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A Multi-Hazard Digital Twin Framework for Climate Adaptation Planning of Interdependent Critical Urban Infrastructure

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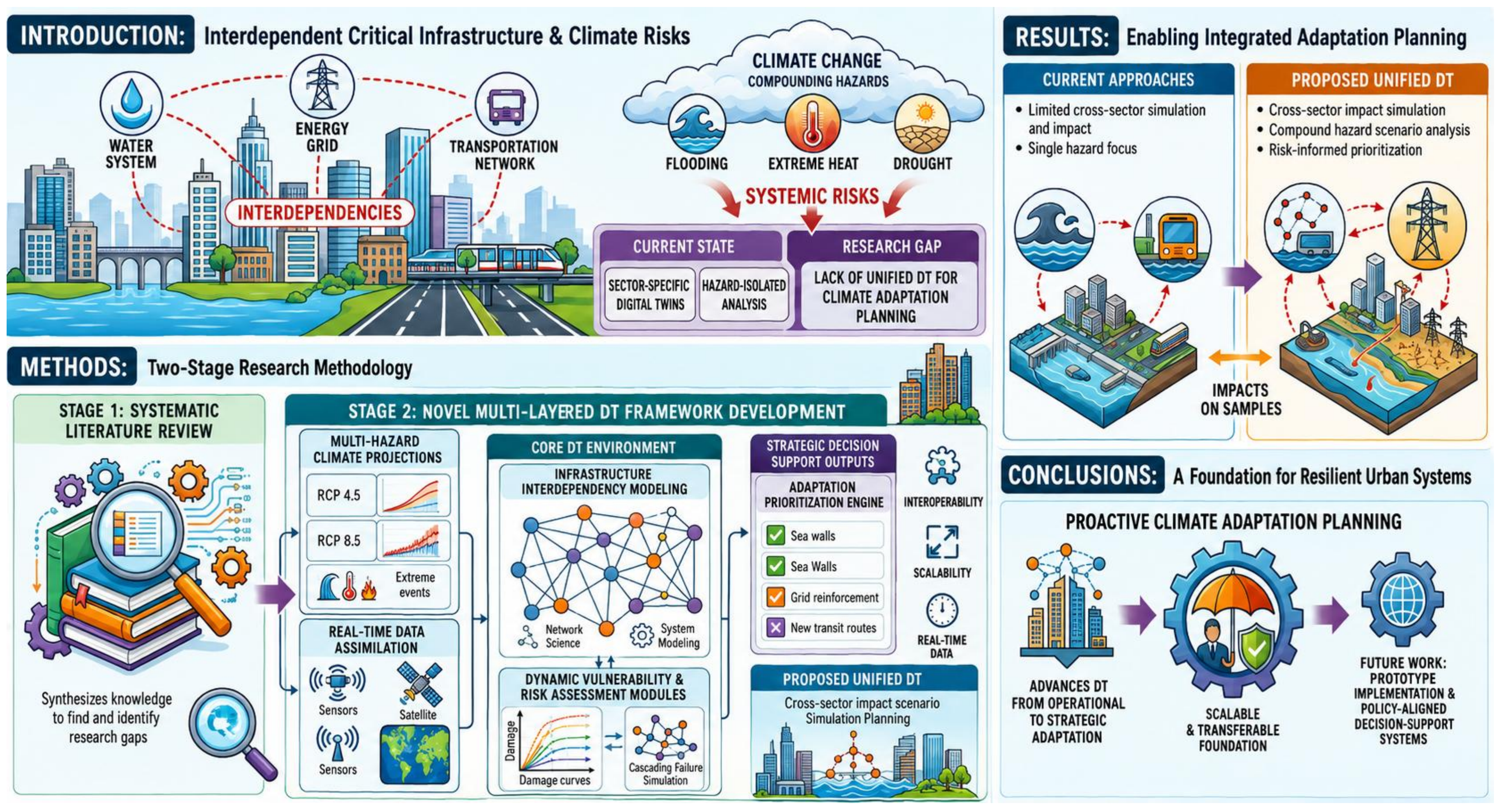
INTRODUCTION & AIM

Climate change is intensifying compound and cascading hazards such as flooding, extreme heat, drought, and infrastructure disruption, posing severe risks to interdependent urban systems including transportation, water, and energy networks. Digital Twin (DT) technology has emerged as a promising approach for infrastructure monitoring and smart city management through the integration of BIM, IoT, simulation models, and real-time data.

However, existing DT applications remain largely sector-specific and hazard-isolated, limiting their ability to capture cross-sector dependencies and cascading climate impacts. Furthermore, most current frameworks focus on operational monitoring rather than long-term climate adaptation and resilience planning. This study addresses these limitations by proposing an integrated multi-hazard Digital Twin framework for climate adaptation planning of interdependent critical urban infrastructure systems.



METHOD

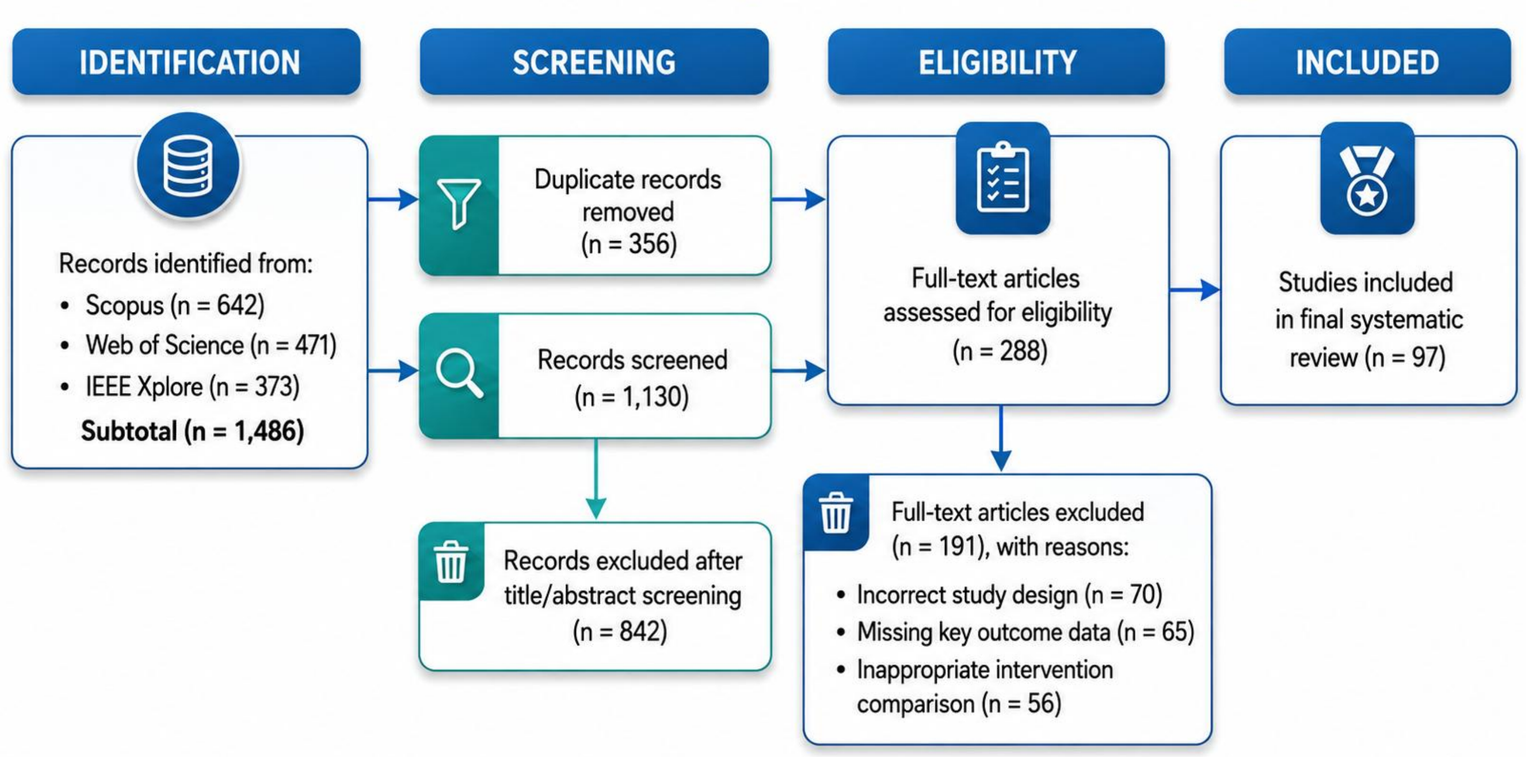
A systematic literature review was conducted following PRISMA guidelines to investigate the application of Digital Twin technologies for climate adaptation and resilient infrastructure planning. Relevant studies published between 2015 and 2026 were retrieved from Scopus, Web of Science, and IEEE Xplore using structured keyword combinations including "Digital Twin," "Climate Adaptation," "Critical Infrastructure," "Infrastructure Interdependency," "Multi-Hazard Modeling," and "Urban Resilience."

The selected studies were screened and analyzed through a combined quantitative and thematic synthesis approach. The review focused on:

- Digital Twin architectures and interoperability
- Multi-hazard climate risk modeling
- Infrastructure interdependency analysis
- Dynamic vulnerability assessment
- Real-time data integration and simulation
- Adaptation planning and decision-support mechanisms

Based on the identified research gaps, a multi-layered Digital Twin framework was developed integrating climate hazard projections, interdependent infrastructure networks, dynamic risk assessment, and adaptation prioritization within a unified decision-support architecture.

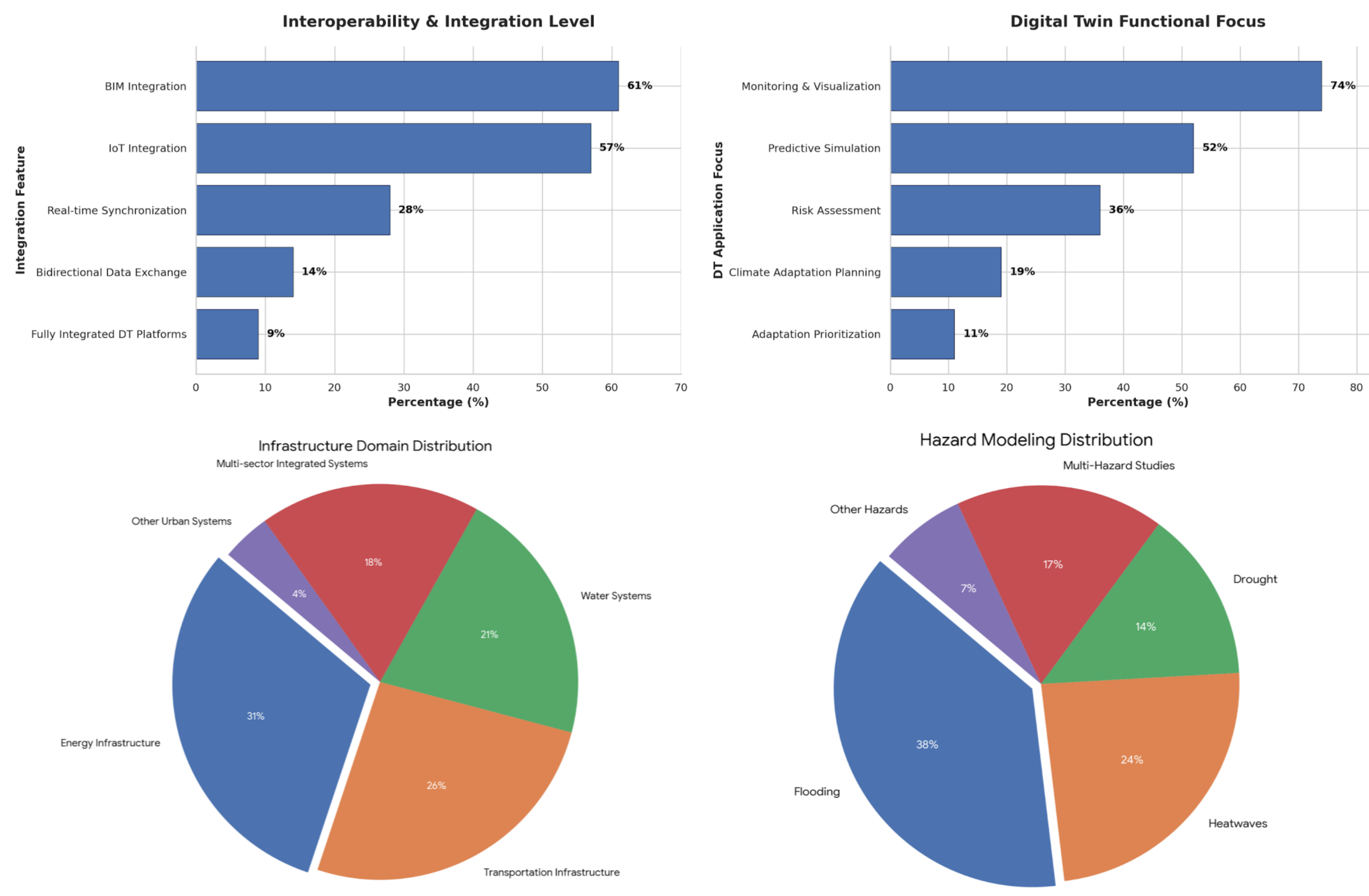
PRISMA Methodological Workflow Diagram



RESULTS & DISCUSSION

The analysis of 97 studies reveals that current Digital Twin research for infrastructure resilience remains highly fragmented and predominantly sector-oriented. Approximately 72% of studies focus on single infrastructure sectors, while only 18% investigate interdependent infrastructure interactions. Similarly, nearly 69% of existing DT applications address individual hazards rather than compound or cascading climate events. Real-time interoperability and bidirectional data exchange remain limited, appearing in less than 15% of reviewed studies.

The findings indicate that most existing frameworks emphasize operational monitoring and asset management, with limited integration of dynamic climate adaptation planning and resilience-oriented decision support. Large-scale urban implementation, uncertainty-aware modeling, and cross-sector adaptation prioritization remain major research gaps. To address these limitations, this study proposes a scalable multi-layered Digital Twin framework integrating hazard projections, infrastructure interdependency analysis, dynamic vulnerability assessment, and adaptation prioritization for proactive climate resilience planning.



Aspect	Current State	Identified Gap
Hazard Modeling	Mostly single-hazard focused	Lack of compound and cascading hazard integration
Infrastructure Scope	Sector-specific systems	Limited interdependency modeling
DT Functionality	Monitoring and visualization	Weak adaptation planning capability
Data Integration	Partial interoperability	Lack of seamless real-time synchronization
Risk Assessment	Static and scenario-based	Limited dynamic vulnerability analysis
Decision Support	Operational focus	Absence of adaptation prioritization engines
Validation	Conceptual or pilot-scale	Limited city-scale implementation
Governance Integration	Technical framework dominant	Weak policy and governance linkage
Scalability	Isolated implementations	Lack of transferable urban-scale frameworks

CONCLUSION

- Current Digital Twin applications for urban infrastructure are largely sector-specific and focused on operational monitoring, with limited integration of multi-hazard modeling and infrastructure interdependency analysis.
- This study proposes a scalable multi-layered Digital Twin framework integrating climate hazards, infrastructure networks, risk assessment, and adaptation planning for resilient urban infrastructure systems.

FUTURE WORK / REFERENCES

- Develop real-time Digital Twin prototypes integrating IoT-enabled infrastructure monitoring systems.
- Incorporate AI-driven predictive analytics and uncertainty-aware climate risk modeling. Extend the framework toward district- and city-scale resilience assessment applications.
- Integrate governance, policy, and socio-economic adaptation indicators within DT environments. Validate the proposed framework using real-world urban infrastructure case studies.