metrics best measure their environmental performance, resource efficiency, and overall adaptive capacity?

This article adopts a systematic methodology (Section 2) to consolidate current literature concerning climate change impacts, quantification methodologies, strategies for mitigation and adaptation, intelligent disaster management, eco-design, and metrics for assessing climate resilience within the framework of buildings and urban environments.

The outcomes of this review hold significant practical implications for urban planning, policy formulation, and design strategies. By distilling the collective wisdom from a multitude of studies, this review empowers decision-makers to make informed choices in the face of a changing climate, ensuring the creation of resilient, adaptive, and eco-friendly urban environments.

This review article is structured to traverse the landscape of climate change impacts on buildings and cities, beginning with an examination of the direct effects (Section 3.1). It then transitions into a discourse on methodologies and metrics for quantification, offering insights into the state of the art in measurement techniques (Section 3.2). Subsequently, strategies for both mitigation and adaptation are explored, emphasizing the need for proactive approaches to enhancing urban resilience (Section 3.3). The article proceeds to explore smart disaster management, showcasing innovative technologies and approaches that safeguard urban structures and inhabitants (Section 3.4). The pivotal role of eco-design and climate resilience in shaping buildings and cities is given dedicated attention (Section 3.5), followed by a comprehensive exploration of metrics that gauge eco-centric and climate-resilient achievements (Section 3.6).

In Section 4, we explore the policy and practical implications of the research questions addressed in this review article. Additionally, we integrate case studies to offer practical context, pinpoint potential areas for future research, identify gaps, and underscore the pivotal importance of engaging stakeholders, especially local communities, in the mitigation of climate change impacts on buildings and cities.

As urban centers face unprecedented challenges, this review article endeavors to consolidate and illuminate the pathways that lead to a more resilient, adaptive, and sustainable urban future in the face of climate change.

2. Methodology

This review article employs a systematic approach to synthesize existing literature on climate change impacts, quantification methods, mitigation and adaptation strategies, smart disaster management, eco-design, and climate resilience metrics in the context of buildings and cities.

Simulation data collection

In this study, valuable insights into climate change impacts were gained through the meticulous collection of simulation data, focusing on key indicators such as Heating Degree Days (HDD), Cooling Degree Days (CDD), precipitation patterns, and sea-level rise. These data points serve as essential metrics for assessing the multifaceted effects of climate change on buildings and cities.

Central to our data acquisition is the utilization of the IPCC WGI Interactive Atlas[9], a comprehensive and authoritative tool developed by the Intergovernmental Panel on Climate Change (IPCC) Working Group I. The Interactive Atlas offers a user-friendly interface that grants access to a wealth of climate model outputs, scenarios, and projections. Through this tool, users can explore and visualize a wide range of climate variables and their potential evolution under various emission scenarios.

The IPCC WGI Interactive Atlas aggregates the outputs of the Coupled Model Intercomparison Project Phase 6 (CMIP6), a globally coordinated effort aimed at advancing our understanding of climate systems. CMIP6 employs state-of-the-art climate models to simulate a spectrum of climate variables, facilitating informed decision-making and comprehensive assessments of climate change impacts (in Section 2.2)[1].

With the IPCC WGI Interactive Atlas as our cornerstone resource, we harnessed the power of cutting-edge simulations to unravel the intricate relationships between changing climate patterns and their implications for buildings and urban environments. This approach enables a robust analysis of Heating and Cooling Degree Days, precipitation trends, and sea-level rise, contributing to a comprehensive understanding of the challenges and opportunities that lie ahead in the realm of climate-resilient urban development.

3. Comprehensive insights: Climate change impacts, metrics, strategies, and resilience in urban environments

This section comprehensively investigates multiple facets of climate change's influence on urban environments, encompassing: 1) the direct impacts on buildings and cities; 2) methodologies and metrics to assess these effects; 3) adaptive and mitigation strategies for urban resilience; 4) intelligent disaster management to bolster building and city resilience; 5) the pivotal contribution of eco-design and climate resilience in shaping urban spaces; and 6) the utilization of specific metrics to gauge eco-design and climate resilience within buildings and cities.

3.1. Climate change impacts on buildings and cities

Climate change can have a wide range of impacts on buildings[10] and cities[11,12], both in terms of their construction and operation. These impacts can vary depending on factors such as geographical location, local climate conditions, building design, and infrastructure[13]. The key ways in which climate change can affect buildings and cities include:

- **Increased Temperature, Energy Demand, and Urban Heat Island Effect**: Climate change, specifically the increase in temperature, can have significant impacts on energy demand in both the North and South regions[14] (in Chapter 5) (SMRY[15]). These impacts can vary based on factors such as geographical location, existing energy infrastructure, and the level of temperature increase[1,16,17]. In fact, as temperatures rise, the northern regions are likely to experience a reduced need for heating during the colder months (**Figure 1**). This could lead to decreased energy demand for heating systems. Paradoxically, even in traditionally cooler areas, higher temperatures can lead to increased demand for cooling during hotter months (**Figure 2**). This could be due to a rise in the use of air conditioning and cooling systems. Similar to the North, the South region will likely experience increased cooling demand due to higher temperatures (**Figure 2**). This can lead to higher electricity consumption and potentially put strain on the power grid during peak demand periods as more air conditioning units and cooling systems are used to maintain indoor comfort[14,18,19]. In addition, higher temperatures can lead to increased heat stress in urban areas, especially due to the urban heat island effect, where cities are significantly warmer than surrounding rural areas due to human activities and a lack of vegetation[20,21].

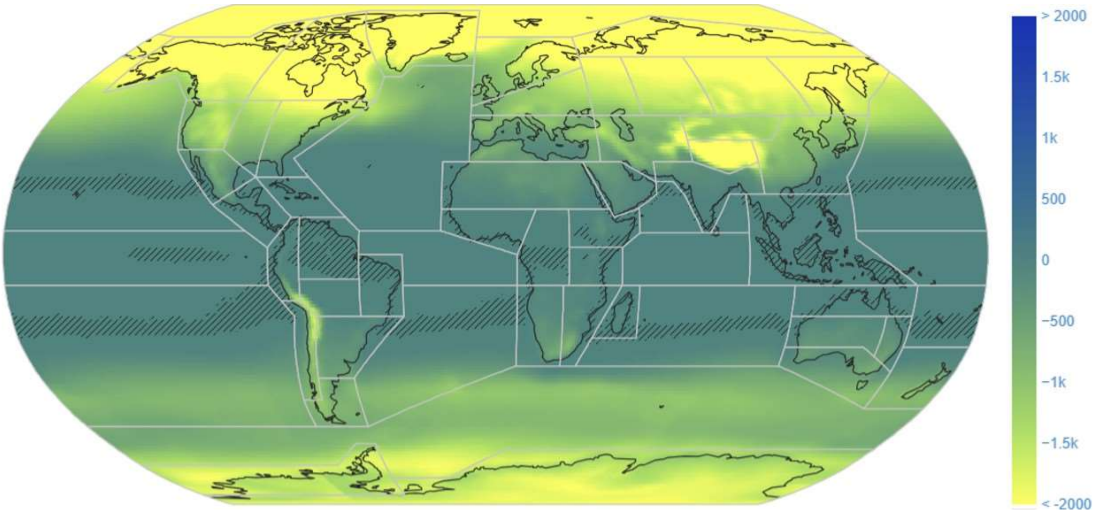

Figure 1. Projected Change in Heating Degree Days (HDD) for the Long Term (2081-2100) Under the SSP5-8.5 Scenario, Relative to the 1995–2014 Baseline, Annual Average, Across 27 CMIP6 Models. Heating Degree Days (HDD) represent the sum of degrees by which a day's average temperature falls below a reference temperature, typically indicating the demand for heating energy[14] (in Chapter 2, Section VI). SSPs, or Shared Socioeconomic Pathways, are scenarios used in climate modeling to explore different potential futures based on varying levels of socioeconomic development, energy use, and policy choices[1] (**Figure 2**). CMIP6 refers to the Coupled Model Intercomparison Project Phase 6, which is a global climate model experiment coordinated by the World Climate Research Programme[1] (Section 2.2).

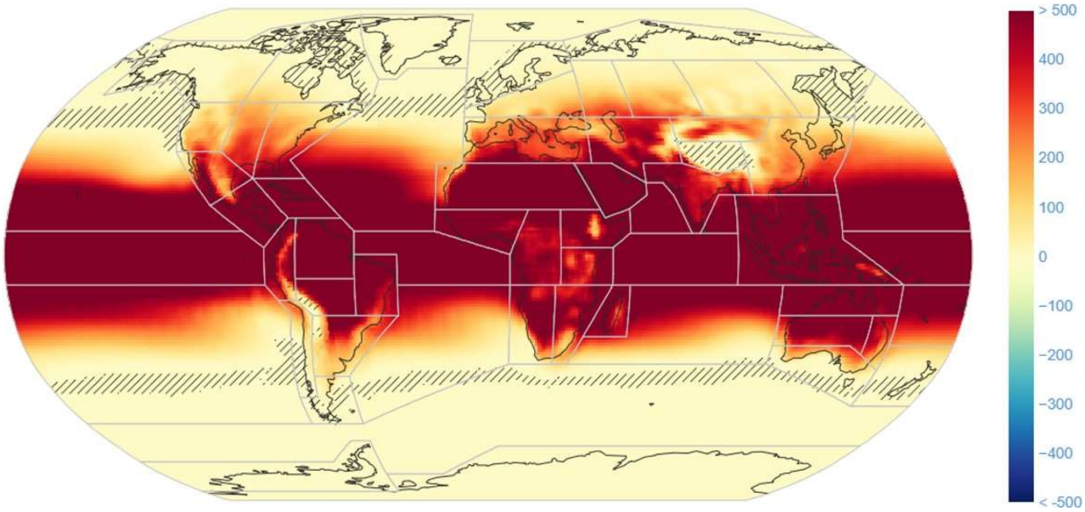

Figure 2. Projected Change in Cooling Degree Days (CDD) for a Warming of 2 °C Above Pre-Industrial Levels Under the SSP5-8.5 Scenario, Relative to the 1850–1900 Baseline, Annual Average, Across 27 CMIP6 Models. Cooling Degree Days (CDD) represent the sum of degrees by which a day's average temperature exceeds a reference temperature, typically indicating the demand for cooling energy[14] (Chapter 2, Section VI). SSPs, or Shared Socioeconomic Pathways, serve as frameworks within climate modeling to investigate diverse prospective scenarios rooted in fluctuating degrees of socioeconomic progress, energy consumption, and policy trajectories[1] (**Figure 2**). CMIP6, an acronym for the Coupled Model Intercomparison Project Phase 6, signifies an internationally coordinated endeavor by the World Climate Research Programme to conduct a comprehensive global climate modeling initiative[1] (Section 2.2).

- **Extreme Weather Events**: More frequent and intense extreme weather events, such as hurricanes, storms, floods, wildfires, and heatwaves[22,23], can damage buildings and infrastructure, transportation systems, utilities, and communication networks, disrupting city functions and residents' lives[2,24].
- **Sea Level Rise**: Coastal cities are particularly vulnerable to sea level rise (**Figure 3**)[25], which can lead to increased flooding, erosion, and saltwater intrusion into infrastructure. Buildings and underground utilities can be compromised, and increased moisture can contribute to decay and mold growth[26].
- **Water Scarcity or Flooding and Drainage Issues**: Changes in precipitation patterns (**Figure 4**)[1] can lead to water scarcity in some regions[27,28], or flooding and drainage issues[29,30] in other regions, affecting water supply, sanitation[31,32], and agriculture[33,34]. Buildings and cities may need to adopt water-efficient technologies and practices.
- **Health Risks**: Climate change can exacerbate health risks in urban areas due to increased heat-related illnesses, respiratory problems from poor air quality, and the spread of diseases carried by insects[2].
- **Insurance Costs**: Increased climate-related risks can lead to higher insurance costs for both individuals and businesses, potentially affecting property values and investment decisions[2,32].
- **Migration and Population Shifts**: Climate change impacts can lead to population shifts as people move away from vulnerable areas, which can have implications for urban development, housing demand, and social dynamics[2].
- **Economic Impacts**: Climate change-related damages to buildings and infrastructure can have significant economic consequences for cities, affecting local economies, property values, and public finances[2].

Addressing these impacts requires a combination of strategies, including better urban planning, resilient building design, sustainable infrastructure, improved emergency response plans, and global efforts to mitigate climate change through reduced greenhouse gas emissions.

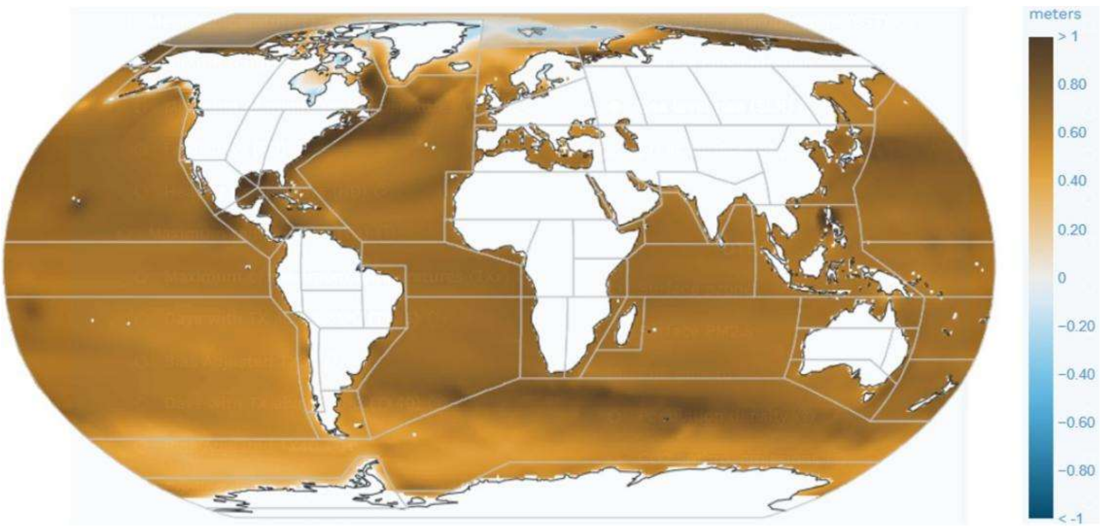

Figure 3. Projected Change in Sea Level Rise (SLR) for the Long Term (2081-2100) Under the SSP5-8.5 Scenario, Relative to the 1995-2014 Baseline, Annual Average, Based on CMIP6 Models. CMIP6 refers to the Coupled Model Intercomparison Project Phase 6, which is a global climate model experiment coordinated by the World Climate Research Programme. SSP5-8.5 is a specific Shared Socioeconomic Pathway that represents a high greenhouse gas emissions and high climate change scenario[1] (Section 2.2).

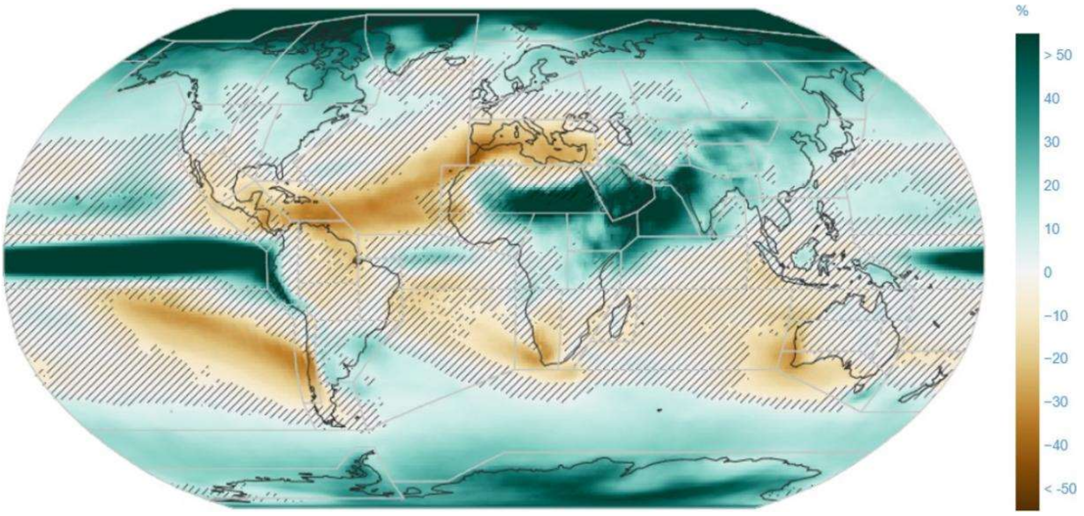

Figure 4. Projected Change in Total Precipitation (PR) as a Percentage for the Long Term (2081-2100) Under the SSP5-8.5 Scenario, Relative to the 1995-2014 Baseline, Annual Average, Across 33 CMIP6 Models. CMIP6 refers to the Coupled Model Intercomparison Project Phase 6, which is a global climate model experiment coordinated by the World Climate Research Programme. SSP5-8.5 is a specific Shared Socioeconomic Pathway that represents a high greenhouse gas emissions and high climate change scenario[1] (Section 2.2).

Case Study: Miami, Florida, USA—Climate change impacts on urban development plans

Miami, Florida, often referred to as the "Magic City," is a prime example of a metropolitan area profoundly affected by the consequences of climate change. This case study explores how climate change has impacted urban development plans in Miami and the measures taken to address these challenges[35].

Miami is situated in a low-lying coastal region susceptible to sea-level rise and extreme weather events. Rising sea levels, increased flooding, and more frequent hurricanes have prompted significant concerns for the city's future development. The city's urban planners and policymakers have been compelled to adapt to these changing conditions[35].

Climate Change Impacts:

- **Sea-Level Rise**: Miami faces one of the highest rates of sea-level rise in the United States. This threatens low-lying neighborhoods, infrastructure, and vital assets such as the Port of Miami[36].
- **Increased Flooding**: Miami experiences frequent tidal flooding, often referred to as "sunny-day flooding"[37], which disrupts daily life and economic activities. The city's stormwater drainage systems are struggling to cope with these rising waters[38].
- **Hurricane Vulnerability**: Miami is highly vulnerable to hurricanes. As climate change intensifies storms, the risk to the city's infrastructure and residents increases significantly[39].

Urban Development Plans and Adaptation Strategies:

- **Elevating Infrastructure:** Miami has incorporated climate resilience into urban development plans by elevating critical infrastructure[40], including roads and seawalls. The city's upgraded stormwater drainage systems are designed to manage increased flooding.
- **Building Code Revisions:** To address the risk of hurricane damage, Miami has updated its building codes to require stricter construction standards, particularly for new developments and retrofitting existing structures[41].
- **Green Infrastructure:** The city is investing in green infrastructure, including mangrove restoration and the creation of parks designed to absorb excess water. These projects aim to mitigate the effects of sea-level rise and provide recreational space for residents[42].

- **Climate Resilience Bonds:** Miami has explored innovative financing mechanisms, such as climate resilience bonds, to fund adaptation projects. These bonds generate revenue for climate adaptation efforts while involving community stakeholders[43].
- **Climate Action Plans:** The city has developed comprehensive climate action plans that outline strategies for reducing greenhouse gas emissions and adapting to climate change. These plans engage local communities and prioritize equity considerations[44,45].

Challenges and Future Directions:

- **Funding:** The cost of climate adaptation and resilience projects remains a significant challenge[2]. Miami must secure funding for large-scale infrastructure investments to protect its vulnerable coastal communities effectively[46,47].
- **Equity:** Ensuring that climate adaptation efforts benefit all residents, including historically marginalized communities, is an ongoing challenge[2,16]. Miami must address disparities in vulnerability and resilience[47].
- **Long-Term Planning:** Miami continues to refine its long-term urban development plans to account for evolving climate change projections, which requires regular updates and adjustments[48].

Miami serves as a compelling case study of a city proactively addressing the impacts of climate change on urban development. By elevating infrastructure, revising building codes, and engaging in green infrastructure projects, Miami demonstrates its commitment to protecting residents and preserving the city's economic vitality in the face of climate change. However, ongoing challenges in funding, equity, and long-term planning underscore the need for continued adaptation efforts and engagement with the community to ensure a resilient and sustainable future for the Magic City.

3.2. Quantifying the effects of climate change on buildings and cities: Methods and metrics for assessment

Measuring the impacts of climate change on buildings and cities involves a multidisciplinary approach that considers various physical, environmental, and social factors. Below are several commonly employed methods and metrics for quantifying and evaluating the impacts of climate change on buildings and urban environments[49,50]:

- **Temperature Monitoring**: Installing temperature sensors in buildings and across cities to track changes in local temperatures, identify urban heat islands[51], and assess heat stress on infrastructure and residents[52,53].
- **Energy Consumption Analysis**: Monitoring energy consumption data for heating and cooling systems to identify shifts in demand due to changing climate conditions[54,55].
- **Precipitation Patterns**: Analyzing historical and current rainfall data to understand shifts in precipitation pat- terns, assess flood risks, and evaluate stormwater management systems[56,57].
- **Sea Level Rise Monitoring**: Using tide gauges and satellite data to track sea level rise near coastal cities and assess potential flooding risks[58,59].
- **Building Performance Simulation**: Utilizing computer modeling and simulations to predict how buildings will respond to changing climatic conditions, including temperature, humidity, and energy demand[60].
- **Air Quality Monitoring**: Measuring air quality indicators such as particulate matter (PM2.5), ozone (O_3), and nitrogen dioxide (NO_2) to assess pollution levels and their impact on indoor and outdoor environments[61,62].
- **Health Data Analysis**: Studying health data to understand the relationship between climate change

impacts (e.g., heatwaves, air quality) and public health outcomes[63].

- **Economic Indicators**: Assessing economic factors, such as insurance claims, property values, and business disruptions, to quantify the economic impacts of climate change on buildings and cities[64].
- **Social Vulnerability Analysis**: Evaluating the social vulnerability of different populations within cities to assess their susceptibility to climate change effects and inform targeted adaptation strategies[64,65].
- **Greenhouse Gas Emissions Tracking**: Monitoring and reporting greenhouse gas emissions from buildings, transportation, and industrial activities to gauge their contribution to climate change and identify areas for reduction[66].
- **Urban Planning and Zoning Review**: Evaluating existing urban plans and zoning regulations to determine their resilience to climate change impacts and updating them accordingly[67].
- **Community Engagement and Perception Surveys**: Conducting surveys and engaging with community members to understand their perceptions of climate change impacts and gather valuable qualitative data[68].
- **Remote Sensing and Satellite Imagery**: Using satellite data to monitor changes in land use, vegetation cover, and urban expansion, which can indicate climate change effects[69].
- **Water Resource Management**: Analyzing water availability, usage, and quality to assess the impact of changing precipitation patterns on water supply and sanitation systems[70,71].
- **Biodiversity Assessment**: Studying changes in local ecosystems and biodiversity to understand ecological impacts and potential cascading effects on urban environments[72,73].

These methods and metrics collectively provide a comprehensive understanding of how climate change is affecting buildings and cities. The data gathered from these assessments can guide policymakers, urban planners, architects, and other stakeholders in developing effective strategies for climate adaptation and resilience.

Reference models and algorithms in past research

In this section, we delve into a comprehensive overview of reference models and algorithms utilized in past research, offering readers valuable insights and resources for understanding the foundations of our study.

- **Climate Change Vulnerability Assessment Models:**
    - **The IPCC Assessment Framework:** The Intergovernmental Panel on Climate Change (IPCC) has developed a comprehensive assessment framework that includes models for evaluating the vulnerability of urban areas to climate change impacts. This framework considers exposure, sensitivity, and adaptive capacity[74].
    - **The Coastal Vulnerability Index (CVI):** This model assesses the vulnerability of coastal regions, including urban areas, to sea-level rise and storm surge. It integrates factors like coastal geomorphology, sea-level rise projections, and socioeconomic data[75,76].
- **Urban Flood Modeling:**
    - **Hydraulic and Hydrological Models:** Models like SWMM (Storm Water Management Model)[77] and HEC-RAS (Hydrologic Engineering Center's River Analysis System)[78] are commonly used to simulate urban flooding and stormwater management. They consider rainfall, terrain, land use, and drainage infrastructure.
- **Sea-Level Rise Projections:**
    - **SLAMM (Sea-Level Affecting Marshes Model):** SLAMM is used to project the effects of sea-level rise on coastal wetlands, which indirectly impacts urban development. It can be adapted

to assess the vulnerability of urban areas to sea-level rise[79].

- **Building Energy Consumption Models:**
    - **EnergyPlus:** This is a widely-used building energy simulation software that models the energy consumption of buildings under various climate scenarios. It can help assess the impact of rising temperatures on cooling loads and energy demand[80].
- **Transportation and Mobility Models:**
    - **Integrated Transportation and Land Use Models**: Models like TRANUS[81] and UrbanSim[82] simulate urban transportation and land use patterns, helping planners assess the resilience of transportation infrastructure to extreme weather events.
- **Social Vulnerability Assessment Models:**
    - **Social Vulnerability Index (SoVI)**: SoVI assesses the vulnerability of communities to environmental hazards, considering socioeconomic factors, demographics, and access to resources. It can be used to identify vulnerable populations in urban areas[83].
- **Machine Learning Algorithms:**
    - **Random Forest and Decision Trees**: These algorithms can be applied to predict climate-related risks and assess the impact of climate change on urban development by analyzing historical and climate data[84].
- **GIS-Based Spatial Analysis:**
    - **Geographic Information Systems (GIS):** GIS tools and spatial analysis techniques are widely used to model the spatial distribution of climate change impacts, such as flooding, heat islands, and sea-level rise, within urban areas[85].

These examples represent a range of modeling and algorithmic approaches used in research related to climate change impacts on urban development plans. Researchers can adapt and apply these models and algorithms to specific urban contexts to assess vulnerabilities, plan adaptation strategies, and enhance the resilience of cities in the face of climate change.

3.3. Strategies for mitigating and adapting to climate change impacts in buildings and urban environments

Mitigating and adapting to climate change in buildings and cities requires a comprehensive and multifaceted approach[86,87]. Below are fundamental approaches encompassing both mitigation, aimed at curbing greenhouse gas emissions, and adaptation, focused on fortifying resilience against climate-induced effects[88]:

3.3.1. Mitigation strategies

- **Energy Efficiency Improvements**: Enhance the energy efficiency of buildings through better insulation[89,90], high-efficiency lighting, appliances, and Heating, Ventilation, and Air Conditioning (HVAC) systems[91] to reduce energy consumption and emissions[92,93].
- **Renewable Energy Integration**: Integrate renewable energy sources[14,94] such as solar panels[25,95], wind turbines[96,97], and geothermal systems to generate clean energy and decrease reliance on fossil fuels[98,99].
- **Green Building Design**: Adopt sustainable building practices, such as green roofs[5], efficient ventilation, and passive solar design[100]—which involves architectural and construction strategies that harness natural sunlight and heat to enhance energy efficiency and indoor comfort within buildings—to minimize energy use and carbon emissions[101,102].
- **Low-Carbon Materials**: Use low-carbon construction materials like recycled content, sustainable wood, and low-embodied-energy materials to reduce emissions associated with building materials[103].

- **Transit-Oriented Development**: Plan cities with well-connected public transportation systems to reduce private vehicle use and lower transportation-related emissions[104].
- **Waste Reduction and Recycling**: Implement waste reduction and recycling programs to reduce landfill emissions and promote a circular economy for building materials[105].
- **Urban Planning**: Design compact, walkable neighborhoods that reduce the need for long commutes and encourage active transportation[106].

3.3.2. Adaptation strategies

- **Climate-Resilient Design**: Develop buildings and infrastructure that can withstand extreme weather events, floods, and heatwaves[6].
- **Elevated Construction**: In coastal areas, raise buildings and infrastructure above anticipated sea levels to mitigate the risk of flooding[107].
- **Green Infrastructure**: Incorporate green spaces, parks, and permeable surfaces to manage stormwater and reduce the urban heat island effect[108].
- **Water Management**: Implement sustainable water management practices such as rainwater harvesting, water efficient appliances, and wastewater treatment systems[109].
- **Emergency Preparedness**: Develop and communicate emergency plans to respond effectively to climate-related disasters[110,111].
- **Health and Safety Measures**: Enhance healthcare and emergency services to address health risks associated with climate change, such as heat-related illnesses[112].
- **Community Engagement**: Involve local communities in climate adaptation planning to ensure that strategies are relevant and effective[113].
- **Biodiversity Promotion**: Preserve and restore natural habitats within cities to enhance biodiversity and support ecosystem services[114].
- **Flexible Zoning**: Update zoning regulations to allow for flexible land use and development patterns that can adapt to changing climate conditions[115].
- **Education and Awareness**: Raise public awareness about climate change impacts and the importance of individual and collective action[116].

Combining these strategies, tailored to specific local contexts, can contribute to both mitigating climate change by reducing emissions and adapting to its inevitable impacts on buildings and cities. Collaboration between governments, urban planners, architects, engineers, businesses, and communities is essential to creating resilient and sustainable urban environments.

3.4. Smart disaster management: Ensuring resilience in buildings and cities

Managing disasters in smart buildings and cities requires a combination of advanced technologies, data-driven strategies, and proactive planning[7,117]. Effectively managing disasters within intelligent urban environments involves:

- **Integrated Sensor Networks**: Deploy sensor networks throughout buildings and cities to monitor various parameters such as temperature, humidity, air quality, structural integrity, and water levels. These sensors provide real-time data for the early detection of disasters[118].
- **Data Analytics and AI**: Utilize data analytics and artificial intelligence (AI) to process and analyze the information collected from sensors. AI algorithms can identify patterns, anomalies, and potential disaster triggers, enabling timely responses[119].
- **Early Warning Systems**: Develop early warning systems that can predict and notify residents and authorities about impending disasters such as earthquakes, floods, or severe weather events. These

systems can provide critical time for evacuation and preparation[120,121].

- **Emergency Communication Channels**: Establish reliable communication channels, including mobile apps and automated notifications, to keep residents informed about disaster situations and evacuation procedures[122].
- **Remote Control and Automation**: Implement remote control and automation systems that allow buildings and city infrastructure to be managed and adjusted remotely during disasters, ensuring the safety of occupants and reducing damage[123].
- **Building Resilience**: Design smart buildings with disaster-resistant features such as earthquake-resistant structures, fire-resistant materials, and backup power systems to ensure functionality during crises[6,7].
- **Energy and Resource Management**: Smart grids and energy management systems can reroute power during outages, prioritize critical services, and optimize energy consumption to ensure essential services remain operational[70,71].
- **Traffic Management**: Implement smart traffic management systems to redirect traffic, manage congestion, and facilitate emergency vehicle movement during disasters[124].
- **Predictive Modeling**: Use predictive modeling to simulate disaster scenarios, assess potential impacts, and optimize response strategies for different types of disasters[125].
- **Community Engagement**: Educate residents about disaster preparedness and response through digital platforms, workshops, and community meetings. Encourage active participation and collaboration in disaster management efforts[113].
- **Rescue and Relief Coordination**: Develop platforms that enable efficient coordination among first responders, emergency services, and relief organizations to ensure a swift and organized response[126].
- **Backup Systems and Redundancies**: Build redundancy into critical systems to ensure that failures in one area do not lead to a complete system breakdown during disasters[8].
- **Post-Disaster Recovery**: Smart technologies can aid in post-disaster recovery by providing real-time data on damage assessment, helping prioritize recovery efforts, and facilitating efficient resource allocation[127].
- **Privacy and Security**: Implement robust cybersecurity measures[128] to protect sensitive data and prevent malicious actors from exploiting smart systems during disasters[129].
- **Regular Testing and Training**: Conduct regular disaster drills and training exercises to familiarize residents, responders, and authorities with smart disaster management systems and protocols[130].

By leveraging smart technologies, data analytics, and collaborative efforts, cities and buildings can enhance disaster management capabilities, reduce risks, and mitigate the impact of disasters on residents and infrastructure.

3.5. The crucial role of eco-design and climate resilience in shaping buildings and cities

The integration of eco-design and climate resilience plays a pivotal role in shaping the future of buildings and cities, ensuring their sustainability, functionality, and adaptability in the face of complex environmental challenges. This synergy between eco-design and climate resilience goes beyond aesthetics and traditional construction practices; it encompasses a profound shift in how we envision, plan, construct, and inhabit our urban spaces[6].

- **Holistic Sustainability**: Eco-design considers the entire lifecycle of buildings and cities, from material selection and construction methods to energy efficiency and waste management. By minimizing resource consumption, reducing emissions, and promoting circular economy principles, eco-design ensures that structures are environmentally responsible and contribute positively to their surroundings.

- **Resource Efficiency**: Integrating eco-design principles helps optimize resource utilization, from energy and water to materials. This not only reduces the ecological footprint but also enhances the long-term affordability and feasibility of buildings and infrastructure.
- **Climate Adaptation**: Climate resilience ensures that buildings and cities are equipped to withstand and recover from the increasing frequency and intensity of climate-related events, such as extreme weather, floods, and heatwaves. Resilience strategies include flood-resistant design, efficient stormwater management, and the preservation of green spaces.
- **Enhanced Comfort and Well-Being**: Eco-design prioritizes indoor environmental quality, promoting natural lighting, optimal air circulation, and reduced pollutants. Climate resilience measures ensure that structures remain habitable and comfortable even under changing climatic conditions.
- **Future-Proofing**: Incorporating eco-design and climate resilience safeguards investments against the uncertainties of a changing climate. It anticipates the potential challenges that buildings and cities might face and equips them with features that help minimize risks.
- **Biodiversity and Ecosystem Services**: Both eco-design and climate resilience acknowledge the importance of integrating natural ecosystems within urban areas. Green spaces, biodiversity corridors, and sustainable landscaping not only enhance the aesthetic appeal but also provide critical ecosystem services such as air purification, flood regulation, and temperature moderation.
- **Community and Social Equity**: A focus on eco-design and climate resilience fosters inclusive and equitable urban environments. Access to green areas, efficient public transportation, and disaster-ready infrastructure benefits all residents, promoting social cohesion and well-being.
- **Global Responsibility**: As buildings and cities collectively contribute to a significant portion of greenhouse gas emissions, embracing eco-design and climate resilience becomes a global responsibility. By setting examples and adopting sustainable practices, urban centers can inspire positive change on a broader scale.

In essence, the amalgamation of eco-design and climate resilience transcends conventional architectural and urban planning practices. It envisions a harmonious coexistence between human activities and the environment, fostering cities that not only withstand climate challenges but also thrive sustainably, providing a high quality of life for current and future generations. As we navigate an era of rapid urbanization and environmental uncertainties, these principles stand as guiding beacons for shaping resilient, adaptive, and environmentally conscious built environments.

3.6. Measuring eco-design and climate resilience in buildings and cities

Measuring eco-design and climate resilience in buildings and cities involves a combination of quantitative and qualitative assessments that evaluate various aspects of sustainability and resilience[6]. Some commonly employed methods and metrics for measuring eco-design and climate resilience include[131]:

3.6.1. Eco-design measurement

- **Life Cycle Assessment (LCA)**: LCA evaluates the environmental impacts of a building or city over its entire life cycle, including construction, operation, and demolition. It quantifies aspects like energy consumption, material use, emissions, and waste generation[132,133].
- **Energy Performance Metrics**: Metrics such as Energy Use Intensity (EUI) and Energy Star ratings

provide insights into a building's energy efficiency and its performance relative to similar structures[134].

- **Green Building Certifications**: Certifications like LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) offer standardized frameworks for assessing sustainable design, construction, and operation[135].
- **Embodied Carbon Assessment**: This measures the carbon emissions associated with the production, transportation, and assembly of building materials, providing insight into the carbon footprint of a structure[136].
- **Water Efficiency Metrics**: Metrics like Water Use Intensity (WUI) and WaterSense ratings quantify a building's water efficiency and its ability to conserve water resources[131].
- **Indoor Environmental Quality (IEQ) Assessment**: Evaluates factors such as indoor air quality, natural lighting, acoustics, and thermal comfort to ensure occupants' well-being[61,62].

3.6.2. Climate resilience measurement

- **Risk and Vulnerability Assessment**: Identifies potential climate-related risks and vulnerabilities that a building or city might face, considering factors such as location, exposure to hazards, and population density.
- **Adaptation Strategies Review**: Evaluates the implementation of climate adaptation strategies, such as flood barriers, green infrastructure, and emergency response plans.
- **Infrastructure Resilience**: Assesses the ability of critical infrastructure (e.g., utilities, transportation networks) to withstand and recover from climate-related stressors.
- **Community Engagement and Participation**: Measures the level of community involvement in climate resilience planning and the integration of local knowledge and needs[113].
- **Biodiversity and Ecosystem Services**: Assesses the presence and health of natural ecosystems within cities, which contribute to climate resilience by providing services like flood control and temperature regulation.
- **Economic Resilience**: Analyzes the economic stability and adaptability of buildings and cities in response to climate impacts, including potential disruptions to local economies.
- **Regulatory Compliance**: Measures the alignment of building codes, zoning regulations, and land use plans with climate resilience goals.
- **Post-Disaster Recovery**: Assesses the speed and effectiveness of recovery efforts following climate-related disasters[127].

The combination of these methods provides a comprehensive understanding of both eco-design and climate resilience in buildings and cities. Measurement and evaluation should be an ongoing process to track progress, identify areas for improvement, and ensure that sustainable and resilient principles are effectively implemented.

4. Discussion

In this discussion section, we delve into the policy and practical implications of the research questions explored in this review article. We also incorporate case studies to provide practical context, identify potential future research directions and gaps, and emphasize the crucial role of stakeholder involvement, particularly with local communities, in addressing climate change impacts in buildings and cities.

4.1. Policy implications and practical applications

The analysis of this review article has several practical implications for various stakeholders, including policy-makers, urban planners, architects, engineers, and local communities. These implications can guide real-world actions in the context of climate change impacts on buildings and cities:

4.1.1. Policymakers and governments

- **Strengthening Building Codes**: Policymakers should prioritize the revision and enforcement of building codes to enhance structural resilience against climate-induced hazards. This includes adopting updated engineering standards that consider changing climatic conditions[137].
- **Promoting Energy Efficiency**: Governments can incentivize energy-efficient building designs and retrofits by offering tax incentives, grants, or subsidies. Encouraging the use of renewable energy sources can also reduce energy demand and greenhouse gas emissions[92,93].
- **Urban Planning**: City planners should prioritize sustainable urban development, including green spaces, pedestrian-friendly environments, and efficient public transportation. These measures can improve overall urban functionality and reduce the urban heat island effect[138,139].
- **Disaster Management**: Investment in smart disaster management systems, including early warning systems, evacuation plans, and resilient infrastructure, should be a priority for governments at all levels[119,122,124].

4.1.2. Urban planners and architects

- **Green Infrastructure**: Urban planners and architects should integrate green infrastructure, such as green roofs, vertical gardens, and permeable pavements, into building and urban design to mitigate the urban heat island effect and enhance overall environmental sustainability[5,108].
- **Sustainable Materials**: The use of sustainable and climate-resilient construction materials should be encouraged. This includes materials that can withstand extreme weather conditions and reduce the carbon footprint of buildings[89].
- **Eco-design**: Incorporating eco-design principles into building projects can significantly improve their environmental performance. This includes considering life-cycle assessments and resource efficiency throughout the design and construction process[140].

4.1.3. Engineers and builders

- **Resilient Construction**: Engineers and builders should prioritize resilient construction techniques, which may include elevated foundations, reinforced structures, and flood-resistant building materials, to ensure the longevity of buildings in the face of climate change impacts[5,6].
- **Renewable Energy Integration**: The integration of renewable energy sources, such as solar panels and wind turbines, should be incorporated into building designs to reduce energy demand and increase self-sufficiency[3,14,88].

4.1.4. Local communities

- **Community Engagement**: Local communities should actively engage with policymakers, urban planners, and developers to ensure their voices are heard in the decision-making process regarding urban development and climate adaptation measures[113].
- **Disaster Preparedness**: Communities should be educated and prepared for climate-induced hazards, with access to information and resources to respond effectively in times of crisis[7,117].

In summary, the practical implications of this review research are extensive and encompass a wide range of actions that various stakeholders can take to address climate change impacts in buildings and cities. By implementing these recommendations, stakeholders can contribute to the creation of more resilient, sustainable, and adaptive urban environments in the face of climate change.

4.2. Case studies for practical context

To provide practical context for these policy implications, we present a few case studies that exemplify successful approaches to addressing climate change impacts in buildings and cities:

4.2.1. The Copenhagen climate adaptation plan, Denmark

- **Policy Implications**: Copenhagen has been proactive in addressing climate change impacts. The city's climate adaptation plan emphasizes sustainable urban development, including building resilient infrastructure and creating green spaces[141,142]. Strict building codes and standards encourage eco-friendly construction practices.
- **Practical Applications**: Copenhagen boasts an extensive cycling network, energy-efficient buildings, and integrated public transportation systems. Innovative green infrastructure, like green roofs and urban gardens, helps mitigate the urban heat island effect[141,142].

4.2.2. Singapore's green building initiatives

- **Policy Implications**: Singapore's Building and Construction Authority (BCA) has introduced stringent energy efficiency standards and green building incentives. This includes measures to reduce energy demand, encourage renewable energy adoption, and promote sustainable building materials[143].
- **Practical Applications**: Singapore's skyline is adorned with greenery, including the award-winning Gardens by the Bay. This green architecture helps combat urban heat, lower energy consumption, and create a more pleasant urban environment[144].

4.2.3. Post-hurricane sandy resilience efforts in New York City, USA

- **Policy Implications**: After Hurricane Sandy in 2012, New York City overhauled its policies to enhance resilience. This included implementing updated building codes for flood-prone areas and bolstering disaster management systems[145,146].
- **Practical Applications**: Initiatives like the "Big U" project have fortified Manhattan's coastline to protect against future storm surges. The city has also expanded its green infrastructure and improved evacuation plans[147].

4.2.4. The Curitiba Bus Rapid Transit (BRT) system, Brazil

- **Policy Implications**: Curitiba's BRT system is a model for sustainable urban planning. The city invested in public transportation, reducing traffic congestion and emissions. This aligns with climate change mitigation strategies[148].
- **Practical Applications**: The BRT system prioritizes efficient, environmentally friendly transportation. It serves as an example of how well-planned urban mobility can reduce energy demand and greenhouse gas emissions[148].

4.2.5. Medellín's transformation, Colombia

- **Policy Implications**: Medellín's transformation from a crime-ridden city to an innovation hub involved urban planning focused on inclusivity, public transportation, and green spaces[149,150].
- **Practical Applications**: The Medellín Metrocable is a prime example of integrating urban functionality with climate resilience. This cable car system connects marginalized neighborhoods to the city center while minimizing environmental disruption[149,150].

These case studies illustrate how diverse policies and practical applications can address climate change impacts in various urban contexts. They showcase the importance of integrating sustainable and resilient practices into urban development, infrastructure, and transportation systems to create more adaptive and environmentally friendly cities.

4.3. Future research directions and identified gaps

While progress has been made in understanding climate change impacts on buildings and cities, several research directions and gaps should be addressed:

4.3.1. Long-term impact assessment

- **Future Research Direction**: Conduct long-term assessments of climate change impacts[1,16] on buildings and cities. Focus on how changing weather patterns, sea-level rise, and evolving risk factors[23–25] affect urban areas over decades and even centuries.
- **Identified Gap**: Current research often focuses on short- to medium-term impacts. There is a need for studies that explore the cumulative and persistent effects of climate change on urban environments[151].

4.3.2. Social and economic impacts

- **Future Research Direction**: Investigate the social and economic consequences of climate change in urban areas. Explore how vulnerable populations are disproportionately affected and the role of equity in climate resilience[2].
- **Identified Gap**: While there is growing awareness of the importance of social and economic dimensions, more comprehensive research is needed to understand the complexities of these impacts and develop strategies to address them effectively[2].

4.3.3. Technological advancements

- **Future Research Direction**: Continue to advance research in innovative construction materials, energy-efficient technologies, and smart urban systems. Explore how emerging technologies like AI, IoT, and blockchain can enhance urban resilience[7].
- **Identified Gap**: The rapid pace of technological change requires ongoing research to evaluate the effectiveness and sustainability of new technologies in mitigating and adapting to climate change impacts[152].

4.3.4. Integrating nature-based solutions

- **Future Research Direction**: Investigate the effectiveness of nature-based solutions (e.g., green infrastructure, urban forestry) in mitigating climate change impacts[108]. Explore how these solutions can be integrated into urban planning and design.
- **Identified Gap**: While there is growing interest in nature-based solutions[153], there is a need for empirical research to quantify their benefits, assess their long-term sustainability, and determine best practices for implementation.

4.3.5. Resilience metrics and assessment tools

- **Future Research Direction**: Develop standardized and comprehensive metrics and assessment tools to measure urban resilience to climate change[49,50]. These tools should consider factors like infrastructure, social cohesion, and governance.
- **Identified Gap**: Existing resilience metrics vary widely and may not capture the full range of urban vulnerabilities and strengths. Standardized assessment tools can provide a common framework for

evaluating and comparing resilience efforts.

4.3.6. Human behavior and decision-making

- **Future Research Direction**: Study human behavior and decision-making[25,95–97] in the context of climate change adaptation and mitigation in urban areas. Understand how individuals, communities, and policymakers respond to climate-related challenges[154].
- **Identified Gap**: Human behavior plays a critical role in shaping the success of climate resilience strategies[154]. Research should delve into behavioral economics, communication strategies, and governance models that promote climate-conscious decisions.

4.3.7. Indigenous knowledge and traditional practices

- **Future Research Direction**: Explore the integration of indigenous knowledge and traditional practices into urban planning and climate resilience strategies. Collaborate with indigenous communities to learn from their sustainable practices[155,156].
- **Identified Gap**: Indigenous communities often possess valuable knowledge about living sustainably in harmony with nature. Research should seek to bridge the gap between indigenous wisdom and mainstream urban planning[155,156].

4.3.8. Cross-disciplinary research

- **Future Research Direction**: Encourage more cross-disciplinary collaboration among researchers from fields such as climate science, architecture, engineering, social sciences, and public health to address complex urban climate challenges[157].
- **Identified Gap**: Solving urban climate challenges requires holistic approaches that consider both physical and social dimensions. Cross-disciplinary research can help generate innovative solutions[2].

Identifying and addressing these research directions and gaps can contribute to more effective strategies for mitigating and adapting to climate change impacts in buildings and cities, ultimately creating more resilient and sustainable urban environments.

4.4. Stakeholder involvement, especially with local communities

Local communities play a central role in the implementation of climate change mitigation and adaptation strategies. Engaging stakeholders, including residents, businesses, and community organizations, is essential for the success of policies and initiatives. Their local knowledge can inform decision-making processes, ensuring that solutions are contextually relevant and equitable[113].

To effectively engage various stakeholders in this endeavor, consider the following:

4.4.1. Local communities

- **Future Research Direction**: Research should focus on the development of community-based adaptation and mitigation strategies. Explore how to empower local communities to actively participate in decision-making processes related to urban development and climate resilience.
- **Identified Gap**: While there is a growing recognition of the importance of community engagement, there is often a gap in translating this recognition into meaningful participation. Research can help bridge this gap and identify best practices for community involvement.

4.4.2. Community outreach and education

- **Future Research Direction**: Investigate effective methods for educating and raising awareness among local communities about climate change impacts and resilience strategies. Explore how to tailor educational initiatives to the specific needs and cultural contexts of different communities.

- **Identified Gap**: Many communities, particularly vulnerable ones, may lack access to information and resources related to climate change. Research can help identify the most effective communication channels and educational tools to reach these communities.

4.4.3. Co-design and co-planning

- **Future Research Direction**: Promote co-design and co-planning processes that involve local communities in the development of urban resilience strategies. Explore participatory design methods that empower communities to contribute to the design of their neighborhoods[158].
- **Identified Gap**: Traditional urban planning processes often exclude the voices of local residents. Research should focus on innovative ways to engage communities in shaping their urban environments, ensuring that solutions are contextually relevant.

4.4.4. Equity and social justice

- **Future Research Direction**: Investigate the equity dimensions of climate change impacts and resilience strategies. Explore how to ensure that vulnerable and marginalized communities have equal access to resources and opportunities for resilience[2,16].
- **Identified Gap**: Climate change disproportionately affects disadvantaged communities[1,16,159]. Research can help identify policy and planning approaches that promote social justice and equitable distribution of resources.

4.4.5. Collaborative governance models

- **Future Research Direction**: Study collaborative governance models that involve local communities in decision-making processes related to climate adaptation and mitigation. Explore how to create inclusive and transparent governance structures[160].
- **Identified Gap**: Effective governance models that involve multiple stakeholders, including communities, are critical for implementing climate resilience strategies[161]. Research can help identify governance structures that promote cooperation and accountability.

4.4.6. Knowledge sharing and capacity building

- **Future Research Direction**: Investigate how to facilitate knowledge sharing and capacity building within local communities. Explore methods to empower community members to become active participants in climate resilience initiatives[162].
- **Identified Gap**: Building local capacity and knowledge is essential for communities to adapt to climate change. Research can identify effective strategies for providing communities with the skills and resources they need.

By actively involving local communities and other stakeholders in the research, planning, and implementation of climate resilience strategies, we can create more inclusive, effective, and sustainable solutions for addressing climate change impacts in buildings and cities.

In conclusion, addressing climate change impacts in buildings and cities is a complex endeavor that requires a combination of policy interventions, practical applications, ongoing research, and active engagement with local communities. By adopting innovative strategies, drawing on case studies, identifying research gaps, and involving stakeholders, we can work towards building more resilient and sustainable urban environments in the face of climate change.

5. Conclusion

In conclusion, this comprehensive review has delved into the multifaceted interactions between climate change and the built environment, illuminating the intricate tapestry of challenges and opportunities that lie ahead. The impacts of climate change on buildings and cities are undeniable, necessitating a strategic and holistic approach to safeguard urban landscapes against an increasingly unpredictable climate. The methodologies and metrics explored in this study provide valuable tools for assessing and quantifying these impacts, enabling informed decision-making and proactive planning. Through the lens of adaptation and mitigation strategies, the article underscores the urgency of integrating resilient design principles and innovative solutions into urban planning, equipping cities to effectively navigate the complex web of climate challenges.

Moreover, the concept of smart disaster management emerges as a crucial linchpin in enhancing urban resilience. By harnessing technology, data-driven insights, and community engagement, cities can fortify their defenses against natural disasters, minimizing losses and ensuring swift recovery. The indispensable role of eco-design and climate resilience surfaces as a transformative force, offering a harmonious synergy between sustainable development and climate adaptation.

As this review draws to a close, it is evident that a paradigm shift is underway—one that envisions cities as dynamic, adaptive, and resilient ecosystems. By embracing innovative strategies, harnessing scientific advancements, and prioritizing community engagement, cities can emerge not merely as survivors but as thriving hubs that thrive amidst adversity. As we stand at the crossroads of urban evolution, this review serves as a guiding compass, illuminating a trajectory towards urban resilience and sustainability in an era defined by climate change.

Availability of data and material

The data used in this study, along with the details of the methodology adopted, are comprehensively described in the methodology section (Section 2) of this article.

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Conflict of interest

The author declares no conflict of interest.

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