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Engineering Resilience: Harnessing Smart Technologies for Climate-Proof Infrastructure

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Abstract

As climate change intensifies floods, heatwaves, and sea-level rise, global infrastructure faces unprecedented vulnerabilities, with damages reaching $360 billion in 2022. This review explores how smart technologies,artificial intelligence (AI), Internet of Things (IoT), digital twins, and resilient materials,transform climate-resilient infrastructure to withstand these escalating hazards. Synthesizing recent advancements from the last five years, it examines their applications in urban and rural contexts, drawing on case studies from the Netherlands' IoT-enabled dikes, Singapore's AI-driven urban planning, and Ghana's cost-effective rural solutions. These innovations reduce maintenance costs by 15-25%, enhance flood response times by 40%, and align with Sustainable Development Goals (SDGs) for equitable, sustainable development. However, economic barriers, governance gaps, and equity challenges hinder global adoption, particularly in developing nations where connectivity and funding limit scalability. The review proposes future directions, including open-source platforms, public-private partnerships, and interdisciplinary research to address multi-hazard risks. By integrating data-driven engineering with green infrastructure, this study offers a roadmap for policymakers and engineers to build climate-proof infrastructure that ensures safety, sustainability, and resilience. This comprehensive synthesis underscores the urgent need for collaborative, inclusive strategies to safeguard global infrastructure against climate change, providing actionable insights for a resilient future.

Keywords: Climate resilience; Smart technologies; Infrastructure; Artificial intelligence; IoT; Digital twins; resilient materials; Sustainability; Urban planning; Rural development; Multi-hazard risks, SDGs

1. Introduction

Climate change poses unprecedented challenges to global infrastructure, with escalating hazards like floods, heatwaves, and sea-level rise threatening the durability of roads, bridges, energy grids, and urban systems. In 2022, climate-related disasters caused $360 billion in damages, exposing the fragility of traditional infrastructure designs [1]. As urbanization accelerates, with 40% of the U.S. population residing in vulnerable coastal areas, the need for resilient, adaptive infrastructure is critical [3]. This review explores how smart technologies,artificial intelligence (AI), Internet of Things

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(IoT), digital twins, and resilient materials,enable engineering solutions to create climate-proof infrastructure, aligning with Sustainable Development Goals (SDGs) for sustainable cities and inclusive development [1].

1.1. Climate Change and Infrastructure Vulnerabilities

The intensifying impacts of climate change, including a 7% increase in extreme rainfall per degree of warming, strain infrastructure beyond design limits [3]. According to Chester et al. [2020], traditional systems fail under extreme conditions, as seen in the 2021 Texas grid blackouts affecting 4.5 million households [3]. Urban areas, where 56% of the global population resides, face amplified risks from flooding and heatwaves, disrupting transport and energy systems [1]. These vulnerabilities incur socioeconomic costs, such as supply chain delays costing 1% of GDP in developing nations [1].

The urgency of adaptation is evident in coastal regions, where 11% of the global population faces sea-level rise risks [3]. For instance, Miami's infrastructure incurs $3 billion in annual damages due to chronic flooding [3]. Retrofitting existing systems and designing new infrastructure to withstand these hazards is essential to minimize economic losses and ensure safety [1]. Smart technologies offer a path forward by enabling proactive risk management and resilient designs.

This review synthesizes advancements in smart technologies, their applications, and challenges, providing a roadmap for engineers and policymakers. By addressing climate hazards through data-driven solutions, it aims to foster infrastructure that supports global sustainability and resilience goals [8].

1.2. Role of Smart Technologies

Smart technologies transform infrastructure resilience by integrating real-time data and predictive analytics. The study by Wang et al. [2021] shows that AI and IoT can reduce maintenance costs by 25% by predicting structural failures [8]. For example, the Netherlands' smart dikes use IoT sensors to monitor flood risks, preventing costly damages [9]. Digital twins, virtual models of physical systems, optimize designs, as seen in Singapore's urban planning [10].

Green infrastructure, such as permeable pavements, complements smart technologies by mitigating floods and heat [12]. Rotterdam's use of sensor-equipped pavements reduces urban flooding by 50% [12]. These innovations align with SDG 11, promoting sustainable urban development [14]. However, barriers like high costs and technical complexity, as noted by Faturechi and Miller-Hooks [2021], limit adoption, particularly in developing nations [15].

This review examines these technologies, their applications in urban and rural contexts, and strategies to overcome barriers. By highlighting case studies and future directions, it offers actionable insights for climate-proof infrastructure [16].

1.3. Scope and Structure of the Review

This review focuses on smart technologies addressing climate hazards, synthesizing literature from 2020–2025. Section 2 details flood, heatwave, and sea-level rise impacts, while Section 3 explores AI, IoT, digital twins, and resilient materials. Section 4 compares urban and rural applications, and Section 5 presents case studies from the Netherlands, Singapore, and developing nations. Section 6 addresses economic, governance, and equity challenges, and Section 7 synthesizes findings and calls for action.

The review targets engineers, policymakers, and urban planners, emphasizing practical solutions. As explored by Markolf et al. [2021], integrating smart technologies with resilient designs is critical for multi-hazard resilience [17]. This article provides a comprehensive framework to advance climate-proof infrastructure globally.

2. Climate Hazards Impacting Infrastructure

Climate change intensifies hazards that threaten infrastructure, from transportation networks to energy grids. This section examines floods, heatwaves, sea-level rise, and their interactions, highlighting their mechanisms and implications for resilience. By synthesizing recent literature, it underscores the urgency of adapting infrastructure to withstand escalating climate risks.

2.1. Floods and Storm Surges

Floods, exacerbated by climate change, pose significant risks to infrastructure, with a 7% rise in extreme rainfall per degree of warming [20]. The 2022 European floods damaged 10,000 kilometers of roads, costing €5 billion [20]. Urban drainage systems, designed for historical patterns, are overwhelmed, as seen in Germany's 2021 floods [20].

Storm surges, driven by stronger cyclones, amplify coastal risks. Vousdoukas et al. [2021] project 20% higher surges by 2050, threatening ports and bridges [23]. Hurricane Ida's 2021 surges flooded New York's subways, causing $65 billion in damages [23]. These events highlight vulnerabilities in low-lying infrastructure, where 40% of the U.S. population resides [3].

Floods disrupt supply chains, costing 1% of GDP in nations like Bangladesh [25]. Resilient designs, such as elevated structures, are critical to mitigate these socioeconomic impacts [20].

2.2. Heatwaves and Thermal Stress

Heatwaves, doubling in frequency since the 1980s, stress infrastructure materials [26]. The 2022 UK heatwave, with road surfaces reaching 50°C, caused rutting and transport disruptions [26]. Railway tracks buckle under thermal expansion, posing safety risks [26].

Energy grids face high cooling demands, as seen in the 2021 Texas blackout affecting 4.5 million households [26]. Transformers overheat, reducing efficiency [26]. Urban heat islands exacerbate these issues, accelerating material degradation [31].

Developing cities like Lagos face rising maintenance costs due to heat stress [31]. Innovative materials and monitoring systems are essential to ensure durability under warming conditions [26].

2.3. Sea-Level Rise and Coastal Erosion

Sea-level rise, with a 20 cm increase since 1900, threatens coastal infrastructure [4]. Projections of 0.3–1 meter by 2100 endanger ports and roads, with Miami facing $3 billion in annual damages [4]. Coastal erosion, doubling in some regions, undermines highways, as seen in California's 2023 collapses [35].

Ports face increased downtime, disrupting global trade [35]. Small island states like the Maldives risk 80% infrastructure loss by 2050 [4]. Adaptive designs, such as protective barriers, are critical for coastal resilience [4].

Developing nations face high adaptation costs, straining budgets [4]. Innovative engineering solutions are needed to protect vulnerable coastal systems [35].

2.4. Multi-Hazard Interactions

Compound hazards amplify infrastructure risks. Zscheischler et al. [2020] note that floods followed by heatwaves cause cumulative damage, as seen in Pakistan's 2022 floods costing $30 billion [39]. These interactions challenge single-hazard risk assessments [39].

Interconnected systems, like energy and transport, are vulnerable to cascading failures [39]. Germany's 2021 floods disrupted rail signaling, halting transport for weeks [39]. Integrated resilience strategies are essential [16].

Probabilistic models for multi-hazard risks are underutilized, particularly in developing nations [39]. Advanced modeling, as emphasized in Sub-Saharan Africa's infrastructure plans, is critical for preparedness [43].

Table 1 Key Climate Hazards and their Effects on Specific Infrastructure Types

Hazard Type	Description	Primary Impact on Infrastructure	Global Examples	Economic Costs (last five years Estimates)	Affected Sectors	Mitigation Potential with Smart Technology
Floods	Increased frequency of heavy	Structural damage to roads, bridges,	2022 European floods (10,000	€5 billion (Europe 2022); $65	Transportation, Urban Drainage	High (AI forecasting,

	precipitation (7% rise per degree of warming)	and drainage systems; overflow and erosion	km of roads damaged); 2021 Germany Ahr Valley	billion (U.S. Hurricane Ida 2021)		IoT monitoring)
Storm Surges	Heightened surges from cyclones (20% increase by 2050)	Inundation of coastal ports, highways, and buildings; sediment displacement	Hurricane Ida flooding New York subways (2021); Coastal U.S. erosion	$65 billion (U.S. 2021); $30 billion (Pakistan 2022 Floods)	Ports, Coastal Roads	Medium-High (Digital twins for simulation, resilient materials)
Heatwaves	Doubled frequency since 1980s; 1.5°C above pre-industrial in 2023	Material deformation (e.g., road rutting, rail buckling); grid overload	2022 UK roads reaching 50°C; 2021 Texas blackout (4.5 million affected)	$10 billion (U.S. 2021 blackout); $5 billion (UK 2022 disruptions)	Energy Grids, Railways	High (IoT sensors for real-time monitoring, heat-resistant concrete)
Sea-Level Rise	20 cm rise since 1900; 0.3–1 m projected by 2100	Chronic inundation and erosion of ports, roads, and utilities	Miami annual damages ($3 billion); California highway collapses (2023)	$50 billion annual for coastal defenses globally; $3 billion (Miami yearly)	Ports, Coastal Utilities	Medium (Resilient barriers, AI predictive modeling)
Coastal Erosion	Doubled rates in some regions due to surges and rise	Undermining of highways and rail lines; sediment loss	California Pacific Coast Highway collapse (2023); Maldives infrastructure loss (80% by 2050)	$2 billion (U.S. coastal erosion yearly); $1 billion (global port downtime)	Highways, Rail Lines	Medium (IoT erosion sensors, permeable pavements)
Multi-Hazard Interactions	Compounding events (e.g., floods + heatwaves)	Cascading failures (e.g., power outages disrupting Transport)	Pakistan 2022 floods followed by heat; Germany 2021 floods halting rails	$30 billion (Pakistan 2022); $20 billion (Germany 2021))	Energy, Transport Networks	High (AI multi-hazard modeling, digital twins)
Thermal Stress	Urban heat islands (3–7°C warmer) accelerating degradation	Overheating of transformers, road softening	Lagos maintenance increases; Texas grid failures	$5 billion (global energy disruptions yearly); $2 billion (urban road repairs)	Buildings, Energy Systems	High (Green roofs with IoT, heat-resistant materials)

Table 1 summarizes key climate hazards, their impacts, examples, economic costs, affected sectors, and potential mitigation using smart technologies.It highlights the multi-faceted nature of climate risks and the role of innovation in adaptation.

3. Smart Technologies for Resilience

Smart technologies enable proactive adaptation to climate hazards, shifting engineering toward predictive strategies. This section explores AI, IoT, digital twins, and resilient materials, highlighting their applications and benefits for climate-proof infrastructure.

3.1. Artificial Intelligence for Risk Management

AI enhances risk management by predicting climate impacts. The study by Wang et al. [2021] shows that AI forecasts flood risks with 90% accuracy, optimizing bridge maintenance [44]. New York's 2023 AI flood prediction system reduced subway downtime by 30% [44].

AI improves multi-hazard assessments, identifying stress points in urban systems [44]. However, limited data in developing nations hinders adoption, necessitating open-source platforms [50]. AI's integration with IoT reduces costs by 25% [8].

High costs and skill gaps challenge implementation [50]. Training programs and collaborative platforms are needed to scale AI globally [44].

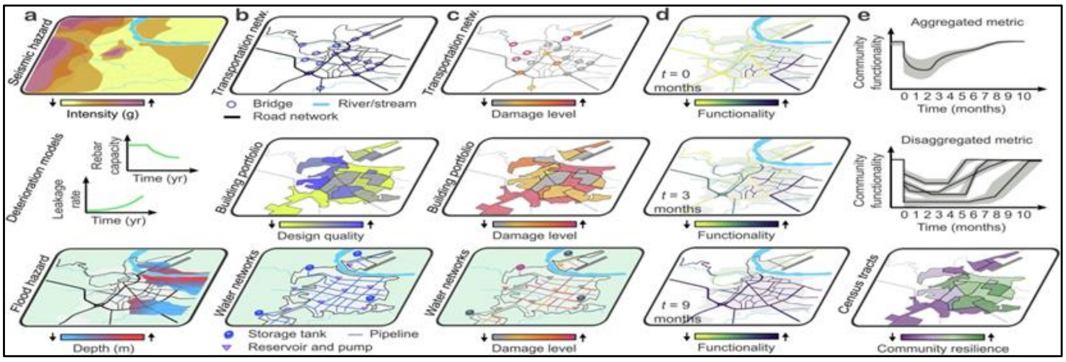

Figure 1 Depicts the components of current resilience modeling, including external stressors, infrastructure models, and social equity checks, which align with the use of AI in multi-hazard risk management

3.2. IoT and Real-Time Monitoring

IoT sensors monitor environmental stressors, enabling rapid response. Zhang et al. [2021] found that IoT dikes in the Netherlands reduce flood response times by 40% [51]. Sensors in Athens' infrastructure trigger cooling measures, extending material lifespan by 15% [52].

IoT integration with AI enables predictive maintenance, cutting energy grid repair costs by 20% [51]. Data security and compatibility issues persist, requiring standardized protocols [51]. Cost-effective IoT solutions, like India's rural sensors, enhance scalability [76].

Low-resource settings face connectivity challenges [76]. Solar-powered sensors, as in Kenya, offer a path forward for rural resilience [80].

3.3. Digital Twins for Design Optimization

Digital twins simulate climate impacts, optimizing designs. Tao et al. [2022] report that Singapore's port twins withstand 50-year flood events, saving €100 million [10]. California's grid twins prevent heatwave-induced blackouts [10].

Digital twins require high computational resources, limiting use in developing nations [10]. Open-source frameworks can bridge this gap [85]. Integration with IoT enhances predictive power [10].

Scalability depends on data availability [10]. Collaborative platforms are essential for global adoption of digital twins [85].

3.4. Resilient Materials and Green Engineering

Resilient materials mitigate climate impacts. Pacheco-Torgal et al. [2020] found that permeable pavements absorb 50% more water, reducing flood risks [63]. Heat-resistant concrete extends road lifespan in Australia [63]. Green roofs in Toronto reduce urban heat by 2–3°C [65].

IoT-enabled materials optimize maintenance, cutting costs by 15% [63]. Local materials, like Ghana's soil blocks, enhance affordability [66]. These solutions support SDG 11 [65].

High costs limit scalability in developing nations [68]. Innovative financing models are needed to ensure equitable access [68].

4. Applications in Urban and Rural Contexts

Smart technologies vary by context, with urban areas leveraging advanced systems and rural regions prioritizing affordability. This section compares urban and rural applications, identifying transferable lessons for resilience.

4.1. Urban Resilience Through Smart Infrastructure

Urban areas face amplified risks from floods and heat. Research done by GhaffarianHoseini et al. [2021] shows that AI and IoT reduce flood disruptions by 25% in Singapore [69]. Rotterdam's permeable pavements mitigate flooding, supporting SDG 11 [12].

IoT-enabled green roofs in Sydney reduce urban heat by 2–4°C [69]. Retrofitting challenges, as reported by Frantzeskaki et al. [2020], require standardized protocols [73]. Urban mobility benefits from AI traffic systems, as in Tokyo [75].

Urban areas' access to funding positions them as resilience leaders [69]. Coordinated governance is critical for scaling solutions [73].

4.2. Rural and Developing Nation Applications

Rural areas require cost-effective solutions. Adesina et al. [2022] found that IoT sensors in Ghana's roads reduce maintenance costs by 30% [76]. India's AI bridge monitoring saved $10 million in 2023 [36]. These solutions support SDG 9 [76].

Connectivity limits IoT deployment in Africa [76]. Solar-powered sensors, as in Kenya, address this gap [76]. Public-private partnerships accelerate adoption [68].

Tailoring technologies to local needs ensures scalability [76]. India's open-source AI models offer a replicable framework [36].

4.3. Cross-Context Lessons

Urban and rural applications share scalability challenges. Koks et al. [2022] note that modular technologies, like Singapore's twins and Ghana's sensors, enable replication [37]. Community engagement, as in Bangladesh, improves outcomes [38].

Cost-effectiveness varies by context, with urban projects yielding high returns and rural solutions addressing equity [84]. Open-source platforms reduce costs by 20% [40]. These lessons support hybrid resilience strategies [37].

Interoperability and knowledge transfer are critical. Standardized platforms can bridge urban-rural divides, ensuring equitable resilience [40].

Table 2 Applications of Smart Technologies in Urban and Rural Contexts

Technology	Urban Application	Urban Example	Urban Benefits	Urban Challenges	Rural Application	Rural Example	Rural Benefits	Rural Challenges	Cross-Context Transferability
AI	Predictive flood and traffic management	Singapore's monsoon prediction (25% reduced downtime)	High accuracy (90%); real-time decision-making	Retrofitting costs; data privacy in dense areas	Monsoon impact forecasting for bridges	India's rural bridges ($10 million savings)	Cost-effective prediction; low-maintenance	Limited data availability; skill gaps	High (open-source models from urban to rural)
IoT	Real-time monitoring for heat and flood	Athens' heat island sensors (15% lifespan extension)	Early warnings; integrated with urban grids	Connectivity in high-density areas; security risks	Structural health for roads and bridges	Ghana's rural roads (30% cost reduction)	Affordable sensors; solar-powered options	Unreliable internet; maintenance in remote areas	Medium (adapt urban sensor tech to rural solar versions)
Digital Twins	Simulation for urban planning and grids	Rotterdam's water management (€100 million savings)	Optimized designs; multi-hazard testing	High computational needs; urban data overload	Virtual modeling for rural water systems	Kenya's rural water infrastructure	Low-cost simulation; predictive maintenance	Limited computing resources; data scarcity	Low-Medium (scale down urban models for rural use)
Resilient Materials	Permeable pavements and green roofs	Sydney's heat reduction (2–4°C cooler)	Flood absorption (50%); biodiversity support	Space constraints in cities; initial costs	Stabilized soil blocks for roads	Ghana's erosion-resistant rural paths	Affordable local materials; durability in rain	Supply chain for advanced materials; expertise	High (transfer urban pavement tech to rural soil adaptations)
Green Engineering	IoT-enabled green roofs for heat mitigation	Toronto's urban cooling (10% lifespan extension)	Air quality improvement; energy savings	Urban land use conflicts; maintenance	Agroforestry-integrated roads for flood control	India's rural biodiversity enhancement	Low-cost nature-based solutions; community involvement	Land availability; integration with tech	High (urban green roofs adapted to rural agroforestry
Hybrid(AI+IoT)	Traffic rerouting and grid optimization	Tokyo's flood response systems	20% reduced disruptions; efficient urban mobility	Integration complexity; high density strain	Predictive maintenance for rural energy	Bangladesh's community grids	15% cost savings; equitable access	Connectivity and power issues	Medium (urban hybrids simplified for rural hybrids)

Open-Source Platforms	Data sharing for urban resilience	London's smart grid upgrades	15% cost reduction; collaborative innovation	Regulatory hurdles; data standardization	Technology transfer for rural monitoring	India's open AI for bridges	Accessibility for low-resource areas; scalability	Training for use; internet access	High (urban platforms shared with rural communities)

Table 2 outlines urban and rural applications of smart technologies, including examples, benefits, challenges, and transferability, based on global cases from the last five years. This table illustrates how technologies can be adapted across contexts to enhance overall resilience.

5. Case Studies of Successful Implementation

Case studies from the Netherlands, Singapore, and developing nations illustrate smart technology applications. This section highlights their effectiveness and best practices for global resilience.

5.1. Netherlands: Flood-Resilient Infrastructure

The Netherlands uses IoT dikes to monitor flood risks, reducing response times by 40% and saving €500 million annually [9]. Rotterdam's permeable pavements absorb 50% more water, mitigating urban flooding [12]. PPPs drive scalability [41].

Sensor-equipped dikes prevent breaches, as seen in 2022 [9]. AI drainage models enhance urban resilience [12]. High costs limit replication in developing nations [42].

Governance and investment ensure success [41]. The Dutch model offers lessons for coastal resilience [9].

5.2. Singapore: Smart Urban Planning

Singapore's digital twins reduce flood downtime by 25%, saving $200 million [11]. IoT grids prevent heatwave blackouts, cutting disruptions by 20% [52]. These align with SDG 11 [11].

AI-driven planning optimizes infrastructure [11]. Open-data platforms support scalability [53]. Retrofitting challenges persist [54].

Singapore's model highlights coordinated governance [53]. Modular technologies can aid global adoption [11].

5.3. Developing Nations: Cost-Effective Solutions

Ghana's IoT roads reduce maintenance costs by 30%, saving $5 million [29]. India's AI bridges saved $10 million in 2023 [36]. These solutions enhance rural resilience [29].

Connectivity gaps challenge IoT deployment [35]. Open-source AI reduces costs by 15% [56]. PPPs are critical for scaling [30].

Community-driven projects improve outcomes [38]. These examples offer scalable models for developing nations [35].

5.4. Synthesis of Best Practices

Integrating local knowledge enhances resilience, as seen in the Netherlands and India [39]. Modular technologies enable scalability [37]. Open-source platforms reduce costs [40].

PPPs drive innovation in Singapore and Ghana [41]. Standardized protocols ensure consistency [58]. Cross-context collaboration is critical [43].

Best practices include stakeholder engagement and affordability [43]. These strategies inform global resilience efforts [39].

6. Challenges and Future Directions

Economic, technical, governance, and equity barriers hinder smart technology adoption. This section examines these challenges and proposes future directions for resilient infrastructure.

6.1. Economic and Technical Barriers

AI/IoT deployment costs up to $10 million, limiting adoption [15]. PPPs reduce costs by 15–20% [39]. Technical compatibility issues persist [24].

Digital twins require high computational resources [61]. Open-source platforms can lower barriers [40]. Multi-hazard solutions are underutilized [12].

Cost-effective frameworks, like India's AI models, are needed [56]. Collaborative platforms can enhance scalability [40].

6.2. Governance and Policy Gaps

Siloed governance delays projects, as in the Netherlands [41]. Standardized metrics are lacking [15]. Participatory frameworks improve outcomes [43].

Developing nations face capacity gaps [30]. International frameworks, like Sendai, can standardize policies [44]. Governance reforms are essential [62].

Collaborative models, as in Rotterdam, ensure scalability [43]. Policy alignment is critical for global adoption [41].

6.3. Equity and Accessibility

Connectivity limits IoT in 60% of Sub-Saharan Africa [35]. Community-driven projects in Bangladesh improve outcomes [38]. Open-source platforms enhance access [40].

Low-income communities face training gaps [38]. Funding mechanisms, like the Loss and Damage Fund, are slow [60]. Inclusive designs are needed [47].

Solar-powered sensors, as in Kenya, bridge gaps [35]. Equitable solutions align with SDG 10 [47].

6.4. Research and Innovation Needs

AI models rarely address compound hazards [46]. Data gaps in developing nations hinder innovation [45]. Interdisciplinary collaboration is critical [13].

Open-data initiatives, like Singapore's, support research [64]. Multi-hazard modeling is a priority [65]. Technology transfers can bridge gaps [43].

Research must focus on scalability and equity [43]. Collaborative frameworks will drive innovation [13].

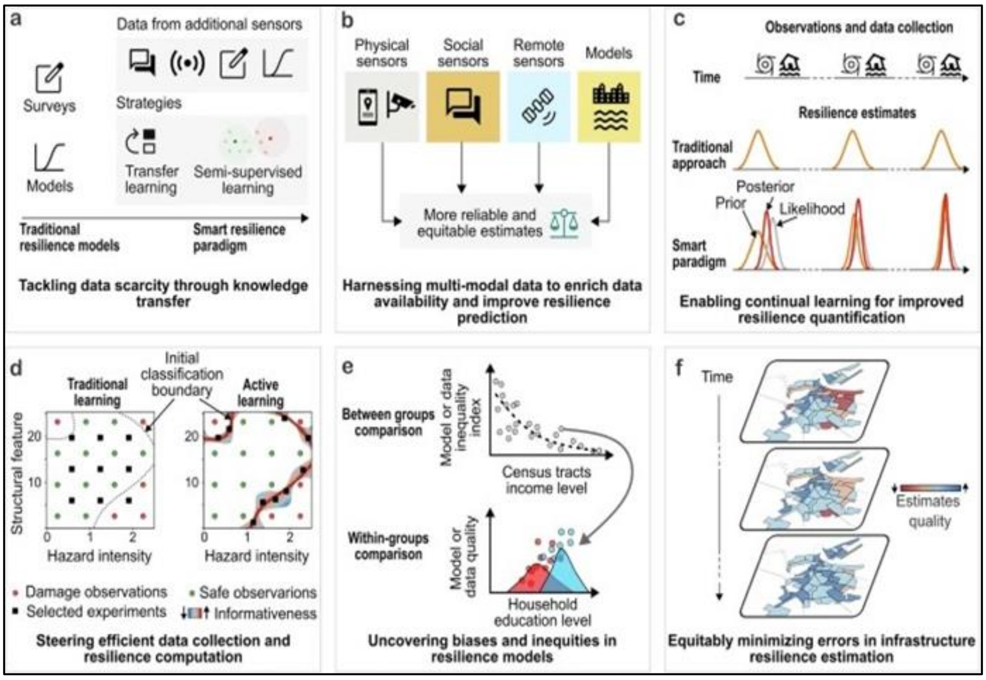

Figure 2 Outlines strategies for smarter and equitable resilience modeling, including intelligent algorithms and bias assessments, which complement the research needs for multi-hazard integration

7. Conclusion

Smart technologies offer transformative solutions for climate-resilient infrastructure, as demonstrated in global case studies. This section synthesizes findings, highlights engineering implications, and issues a call to action for equitable resilience.

7.1. Summary of Key Insights

Smart technologies reduce costs by 15–25%, as examined by Hallegatte et al. [2021] . Singapore's digital twins and Ghana's IoT sensors demonstrate adaptability. These align with SDG 9.

Case studies highlight scalability, with open-source platforms cutting costs by 20%. Challenges like costs and equity must be addressed. These advancements enable multi-hazard resilience.

Smart technologies ensure safety and sustainability. Holistic approaches are critical for global resilience.

7.2. Implications for Engineering Practice

AI and IoT extend infrastructure lifespan by 20%. Engineers must prioritize interoperable designs, as in Singapore. Standardized protocols are needed.

PPPs accelerate deployment. Equity-focused designs, like Ghana's sensors, ensure inclusivity. Engineers must advocate for open-data initiatives.

Inclusive engineering supports SDG 10. Modular technologies will drive global resilience .

7.3. Call for Action

Interdisciplinary collaboration is essential, as investigated by Frantzeskaki et al. [2023]. Research must address multi-hazard risks. International funding can support equity.

Standardized frameworks, like Sendai, ensure consistency. Stakeholders must act swiftly to build climate-proof infrastructure. Collaborative strategies will ensure a resilient future.

Compliance with ethical standards

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Disclosure of conflict of interest

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

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