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Resilient and Sustainable Urban Infrastructure in the Global South: Strategies to Address Climate Change-Linked Vulnerabilities

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Abstract

The impacts of climate change pose serious threats to the sustainability and resilience of urban infrastructure in the Global South, where socioeconomic, technical, and governance challenges intensify vulnerabilities in water, energy, and transport systems. This article explores these vulnerabilities through a literature review and case study analyses and identifies strategies for creating resilient and sustainable urban infrastructure in developing regions. The study highlights critical challenges such as ageing infrastructure, inadequate maintenance, insufficient funding, and rapid urbanisation, which increase the susceptibility of urban systems to climate-related events like floods, droughts, and rising sea levels. Case studies from two countries reveal that the intersection of climate vulnerability with factors such as poor governance, socio-political issues, and limited technological capacity further weakens infrastructure resilience. However, emerging strategies focus on climate-resilient design, improved governance, strengthened public–private partnerships, and community-based solutions. Integrating nature-based solutions, smart technologies, and capacity-building initiatives is vital in enhancing local governments' adaptive capacity to enable the building of sustainable and resilient infrastructure. This article argues that while infrastructure vulnerabilities in the Global South are complex and rooted in historical inequalities, lack of technological competence and financial constraints, targeted strategies—centred on governance reform, climate-resilient design and retrofitting, technological innovations and nature-based solutions, strengthening public–private partnerships, community-based solutions and capacity building—are essential for building resilient and sustainable urban infrastructure. These insights offer guidance for policymakers, planners, and development agencies working to strengthen critical infrastructure in vulnerable regions of the Global South.

Keywords

climate change; Global South; resilience; sustainability; sustainable urban infrastructure; urban infrastructure; vulnerability

1. Introduction

Climate change presents significant challenges to urban infrastructure, affecting its resilience, functionality, and sustainability. Cities in the Global South, including India, South Africa, and Indonesia, face heightened risks from extreme weather events, urban heat islands, flooding, and droughts. These vulnerabilities are exacerbated by rapid urbanisation, informality, and socioeconomic disparities, leading to property loss, service disruptions, and deepening inequalities (Intergovernmental Panel on Climate Change, 2021). Extreme weather events such as hurricanes, heat waves, and heavy rainfall disrupt transportation networks, energy grids, and water systems. Urban heat islands, caused by urban expansion and reduced vegetation, increase local temperatures, compromising infrastructure efficiency and raising energy demands. Urban flooding disproportionately affects vulnerable populations, intensified by rising sea levels (Dharmarathne et al., 2024). Addressing these challenges requires holistic, innovative, and inclusive strategies, such as effective water management and equitable resource allocation, to enhance urban resilience (Ikonomova & MacAskill, 2023). However, cities in the Global South face additional obstacles, including inadequate policies, resource constraints, and a lack of context-specific adaptation strategies.

Governance and financial constraints significantly hinder sustainable urban development. Weak governance structures, short political cycles, and limited access to climate finance exacerbate infrastructure deficits (Dossa & Miassi, 2024). Outdated water and energy systems struggle to meet increasing demands, while technological gaps prevent the adoption of advanced solutions (Rahman et al., 2023). Additionally, the replication of Northern adaptation models proves ineffective, as these approaches often fail to address Southern cities' complex socio-economic and environmental conditions (Chirambo, 2022). Locally tailored solutions that consider regional contexts and constraints are therefore essential. Technological limitations further complicate climate adaptation. Many cities in the Global South lack the expertise and financial resources to implement advanced technologies such as predictive modelling and smart infrastructure. As a result, ageing water and energy systems remain highly vulnerable to climate-induced stresses, further straining urban resilience (Rahman et al., 2023).

Furthermore, climate change exacerbates socio-economic inequalities, disproportionately affecting marginalised populations, particularly those in informal settlements. Flooding, heatwaves, and other climate hazards deepen existing disparities, emphasising the need for inclusive, innovative, and context-specific strategies to enhance resilience and ensure equitable adaptation (Chen, 2024; Dias, 2024; James, 2023; Mondal, 2024). Despite advancements in climate resilience research, significant gaps persist, particularly regarding the Global South. Much of the existing research focuses on cities in the Global North, overlooking the distinct challenges faced by rapidly urbanising Southern cities with infrastructure deficits and socio-economic vulnerabilities (Parnell & Oldfield, 2014). Additionally, many studies prioritise short-term resilience measures, neglecting long-term impact assessments essential for scalable and sustainable solutions (Tyler & Moench, 2012). Climate justice integration in urban planning remains insufficient, particularly in ensuring equitable access to resilient infrastructure for marginalised communities (Schlosberg, 2012; Schlosberg et al., 2017).

To effectively adapt urban infrastructure in the Global South, systematic identification and classification of climate-linked vulnerabilities and strategic adaptation measures are necessary. For instance, critical areas such as retrofitting and infrastructure management remain underexplored (Dixit, 2024). This remains a critical research gap in the Global South context. Additionally, implementing climate-resilient development pathways is challenging due to the absence of comprehensive frameworks that integrate adaptation, mitigation, and sustainability objectives (Langendijk et al., 2024). Another key research gap is the underutilisation of South–South climate finance, which has the potential to support community-driven innovations and enhance resource governance (Chirambo, 2022). Addressing these gaps is crucial for developing context-specific, long-term strategies that strengthen urban resilience in the Global South. To address the first significant research gap mentioned above, the study explored the following research questions:

> RQ1: What are the critical infrastructure vulnerabilities and their relative severity within the context of urban systems in the Global South?
>
> RQ2: What strategies can effectively address these vulnerabilities while enhancing the resilience and sustainability of urban infrastructure in the Global South?

The objectives of the study are to examine the key vulnerabilities in urban infrastructure within the Global South, focusing on their severity and nature. It aims to identify context-specific, sustainable strategies to mitigate these vulnerabilities and foster resilient infrastructure systems capable of addressing climate change challenges. However, the scope of the study encompasses only three sectors of urban infrastructure, including water, energy, and road transportation systems.

This study contributes by identifying critical vulnerabilities in urban infrastructure in the Global South, focusing on the three systems mentioned above. It offers context-specific, sustainable strategies to mitigate these vulnerabilities, emphasising locally tailored solutions to address socio-economic disparities, governance challenges, and technological limitations. The study also highlights the need for integrating climate justice into urban planning, providing a framework for building resilient and equitable infrastructure in the Global South.

2. Conceptualising Climate Change Vulnerabilities, Sustainable and Resilient Urban Infrastructure in the Global South

2.1. Climate Change Vulnerability in the Context of the Global South

The Global South, encompassing developing nations in Africa, Asia, Latin America, and the Pacific, faces disproportionate impacts from climate change due to high exposure to climate hazards, socioeconomic inequalities, and limited adaptive capacities. Geographic factors such as tropical and subtropical locations prone to hurricanes, droughts, and rising sea levels exacerbate these vulnerabilities. Socioeconomic challenges, including poverty, inequality, and dependence on climate-sensitive sectors like agriculture, further enhance risks. For example, smallholder farmers in sub-Saharan Africa and South Asia face declining crop yields and food insecurity due to erratic rainfall and rising temperatures (Lobell et al., 2008).

Urban areas, particularly urban infrastructure and informal settlements, are highly vulnerable to extreme events such as flooding, storms, cyclones, etc. (Hussainzad & Gou, 2024). Specifically, in the context of urban infrastructure, as illustrated in Figure 1, extreme weather events such as droughts, extreme temperatures, heat waves, flooding, cloudbursts, storms, cyclones, hurricanes, etc., make the urban infrastructures, such as water systems, transportation systems, energy systems, etc., vulnerable. The vulnerability arises from the ageing infrastructure, rapid urbanisation and informal settlements, and poor governance and financial constraints (Figure 1). In other words, economic and political constraints in the Global South hinder robust climate adaptation and mitigation efforts, with insufficient financial resources and technological capabilities limiting effective responses to climate challenges (Garcia, 2024). Governance issues and policy gaps further exacerbate vulnerabilities, as political inequalities and inadequate government interventions undermine adaptation strategies (Boas et al., 2023; Ngcamu, 2023).

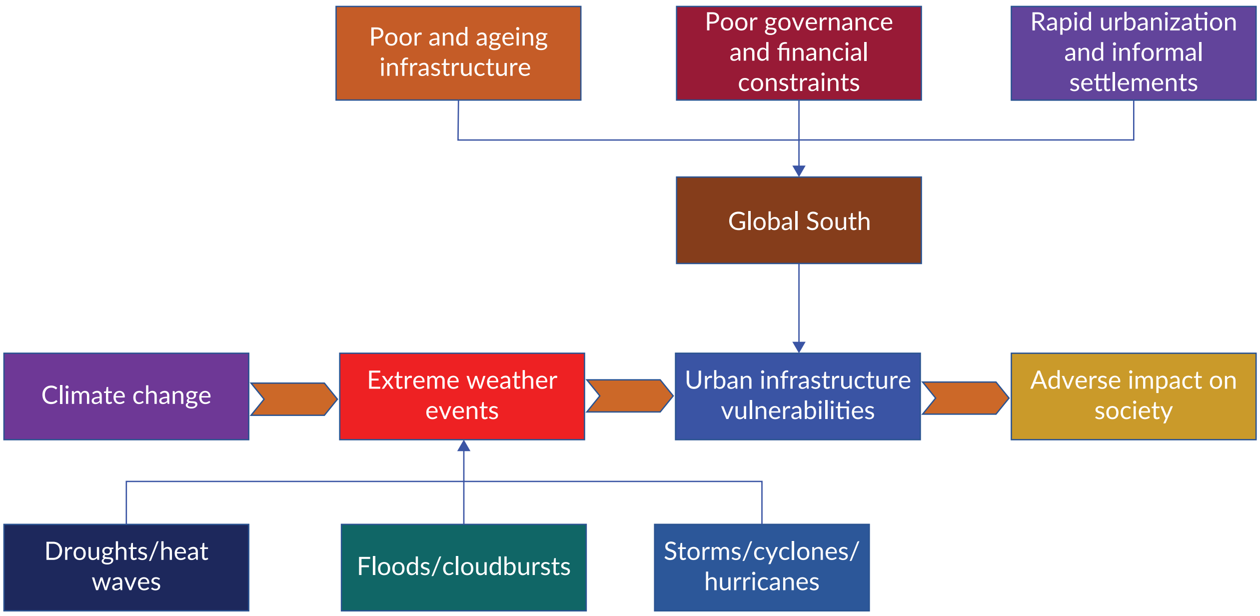

Figure 1. Climate change and urban infrastructure vulnerabilities in the Global South.

2.2. Resilience and Sustainability in Urban Infrastructure

Urban infrastructure plays a critical role in supporting the economic, social, and environmental functions of cities. As urbanisation accelerates, particularly in the Global South, ensuring resilient and sustainable infrastructure has become a priority for policymakers, urban planners, and researchers. Figure 2 presents the concept of resilient and sustainable urban infrastructure, emphasising resilience as the capacity of urban systems to withstand, adapt to, and recover from various shocks and stresses while maintaining essential functions and overall well-being (Walker & Salt, 2006). This concept has gained prominence as cities face increasing challenges from climate change, natural disasters, and rapid urbanisation. Resilient infrastructure reduces vulnerabilities to disasters, economic disruptions, and technological failures, ensuring operational stability, safety, and service continuity, particularly in smart cities that rely on seamless connectivity. The key elements of resilient urban infrastructure, as illustrated in Figure 2, include robustness (the ability to withstand extreme conditions without significant degradation), redundancy (alternative pathways or systems that ensure continued functionality during failures), and adaptability (the capacity to evolve and improve in response to emerging threats; Cao, 2023; Kapse & Jangale, 2024; Li et al., 2023).

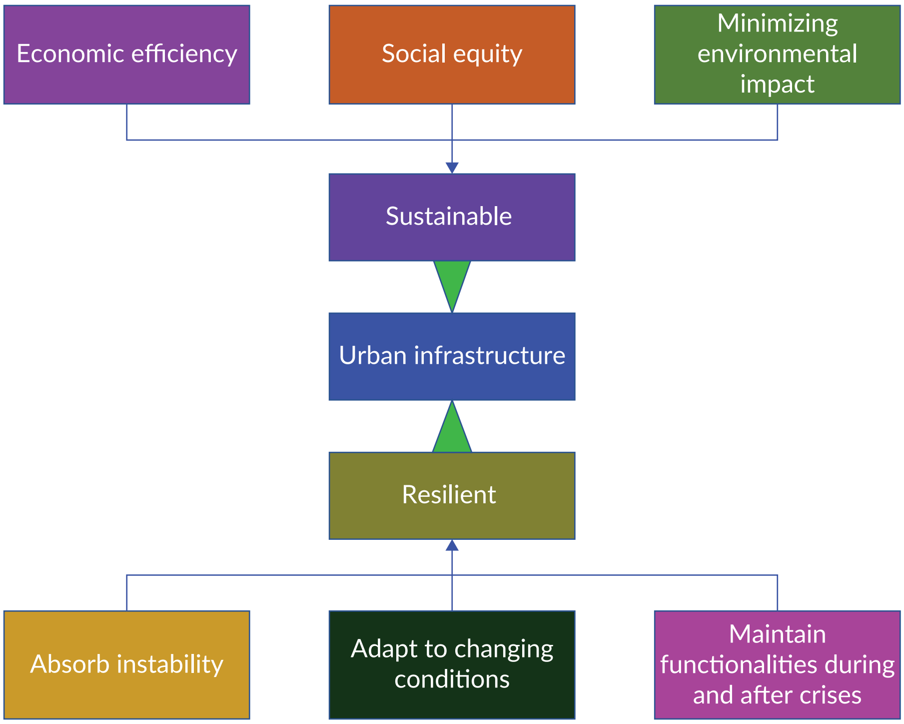

Figure 2. Conceptualising sustainable and resilient urban infrastructure.

Sustainability emphasises the long-term viability of infrastructure systems, focusing on minimising environmental impact, promoting social equity, and ensuring economic efficiency (Adams et al., 2012; El-Diraby & Osman, 2011; Ferrer et al., 2018). It includes environmental stewardship (reducing greenhouse gas emissions and conserving biodiversity), social inclusivity (ensuring equitable access to infrastructure services for marginalised communities), and economic viability (balancing costs with long-term benefits through innovative financing models). Sustainability and resilience are interdependent, as resilient infrastructure ensures recovery and functionality during and after disruptions, while sustainability promotes resource efficiency and minimizes environmental impacts (Trejo & Gardoni, 2022). Performance-based assessments and life cycle analyses help evaluate the environmental impacts of resilient structures, balancing trade-offs between these priorities (Tanguay & Amor, 2024). Additionally, sustainable infrastructure must integrate environmental and societal considerations, ensuring equity and justice while maintaining functionality during adverse events (Sánchez-Silva et al., 2025). The integration of resilience and sustainability into infrastructure planning is essential to addressing vulnerabilities and supporting long-term economic, social, and environmental goals.

2.3. Conceptual Framework for Resilient and Sustainable Infrastructure in Response to Climate Change Vulnerabilities

Premised on the concept of sustainable and resilient urban infrastructure, Figure 3 presents a conceptual framework that explicitly addresses climate change challenges in the Global South. Urban infrastructure in these regions is particularly vulnerable due to intertwined socio-economic and environmental factors, which necessitate a systematic identification of vulnerabilities across various climate scenarios to inform effective mitigation strategies. As depicted in Figure 3, governance, socio-technical systems, and adaptive capacity are central to shaping urban resilience. Governance plays a pivotal role; however, progress is often hindered by weak institutions, corruption, and policy gaps (Bulkeley & Betsill, 2013). Inclusive governance—engaging governments, the private sector, and civil society—can foster collaboration and promote equitable outcomes (Anguelovski et al., 2014). Adaptive governance, in particular, offers a flexible, collaborative, and learning-oriented approach to managing environmental and resource challenges. It emphasises stakeholder participation, cross-scale coordination, and the ability to revise policies and practices in response to evolving conditions. Characterised by flexibility, inclusivity, and social learning, adaptive governance strengthens resilience by dynamically addressing socio-ecological complexities (Akther & Evans, 2024). Building urban climate resilience further requires capacity development through transformative planning, multi-actor engagement, and robust knowledge-sharing mechanisms (Wieszczeczynska et al., 2024).

Socio-technical systems—encompassing the interactions between technology, society, and infrastructure—are critical to advancing sustainability. As illustrated in Figure 3, rapid urbanisation and resource constraints in the Global South necessitate innovative, context-sensitive solutions such as Internet of Things-enabled infrastructure and the integration of renewable energy. The complexity and interdependence of urban infrastructure systems in these regions demand adaptive designs and inclusive service delivery models that account for diverse needs and vulnerabilities (Gürsan et al., 2023; Oates & Sudmant, 2024). Adaptive capacity, shaped by institutional readiness, financial resources, and community engagement, is essential for enhancing resilience. Investments in climate-resilient infrastructure, such as flood-resistant housing and urban green spaces, not only mitigate the impacts of climate change but also generate social and environmental co-benefits (Pelling, 2011). The emerging paradigm of climate urbanism integrates climate adaptation and mitigation into urban planning and governance as it emphasises resilience, sustainability, and equity, promoting climate-smart infrastructure and sustainable urban systems (Rahman et al., 2023). However, it also carries the risk of entrenching social inequalities and displacing marginalised communities if not carefully implemented. Therefore, it is argued that strategic measures and frameworks should be grounded in this conceptual framework for sustainable and resilient urban infrastructure in response to climate change.

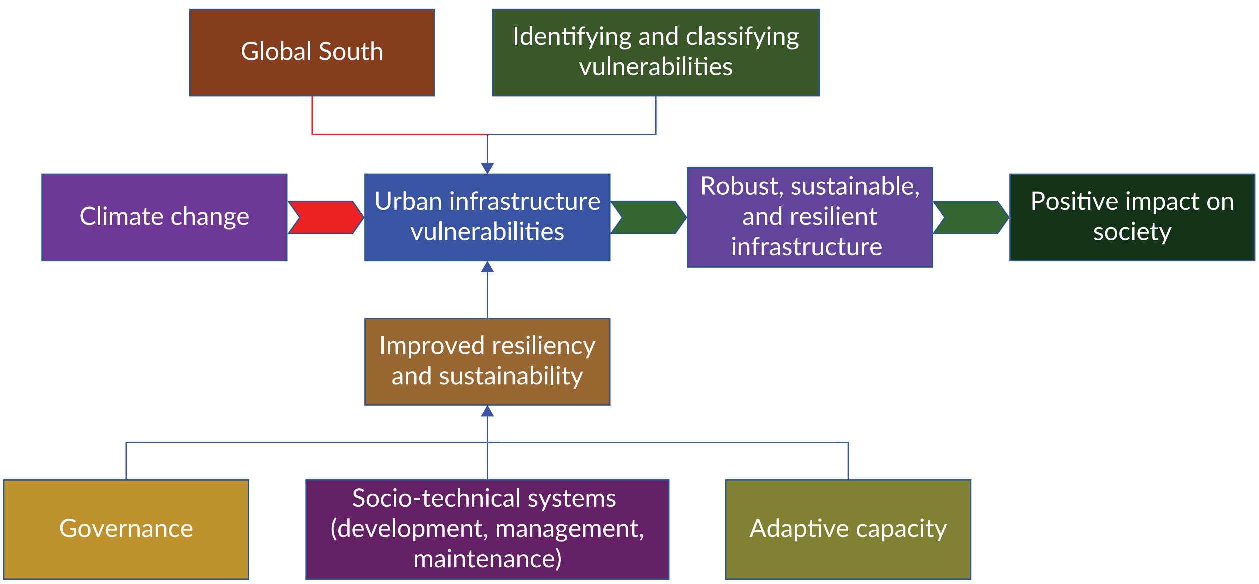

Figure 3. Conceptual Framework for Resilient and Sustainable Infrastructure in response to climate change vulnerabilities.

3. Methodology

This study adopted a qualitative methodology, centring on an in-depth review of literature and case studies to explore the complexities of climate change and the vulnerability, sustainability, and resilience of urban infrastructure. A qualitative approach was selected for its strength in uncovering context-specific dynamics that quantitative methods may overlook, particularly in understanding the lived experiences of marginalised communities and identifying nuanced vulnerabilities within urban systems (Creswell & Poth, 2017). Unlike quantitative techniques, qualitative methods capture the social, cultural, and political dimensions that shape infrastructure resilience (Stake, 1995), making them especially suitable for addressing the socio-economic and governance challenges prevalent in the Global South (Patton, 2002). Moreover, qualitative research emphasises rich, contextual insights into how communities adapt to climate-related impacts, offering a deeper understanding of the factors that contribute to resilience (Denzin & Lincoln, 2011). To support this interdisciplinary analysis, a broad range of sources—including peer-reviewed journal articles, books, policy reports, and reputable online publications—were incorporated.

3.1. Literature Survey and Compilation

A structured methodology guided the literature search process, encompassing the development of a robust search strategy, systematic curation of scholarly materials, application of inclusion and exclusion criteria, and thematic organisation and analysis of selected literature. The review focused on published works addressing climate change, urban infrastructure, vulnerabilities, and strategies.

Peer-reviewed journal articles were the primary sources, supplemented by conference proceedings, books, book chapters, reports, and online articles. Multiple databases, including Web of Science, Scopus, and Google Scholar, were explored. Articles were systematically gathered, categorised, and critically assessed, and search strings tailored to each database used relevant keywords such as climate change, urban infrastructure, vulnerability, disaster, resilience, strategy, Global South, climate change adaptation, and governance.

3.1.1. Inclusion/Exclusion Criteria and Data Extraction

The inclusion criteria were aligned with the RQs and focused on the impacts of climate change on urban systems, infrastructure vulnerabilities, sustainability, and resilience. It also encompassed various sectors of urban infrastructure, such as water, energy, and transportation systems, and strategies addressing these challenges. Conversely, topics unrelated to the impact of climate change on urban infrastructure were excluded, including economic, environmental, social, and cultural aspects outside the study's scope.

Data were systematically extracted using a standardised form, capturing details such as authorship, publication date, research aims, methodology, findings, contributions, recommendations for future research, and limitations. Extracted data were organised in an Excel spreadsheet and evaluated based on four criteria: authenticity, credibility, representation, and meaning. Only articles meeting these criteria were included for further analysis.

3.2. Organisation of Literature

The initial search yielded 4,172 articles and, following a screening process, 504 articles were retrieved. After applying inclusion and exclusion criteria and organising the materials into themes and subthemes, 127 articles were selected for the final review and analysis (Figure 4). Of these, 70.08% were peer-reviewed journal articles, 1.57% conference proceedings, 8.66% books, 3.15% book chapters, 15.75% reports, and 0.79% working papers (Table 1).

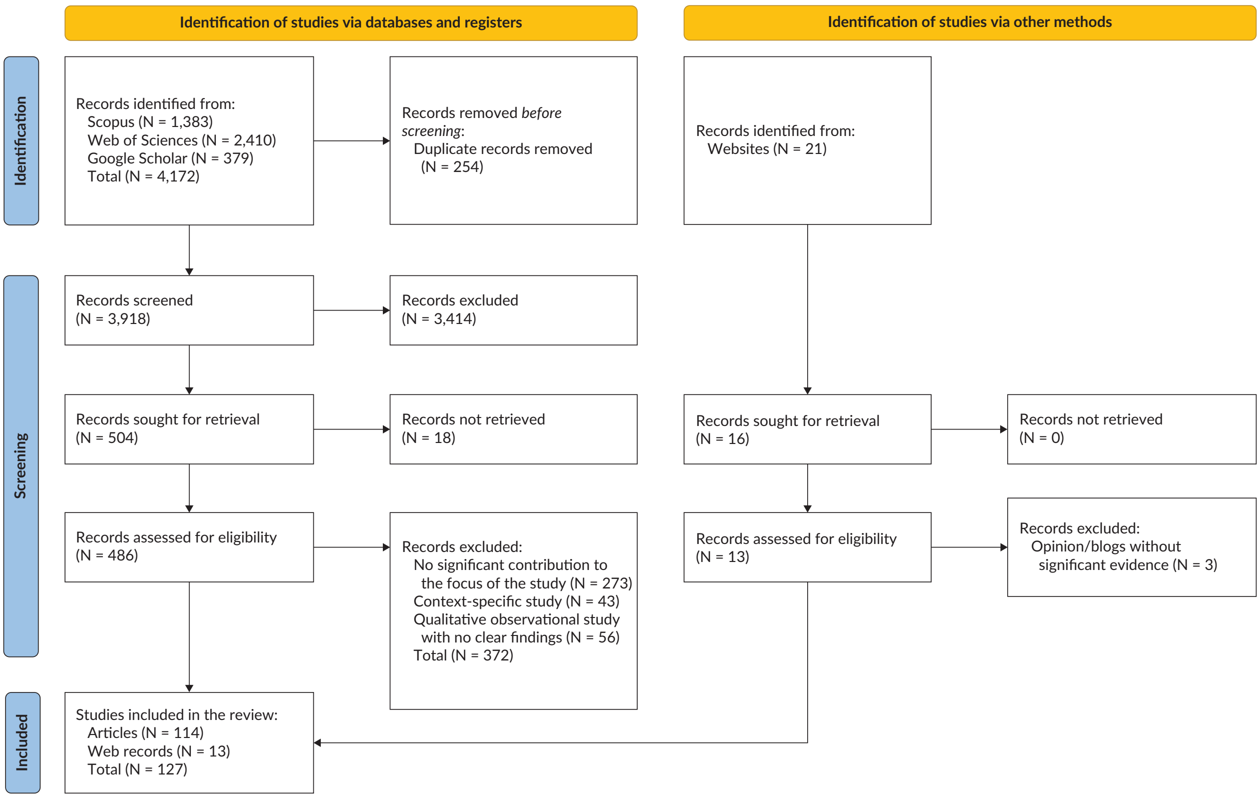

Figure 4. Flow diagram for search and selection of literature.

Table 1. Summary of literature reviewed.

Type of Articles	Numbers	Percentage
Peer-reviewed journals	89	70.08
Books	11	8.66
Book chapters	4	3.15
Conference proceedings	2	1.57
Reports	20	15.75
Others (working papers)	1	0.79
Total	127	100

3.3. Analysis of Literature and Case Study Selection and Analysis

The collected literature was systematically reviewed and analysed, organised into specific themes and subthemes. This thematic analysis provided a structured framework for understanding the study's focus areas, including the interconnections between urban infrastructure, vulnerabilities, and strategies for resilience and sustainability.

The thematic analyses were supplemented with case studies from India and South Africa. The case studies were selected for their significant history of climate-linked extreme events, natural disasters, urban infrastructure vulnerabilities, and the strategic measures undertaken to address these challenges. In India, cities from Odisha, Maharashtra, Delhi, West Bengal, Uttarakhand, Tamil Nadu, and Karnataka were chosen due to their exposure to recurring floods and cyclones. Similarly, Cape Town, Durban, and Johannesburg from South Africa were included for their frequent experiences with extreme weather events, particularly floods and droughts. These case studies offered valuable insights into practical applications and highlighted the potential for transformative strategies to improve urban infrastructure systems in the wake of climate change.

By integrating diverse scholarly sources and case studies, this study offered a comprehensive understanding of the interplay between climate change, urban infrastructure, and sustainable and resilient strategies, contributing to the broader discourse on sustainable and resilient urban infrastructure development.

3.4. Addressing Potential Bias and Limitations of the Methodology

The literature survey may have introduced several biases, including publication bias (overrepresentation of high-impact journals) and geographical bias (overreliance on Global North research). Additionally, methodological bias could arise from focusing on either quantitative or qualitative studies, potentially overlooking valuable insights from the other. Confirmation bias may have influenced the selection of studies that align with existing views on climate change and infrastructure resilience. To mitigate these biases, the study incorporated a broad range of sources—peer-reviewed articles, books, conference proceedings, and reports—while prioritising research from the Global South. Case studies were specifically chosen from India and South Africa, two countries heavily impacted by climate change. Furthermore, the qualitative methodology adopted addressed context-specific challenges and provided a more balanced understanding of urban infrastructure resilience.

It is also acknowledged that the qualitative methodology employed has limitations, including limited generalizability, potential selection bias, reliance on secondary data, and context-specific findings. However, these limitations have been addressed through careful case selection, source triangulation, and critical analysis. While the methodology does not establish causality or incorporate primary data, it effectively captures patterns, challenges, and strategic responses that are relevant to the study's objectives. Despite these constraints, the combination of literature review and case study analysis offers a valuable and acceptable approach for gaining meaningful insights.

4. Climate-Linked Vulnerabilities in Urban Infrastructure

The climate-linked vulnerabilities were examined in terms of their severity and impact on various infrastructures, including water systems, transportation networks, and energy systems, as well as cross-cutting issues. They are discussed in the following sections.

4.1. Level of Vulnerabilities

Table 2 presents the climate-linked vulnerabilities that are generally associated with urban infrastructure. Climate-linked vulnerabilities can be categorised by severity level based on their impact. Generally, there are four levels of vulnerabilities: critical, high, medium, and low severity. Critical vulnerabilities involve catastrophic system failures, often triggered by low-probability but high-consequence events or cascading climate tipping points. Examples include flooded transport systems and energy grid collapses, which can result in widespread disruption and societal impacts (Hallegatte et al., 2013). High-severity vulnerabilities lead to significant disruptions caused by extreme weather events, sea-level rise, and coastal erosion. These events can result in water shortages and thermal damage to infrastructure, posing substantial challenges to urban resilience (Aboulnaga et al., 2019; Proag, 2021). Medium and low vulnerabilities can be grouped and have more localised and incremental impacts, such as urban heat islands and overwhelmed stormwater systems. While these impacts are less severe, they still strain infrastructure and require adaptive measures to mitigate their effects (Dong et al., 2020; Proag, 2021). The classification underscores the need for targeted strategies to address vulnerabilities at different levels of severity.

Table 2. Severity levels of vulnerabilities.

Severity Level	Impact	Examples	Source
Critical	Catastrophic system failure	Low-risk, high-consequence events, with cascading climate tipping points: flooded transport systems, energy grid collapse	Hallegatte et al. (2013)
High	Significant disruption	Extreme weather events, sea level rise, and coastal erosion: water shortages, thermal damage to infrastructure	Aboulnaga et al. (2019); Proag (2021)
Medium/moderate and low	Moderate or minor localised impact and manageable disruptions	Incremental climate variations: urban heat islands, localised flooding and drought, and overwhelmed stormwater systems	Dong et al. (2020); Proag (2021)

4.2. Sectoral Analysis of Vulnerabilities

4.2.1. Water Systems

Water infrastructure systems—including dams, reservoirs, pipelines, treatment plants, and distribution networks—are fundamental to ensuring water security, safeguarding public health, and supporting economic stability. However, climate change is intensifying vulnerabilities within these systems, threatening their reliability and performance. Rising incidences of floods and droughts have profound impacts: Flooding can damage critical infrastructure such as dams and levees, while droughts diminish surface and groundwater availability, placing significant stress on water supply systems, especially in urban areas with limited adaptive capacity (Dong et al., 2020; Wei, 2024). Coastal infrastructure is particularly vulnerable to sea level rise, storm surges, and saltwater intrusion, all of which compromise water quality and underscore the need for climate-resilient infrastructure designs (Nicholls & Cazenave, 2010; Pal et al., 2023). Rising temperatures further exacerbate water system stress by increasing demand and degrading water quality through algal blooms and microbial contamination, complicating treatment processes (Whitehead et al., 2009). Many existing systems, often designed for historical climate patterns, are ageing and ill-equipped to withstand contemporary climate extremes, necessitating urgent modernisation and resilience-focused upgrades (Gleick, 2010). Hydropower systems, which depend on steady water flows, are also at risk. Reduced precipitation can limit energy generation capacity, while extreme weather events pose physical threats to infrastructure integrity (Kumar et al., 2011).

In the Global South, the severity of such vulnerabilities ranges from high to critical. For instance, Mumbai experienced catastrophic flooding in 2005, Chennai in 2022 ("Mumbai under water," 2005; "Severe flooding in Chennai," 2022), Cape Town faced severe drought and water scarcity in 2017 (Cassim, 2018), and KwaZulu-Natal suffered major flood-related damage in 2022 (PreventionWeb, 2023). To address these challenges, key interventions include the deployment of advanced water recycling systems that repurpose treated wastewater for potable and non-potable uses, employing membrane filtration and UV disinfection to enhance water self-sufficiency. During severe droughts, strategies such as water conservation, demand-side management, and rainwater harvesting have proven effective in mitigating scarcity (Devaisy et al., 2023; Movva, 2024; Stankiewicz et al., 2023).

4.2.2. Energy Systems

Climate change has profound implications for energy infrastructure systems, undermining their reliability, efficiency, and security through both direct and indirect impacts associated with extreme weather events and long-term climatic changes. Extreme events—such as heatwaves, storms, and floods—can severely damage power plants, transmission lines, and substations. Flooding, for instance, may submerge critical components, causing widespread outages and costly repairs (Panteli & Mancarella, 2015), while heatwaves reduce the transmission capacity of power lines and heighten the risk of blackouts (Schaeffer et al., 2012). Rising global temperatures increase cooling demands, placing additional stress on energy systems and decreasing the performance of renewable technologies such as solar panels and wind turbines (van Vliet et al., 2016). Water-related risks also jeopardise the operation of thermal and nuclear power plants, as droughts and reduced river flows impair cooling processes. Notably, nearly 40% of thermal power plants are located in water-stressed regions (Byers et al., 2014). Coastal energy infrastructure is particularly exposed to sea-level rise and storm surges, while shifts in wind patterns, solar radiation, and precipitation reduce the reliability of wind, solar, and hydropower generation.

Much of the existing infrastructure, built for past climate norms, is ageing and poorly equipped to handle these new extremes, resulting in escalating maintenance costs and diminished resilience (Sovacool, 2011). Moreover, climate change indirectly increases overall energy demand, exacerbates security risks, and heightens cybersecurity vulnerabilities, emphasizing the need for integrated and adaptive resilience strategies in future energy systems (Cherdantseva et al., 2016; Mohsin et al., 2024).

Energy access remains a critical issue, particularly in peri-urban areas where infrastructure is less developed than in urban centres (Singh et al., 2015; Smith et al., 2022). While urban populations often benefit from robust electricity grids and renewable energy integration, rural and peri-urban communities continue to rely on costly and polluting energy sources such as kerosene and biomass. This disparity highlights the urgency of targeted interventions, including the deployment of off-grid solar systems and microgrids, to enhance energy access, promote equity, and reduce emissions.

4.2.3. Transport Systems

Transport infrastructure—including roads, railways, airports, and ports—is critical to economic development and societal well-being, but is increasingly vulnerable to climate change. Flooding remains one of the most severe threats, causing structural damage, erosion, and service disruptions. The 2011 floods in Thailand, for instance, significantly damaged highways and railways, disrupting supply chains and economic activities (Haraguchi & Lall, 2015). Coastal infrastructure faces additional risks from rising sea levels and storm surges (Lane-Visser & Vanderschuren, 2024).

Extreme temperatures pose further challenges by softening asphalt, buckling rail tracks, and increasing maintenance costs (Chapman, 2007). Heatwaves also affect air travel by reducing aircraft lift and payload capacity (Coffel et al., 2017). Heavy rainfall can trigger landslides and road washouts, while droughts compromise soil stability, undermining infrastructure integrity (Wang et al., 2024). Sea-level rise threatens ports and coastal airports (Yesudian & Dawson, 2021). Cyclone Idai in 2019, for example, devastated transport infrastructure in Mozambique, particularly in Beira, highlighting the vulnerability of the Global South to extreme storms.

Ageing infrastructure, often designed for historical climate conditions, lacks the resilience to cope with current and projected climate stresses (Rising et al., 2022). Addressing these vulnerabilities requires innovative, climate-resilient interventions. Elevated railways offer improved flood resilience and reduce congestion, while climate-proof urban metros incorporate flood barriers and durable materials. Expanding bicycle infrastructure promotes sustainable, low-emission mobility, and the adoption of electric buses, especially when integrated with renewable energy, reduces air pollution and greenhouse gas emissions (Amdal et al., 2017; Singla, 2024). Thus, strengthening the climate resilience of transport systems is essential for sustainable development, especially in the Global South, where infrastructure gaps and exposure to extreme weather events are more pronounced.

4.3. Cross-Cutting Challenges

4.3.1. Socio-Economic Inequalities and Rapid Urbanisation

Climate change disproportionately affects marginalised and low-income communities across infrastructure systems, deepening existing social and economic inequalities. In energy infrastructure, these populations are more likely to experience prolonged outages and have limited access to adaptive technologies and reliable energy sources (Simcock et al., 2017). Similarly, climate-induced disruptions to water infrastructure increase vulnerability among these groups, who often face greater exposure to service interruptions and water scarcity due to inadequate adaptive capacity (Srinivasan et al., 2017). Transport infrastructure also presents significant challenges. Marginalised communities typically rely on public transportation, which is more vulnerable to extreme weather events. The absence of alternative transport options further exacerbates social inequities, highlighting the urgency of inclusive and resilient transport planning (Cinderby et al., 2024).

To address these disparities, inclusive infrastructure planning is essential. This involves actively engaging marginalised groups in decision-making, prioritising equity-focused investments, ensuring affordability and accessibility, and using disaggregated data to guide and evaluate interventions. Such an approach ensures that resilience measures are tailored to the specific needs of vulnerable populations, promoting more just and sustainable outcomes (Cinderby et al., 2024).

4.3.2. Governance and Policy Gaps

Addressing urban infrastructure vulnerabilities requires integrated governance, firm policies, and community engagement, yet significant gaps hinder effective resilience implementation. Governance challenges stem from fragmented approaches to interconnected systems like energy, transport, and water, with delayed initiatives due to poor communication and coordination between local and national governments. Centralised decision-making in the Global South limits local strategies, making decentralisation, capacity building, and resource allocation essential (Aylett, 2015; Leck & Simon, 2013; Tanner et al., 2009). Transparent governance and robust monitoring mechanisms are crucial for accountability, but institutional barriers impede cross-sector collaboration.

Policy gaps further confound resilience efforts, with short-term development priorities often sidelining long-term adaptation. Inclusive policies addressing socioeconomic vulnerabilities are critical (Carmin et al., 2012; Greenwalt et al., 2018). Limited data and financial resources hinder effective planning, emphasising the need for investment in urban big data and computational tools (Rosenzweig et al., 2018). However, arguments have been made to meet the challenges that smart infrastructure standards should be adapted to local contexts and supported by technology transfer (Nguyen et al., 2024). Similarly, social considerations, including intersectionality and participatory approaches, would likely ensure marginalised communities are included and enhance resilience strategies (Greenwalt et al., 2018; Sitas et al., 2021).

5. Case Study Analyses

5.1. Case Study 1: India

Table 3 presents the climate-linked natural disasters and their impact on urban infrastructure. It exposes vulnerabilities exacerbated by rising temperatures, frequent floods, and cyclones in cities like Chennai, Mumbai, Delhi, and Cuttack (Revi & Satterthwaite, 2014). Ageing infrastructure, such as outdated drainage systems and overburdened transportation networks, undermines urban resilience, while social inequities disproportionately affect marginalised communities during disasters (Sharma & Tomar, 2010).

To address these challenges, India has adopted multiple strategies (Gupta, 2020). Climate-resilient infrastructure initiatives include Ahmedabad's Heat Action Plan and Odisha's cyclone shelters. Green and blue infrastructure, such as Kolkata's East Kolkata Wetlands and urban forests, enhances ecological resilience (Pasi, 2014). Integrated water management practices, like Chennai's rainwater harvesting mandates, improve sustainability (Sharma & Tomar, 2010) and smart city programs leverage digital technologies, as seen in Delhi's smart grids and e-governance systems. Infrastructure upgrades are driven by public–private partnerships (PPPs) and policy reforms under programs like the Atal Mission for Rejuvenation and Urban Transformation and the Smart Cities Mission (National Institute of Urban Affairs, 2021). Renewable energy projects, including Gujarat's solar rooftops and Rajasthan's wind farms, further advance sustainability goals (Revi & Satterthwaite, 2014).

Table 3. Severity impact of climate-linked natural events on urban infrastructure in India.

Year	Place	Type of Event	Severity	Major Infrastructure Impacted	Impact on Infrastructure
1999	Odisha	Super cyclone	Critical	Transportation and energy	Destroyed nearly 1.6 million homes, caused power outages, and disrupted communication networks
2005	Mumbai, Maharashtra	Flood	Critical	Transportation	Overwhelmed drainage systems, submerged roads, disrupted rail and air traffic, and caused significant damage to homes and businesses
2008	Cuttack, Odisha	Flood	High	Transportation and water	Submerged low-lying areas, damaged houses, and disrupted local transportation and water supply systems
2013	Kedarnath, Uttarakhand	Flood and landslides	Critical	Transportation and buildings	Destroyed roads, bridges, and homes, disrupted pilgrimage routes, and caused severe transportation challenges
2022	Chennai, Tamil Nadu	Flood	Critical	Transportation, water and energy	Submerged large parts of the city, disrupted transportation, and caused extensive damage to homes, roads, and public utilities, with losses estimated at $3 billion
2020	West Bengal, Odisha	Cyclone Amphan	High	Transportation, water, and energy	Damaged power lines, uprooted trees, and caused significant destruction to homes and public infrastructure, with losses estimated at $13.4 billion
2024	Bengaluru, Karnataka	Flood	High	Transportation	Flooded urban areas, submerged roads, disrupted public transport, and renewed concerns about unplanned urban expansion
2024	Delhi	Heatwave and flood	High	Transportation	Caused airport roof collapse, metro station closures, flight cancellations, and significant damage to public and private infrastructure.

Sources: Indo-Asian News Service (2008), Sayeed (2022), "At 52.9°C, Delhi's Mungeshpur records" (2024), "Here is what happened" (2018), "Severe flooding in Chennai" (2022), "Mumbai under water" (2005), "Cyclone Amphan at 165 kmph" (2020), UN Disaster Management Team (1999).

5.2. Case Study 2: South Africa

Table 4 highlights the climate-linked natural disasters and their impact on urban infrastructure in South Africa. Extreme weather events such as droughts, floods, and rising temperatures have significantly affected cities like Cape Town, Durban, and Johannesburg (Ziervogel et al., 2014).

To address these challenges, South Africa has implemented various climate adaptation strategies. Cape Town's water strategy, developed after the 2018 Day Zero crisis, includes desalination, groundwater extraction, and water reuse to ensure water security (Enqvist & Ziervogel, 2019). Durban's eThekwini Municipality employs ecosystem-based adaptation, such as the Buffelsdraai Landfill Site Community Reforestation Project, which enhances flood resilience, restores ecosystems, and creates jobs (Roberts et al., 2012). Green infrastructure, including urban wetlands, permeable pavements, and green roofs, helps manage stormwater and reduce urban heat islands.

Energy resilience is promoted through the Renewable Energy Independent Power Producer Procurement Programme, which integrates renewable energy into urban grids, reducing coal dependency and improving energy security (Montmasson-Clair, 2020). Urban governance reforms, such as the integrated urban development framework, support climate-resilient planning and equitable service delivery. PPPs, like the Gautrain rapid rail system, enhance sustainable transportation, reducing carbon emissions and congestion.

Table 4. Severity impact of climate-linked natural events on urban infrastructure in South Africa.

Year	Place	Type of Event	Severity	Major Infrastructure Impacted	Impact on Infrastructure
2015–2023	Northern Cape (Karoo region)	Drought	High	Water	The drought reshaped community identity and priorities, fostering a deeper connection to the environment and community
2018	Cape Town	Water crisis	Critical	Water	Cape Town faced the prospect of becoming the first major city to run out of water
2022	KwaZulu-Natal	Floods and landslides	Critical	Transportation, energy, and water	The disaster resulted in the deaths of at least 459 people and destroyed more than 12,000 houses. It severely damaged infrastructure, including roads, health centres, and schools.
2024	New Castle and Utrecht, Eastern Cape, KwaZulu-Natal	Storm complex	High	Transportation and buildings	It damaged over 7,000 houses, caused power outages, and caused significant damage to roads and bridges. The total damage was estimated at US $344 million
2024–2025	Johannesburg	Water crisis	High	Water	Johannesburg experienced severe water crises, with supply cuts lasting up to 86 hours

Sources: Cassim (2018), Coleman (2017), International Federation of Red Cross and Red Crescent Societies (2024), PreventionWeb (2023), Ntisa (2024).

5.3. Insights From the Case Studies

India and South Africa face significant climate-linked natural disasters, such as floods, droughts, rising temperatures, and cyclones, which expose vulnerabilities in urban infrastructure as seen from cities like Chennai, Mumbai, Delhi, Cuttack, Cape Town, Durban, and Johannesburg. Social inequities also disproportionately affect marginalised communities during such disasters, underscoring the need for more inclusive and adaptive solutions.

In response, both countries have adopted strategies to build climate-resilient infrastructure. India's initiatives include climate-resilient infrastructure projects, a Heat Action Plan, cyclone shelters, and green and blue infrastructure. Similarly, South Africa has implemented ecosystem-based adaptation and integrated water management practices, such as desalination and groundwater extraction. Both countries focus on smart city initiatives, green infrastructure, renewable energy projects, and PPPs to enhance sustainability and resilience.

6. Strategies for Building Resilient and Sustainable Infrastructure

Addressing the challenges of urban infrastructure vulnerabilities because of climate change in the Global South requires well-designed and balanced strategic interventions.

Resilient and sustainable urban infrastructure in the Global South is essential due to climate change-related vulnerabilities. Rapid urbanisation, socio-economic disparities, and environmental risks present unique challenges. While there is agreement on the need for resilience, differing viewpoints exist on how to achieve it, particularly regarding the balance between resilience and sustainability, community engagement, and the role of innovative technologies (Oloke et al., 2021). Effective strategies must consider the socio-economic and political contexts (Chu et al., 2017; Greenwalt et al., 2018; Oates & Sudmant, 2024). Smart technologies, such as early warning systems and data analytics, offer potential for enhancing resilience but face challenges in the Global South, including limited resources and technical capacity. Moreover, technology-driven solutions may overlook underlying socio-economic and environmental issues (Osheyor et al., 2024). Tailored solutions that integrate community perspectives and innovative technologies are necessary for equitable and sustainable outcomes. Based on the balanced viewpoints, findings from literature, and case study analyses, the following strategies foster resilient and sustainable urban infrastructure.

6.1. Governance Reforms

Strengthening institutions and decision-making processes is crucial for building resilient and sustainable infrastructure in the Global South to address climate change impacts. In this context, governance reforms, including decentralisation, resource allocation, and technical training, empower local governments to implement context-specific strategies (Aylett, 2015; Tanner et al., 2009). Integrating resilience into urban planning and aligning policies across levels ensures coherent action (Carmin et al., 2012; Leck & Simon, 2013). Data-driven decision-making would enable targeted interventions, and participatory governance would engage marginalised communities, enhancing inclusivity (Georgios & Abdolrasoul, 2024; Rosenzweig et al., 2018). Innovative financing mechanisms and robust regulatory frameworks further strengthen resilience and sustainability (Fankhauser & McDermott, 2014; Lawrence et al., 2018). Governance reforms also play a critical role in ensuring the long-term servicing and financing of infrastructure by clarifying institutional responsibilities, enhancing intergovernmental coordination, and promoting transparency. Tools such as fiscal decentralisation, performance-based budgeting, and PPPs help make infrastructure investments more financially sustainable and adaptive to evolving urban challenges.

6.2. Climate-Resilient Design and Retrofitting

Climate-resilient design and retrofitting are essential for addressing climate change challenges in the Global South, where rapid urbanisation and vulnerability require tailored solutions. Innovative architectural and engineering approaches enhance infrastructure durability and adaptability, with smart technologies improving energy efficiency despite cybersecurity risks (Rasheed et al., 2024). For example, renewable energy systems, like solar panels, reduce carbon footprints despite varying effectiveness across climatic zones (Rasheed et al., 2024). Resilient design for affordable housing enhances flood resistance and disaster preparedness (Adeyemi et al., 2024) and sustainable practices and low-emission materials ensure environmental balance (Hifza & Tariq, 2023). Integrating climate data into planning, geographic information systems-based frameworks, and adaptive measures tailored to local conditions supports resilience and sustainability (Buhl & Markolf, 2022; D'Ambrosio et al., 2023).

6.3. Technological Innovations and Nature-Based Solutions

The integration of smart technologies and nature-based solutions is crucial for resilient and sustainable infrastructure to address climate change. Smart technologies like machine learning and the Internet of Things enable real-time monitoring, predictive analytics, and energy optimisation, enhancing resilience (Rajendran et al., 2025). Nature-based solutions, such as green infrastructure and sustainable urban drainage systems, provide ecosystem services for stormwater management and climate adaptation (Aghaloo et al., 2024). Blue/green infrastructures, including wetlands and parks, mitigate urban heat islands, reduce floods, and boost biodiversity (Hassan et al., 2023). Combining nature-based solutions with traditional infrastructure fosters sustainability, though challenges like financial constraints and social equity must be addressed (Prado et al., 2024; Yılmaz, 2023)

6.4. Strengthening PPPs

PPPs are essential for building sustainable and resilient infrastructure by leveraging the strengths of both the public and private sectors to address climate change. Strategies such as wastewater treatment plants and nature-based solutions have significantly reduced flood risks in Singapore (30%) and Thailand (25%), while Malaysia's networks have prevented 85% of contamination during extreme weather events (Goh et al., 2024). Public–private–people partnerships further enhance inclusivity by involving local communities, with legal frameworks and monitoring mechanisms ensuring accountability (Leshinka et al., 2023).

Financial incentives, such as tax credits, attract investment in renewable energy, aligning PPPs with sustainable development goals (Ugwu et al., 2024). In low-income settings, micro-finance institutions and community-based businesses can act as private partners, funding small-scale projects and delivering essential local services (Putri et al., 2025; Ritchie, 2010). Their participation fosters community ownership, expands stakeholder engagement, and ensures that infrastructure solutions are tailored to local needs.

6.5. Community-Based Solutions

Engaging local stakeholders and fostering inclusivity is essential for developing sustainable, resilient infrastructure in the face of climate change. Participatory processes integrate local knowledge through storytelling and mapping, particularly in smaller cities and rural areas (Eisenhauer et al., 2024). Green infrastructure projects benefit from socioeconomic studies and effective communication channels to involve communities (Mason et al., 2024). Asset-based community development empowers informal settlements by leveraging local resources (Appau et al., 2024). Social capital, including community networks, strengthens resilience (Wambura, 2024). Respecting cultural practices and addressing barriers like resource constraints and language challenges unlocks community-based climate resilience solutions (Haque et al., 2022).

6.6. Capacity-Building Initiatives: Enhancing Local Governments' Technical and Financial Capacities

Enhancing local governments' technical and financial capacities is crucial for sustainable, resilient infrastructure to address climate change. Policies integrating scientific research and local conditions can guide adaptation strategies, leveraging technology to build disaster-resistant infrastructure (Situmorang et al., 2024; Warouw et al., 2023). Active community participation ensures locally relevant measures, while education fosters awareness and sustainability (Situmorang et al., 2024). Cross-regional collaboration enhances knowledge sharing, addressing bureaucratic and resource constraints (Shah, 2024). Training programs address skill gaps, improving governance and adaptation strategies (Perney & D'Angelo, 2023).

7. Discussions and Implications

Urban infrastructure in the Global South faces significant vulnerabilities exacerbated by climate change, necessitating urgent adaptation strategies for resilience and sustainability. Extreme weather events such as flooding, droughts, and rising temperatures disrupt essential services like water, energy, and transportation, which are already strained by socio-economic inequalities and infrastructure deficits (Parnell & Oldfield, 2014). While research on urban resilience is growing, studies addressing the specific challenges of the Global South remain limited, particularly regarding infrastructure ill-equipped to handle new climate stressors (Tyler & Moench, 2012). Many proposed solutions focus on short-term fixes, overlooking the need for scalable, sustainable strategies (Schlosberg et al., 2017). Integrating climate justice into urban planning is also inadequate, leaving marginalized communities vulnerable to climate impacts (Srinivasan et al., 2017). The literature emphasises the need for a nuanced approach to urban infrastructure vulnerabilities, especially in water, energy, and transportation sectors (Dixit, 2024; Langendijk et al., 2024).

To address these challenges, the study of urban resilience must focus on identifying critical infrastructure vulnerabilities and developing context-specific, sustainable strategies. Water systems in cities like Mumbai and Cape Town are increasingly vulnerable to climate-induced disruptions, such as flooding and droughts, requiring climate-resilient designs and retrofitting (Dong et al., 2020; Wei, 2024). Energy infrastructure is similarly at risk, exacerbating energy insecurity, especially in low-income communities (Panteli & Mancarella, 2015; Schaeffer et al., 2012). Transportation infrastructure, particularly in coastal areas, faces threats from rising sea levels and extreme storms (Lane-Visser & Vanderschuren, 2024). These vulnerabilities disproportionately affect marginalized populations, exacerbating social inequities (Simcock et al., 2017).

Infrastructure development involves multiple actors: national governments, local authorities, the private sector, civil society organisations, and international agencies. Governments set policies and regulations, while local authorities oversee implementation but often face capacity gaps (Tanner et al., 2009). The private sector brings innovation but may prioritise profit over equitable access (Leshinka et al., 2023). Civil society organisations ensure marginalised voices are included (Rosenzweig et al., 2018), and international agencies provide financial support, although often limited by local dynamics (Fankhauser & McDermott, 2014).

Capacity gaps in project management and financial oversight hinder effective local governance (Cinderby et al., 2024). A multi-actor approach is essential for inclusive and sustainable infrastructure development (Carmin et al., 2012). This approach must address power imbalances and ensure marginalised groups benefit from infrastructure improvements (Leck & Simon, 2013). Successful collaboration requires capacity building, improved governance, and enhanced accountability (Lv & Sarker, 2024).

Figure 5 presents a strategic framework for overcoming these challenges, including robust governance frameworks for effective coordination (Aylett, 2015; Tanner et al., 2009). Decentralised decision-making and participatory governance are essential (Aylett, 2015; Tanner et al., 2009), but local governments in the Global South face constraints. Smart technologies like the Internet of Things and machine learning can enhance resilience through real-time monitoring and predictive analytics (Rajendran et al., 2025). Nature-based solutions, such as green infrastructure, provide sustainable solutions for managing climate risks (Aghaloo et al., 2024). These solutions must be paired with inclusive governance to ensure marginalized communities participate, fostering local resilience (Eisenhauer et al., 2024; Wambura, 2024).

Figure 5. Strategic framework for sustainable and resilient infrastructure.

Critical implications include enhancing the technical and financial capacities of local governments, promoting cross-regional collaboration, and prioritizing community engagement to develop resilient and sustainable infrastructure in the Global South. As climate change intensifies vulnerabilities, adopting long-term, context-specific resilience strategies is crucial to safeguard urban systems (Situmorang et al., 2024; Warouw et al., 2023).

Policymakers and urban planners must focus on strengthening governance by building local governments' technical and financial capacities (Aylett, 2015; Fankhauser & McDermott, 2014; Lawrence et al., 2018), integrating smart technologies for enhanced resilience (Rajendran et al., 2025), prioritising nature-based solutions for climate risk management (Aghaloo et al., 2024), and promoting multi-actor collaboration (Carmin et al., 2012). Community engagement is crucial to building social capital and enhancing collective resilience (Eisenhauer et al., 2024). Urban planning should incorporate long-term, context-specific strategies, retrofitting existing infrastructure to withstand climate risks (Dong et al., 2020; Wei, 2024). Integrating climate justice into urban planning is essential for ensuring equitable access to resilient infrastructure for vulnerable groups (Srinivasan et al., 2017). By prioritizing these strategies, urban planners can create infrastructure better equipped to handle climate change impacts in the Global South.

8. Conclusion

In response to the impact of climate change on urban infrastructure, this study examined the key vulnerabilities within the Global South, focusing on water, energy, and road transportation systems. It also identified sustainable strategies for mitigating these vulnerabilities and fostering resilient infrastructure systems capable of addressing climate change challenges. Urban infrastructure in the Global South is found to be highly vulnerable to climate change impacts, including extreme weather events such as flooding, droughts, and rising temperatures. These disruptions are further exacerbated by socioeconomic inequalities and infrastructure deficits, highlighting the urgent need for effective adaptation strategies. Key strategies for addressing these challenges include robust governance systems to address policy gaps, climate-resilient design and retrofitting, technological innovations, nature-based solutions, and enhancing the technical and financial capacities of local governments. Community-based solutions and strengthening PPPs are also critical to enabling resilient and sustainable infrastructure in the face of climate change impacts in the Global South.

However, the study has limitations. It is based on a qualitative approach, consisting of a literature review and case study analyses, which lack empirical validation. Despite these limitations, the study contributes significantly by identifying critical urban infrastructure vulnerabilities and proposing relevant strategies to alleviate these vulnerabilities, specifically within the context of the Global South.

Future research on urban infrastructure resilience in the Global South should focus on integrating AI and machine learning for predictive modelling and real-time monitoring, improving the efficiency and adaptability of urban systems. Furthermore, studies into nature-based solutions, their scalability, and cost-effectiveness in diverse urban settings may be explored. Climate-resilient infrastructure designs should be developed, particularly for retrofitting existing systems to handle extreme weather events. Moreover, exploring decentralised, participatory governance models will be key for ensuring inclusive, context-specific adaptation strategies. These areas of the studies are likely to help build long-term, sustainable urban resilience in the face of climate change.

Conflict of Interests

The author declares no conflict of interests.

LLMs Disclosure

Tools such as Spispace for literature search and ChatGPT were used for improving the clarity of the text.

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