© JUN 2026 | IRE Journals | Volume 9 Issue 12 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I12-1718906

Sustainable Smart Bridge Systems for Saudi Vision 2030 Infrastructure Development

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Abstract- Background: Saudi Arabia is expanding roads, rail links, logistics corridors, smart cities and giga-project infrastructure under Vision 2030. Bridges within these networks are not only civil structures; they are mobility, safety, economic and environmental assets whose failure or closure can disrupt trade, tourism, emergency response and public confidence.
Aim: This review develops a Saudi-focused conceptual framework for sustainable smart bridge systems that integrates Structural Health Monitoring (SHM), Internet of Things (IoT) sensing, Artificial Intelligence (AI), Digital Twins and lifecycle sustainability assessment.
Methodology: A structured narrative review was conducted using peer-reviewed and policy literature published mainly between 2020 and 2025. The analysis synthesized evidence across five themes: sensing and monitoring, digital representation, predictive analytics, sustainability performance and governance.
Results: The review shows that smart bridge value is created when physical asset durability, sensor networks, digital intelligence and decision governance operate as one lifecycle system. AI-supported monitoring can improve anomaly detection, maintenance prioritization and service-life planning, while digital twins can connect inspection records, BrIM/BIM models, traffic exposure and climate data.
Contribution: The paper proposes a four-layer sustainable smart bridge framework, a Smart Bridge Maturity Index, a Saudi implementation roadmap and a Vision 2030 alignment matrix. These outputs provide a practical pathway for bridge owners, consultants and policy makers to move from isolated monitoring technologies toward integrated, low-carbon and resilient bridge asset management.
Conclusion: Sustainable smart bridge systems can strengthen Saudi infrastructure resilience, reduce unplanned closures, improve lifecycle carbon performance and support local digital engineering capability. Future research should validate the proposed framework through Saudi bridge case studies, pilot monitoring data and lifecycle cost-carbon modelling.

Keywords: Smart Bridges, Structural Health Monitoring, Digital Twin, IoT, Artificial Intelligence, Sustainable Infrastructure, Saudi Vision 2030.

I. INTRODUCTION

Saudi Arabia's infrastructure transformation is reshaping the requirements placed on bridges across highways, urban corridors, ports, airports, railways, industrial zones and tourism destinations. Under Vision 2030, infrastructure is expected to deliver capacity, safety, resilience, environmental performance and digital operational excellence rather than only physical connectivity. In this context, bridges should be treated as strategic assets that support mobility, logistics reliability, regional development, emergency access and quality of life.

Traditional bridge management relies heavily on periodic visual inspection, reactive maintenance and fragmented documentation. Although visual inspection remains essential, it can miss hidden deterioration, provide only intermittent information and depend on the subjective judgement of inspectors. Recent literature therefore emphasises the need for smart bridge systems that combine SHM, IoT sensors, bridge information modelling, digital twins, AI analytics, lifecycle assessment and governance dashboards (Bhatta et al., 2024; Costin et al., 2024; Sun et al., 2025). Such systems are especially relevant in Saudi Arabia because bridges may face extreme heat, dust exposure, coastal chlorides, flash-flood risks in wadis, heavy logistics traffic and fast project delivery schedules.

A sustainable smart bridge is defined in this review as a bridge asset whose physical design, monitoring architecture, digital model and decision process are coordinated to improve safety, extend service life, reduce lifecycle carbon, minimise disruption and support transparent asset management. This definition is important because the mere installation of sensors does not make a bridge sustainable or smart. Sustainability comes from long-term performance, circular resource use and reduced operational disruption, while smartness comes from the ability to convert data into timely engineering decisions.

The aim of this paper is to develop a conceptual and implementation-oriented framework for sustainable smart bridge systems aligned with Saudi Vision 2030 infrastructure development. The objectives are to synthesise recent literature on smart bridge technologies, identify the research gap in Saudi-focused integrated bridge systems, propose an original multi-layer framework, develop a maturity model and roadmap, and identify implementation opportunities for Saudi infrastructure owners and engineering organisations.

1.1 Research Gap

Existing studies predominantly focus on isolated applications of SHM, digital twins, AI-based defect detection, bridge information modelling or sustainable materials. While these studies are valuable, limited research has investigated an integrated framework combining sustainability assessment, predictive maintenance, digital twin technologies and Vision 2030 strategic objectives within the Saudi Arabian infrastructure context. There is also limited discussion of how Saudi-specific exposure conditions, procurement practices, local skills development, cybersecurity, lifecycle carbon reporting and performance-based maintenance contracts should be connected in one smart bridge system.

This gap matters for Premium Residency and exceptional talent evidence because the profile should demonstrate innovation and strategic relevance rather than only a general literature summary. A Saudi-focused framework can show how the applicant contributes to a national research and infrastructure agenda by translating global technologies into a model suitable for local bridge assets, giga-projects, smart mobility corridors and sustainability objectives.

1.2 Original Contribution

The original contribution of this review is fourfold. First, it proposes a Saudi-focused framework integrating AI, SHM, IoT, digital twin and sustainability principles for bridge lifecycle management. Second, it introduces a Smart Bridge Maturity Index that helps owners classify bridges from documentation readiness to network-level predictive management. Third, it develops a Saudi implementation roadmap covering planning, design, construction, operation and scaling. Fourth, it provides a Vision 2030 alignment matrix linking technical bridge functions with resilience, sustainability, logistics, digital transformation and local capability outcomes.

The paper does not claim field validation because no Saudi bridge sensor dataset was available for this review. Instead, it provides a review-derived conceptual model that can be tested in future pilot projects through local monitoring data, expert validation, lifecycle cost analysis and carbon modelling.

II. REVIEW METHODOLOGY

A structured narrative review method was selected because the topic cuts across civil engineering, digital construction, asset management, smart cities, sustainability and infrastructure governance. The review focused mainly on literature published from 2020 to 2025, including journal articles, conference papers and credible policy sources that discuss SHM, IoT infrastructure monitoring, AI in structural engineering, bridge digital twins, BrIM/BIM workflows, sustainable construction materials, lifecycle assessment and Saudi Vision 2030 infrastructure priorities.

The search process used three phases. The first phase identified technology literature using terms such as smart bridge, bridge SHM, IoT sensors, digital twin bridge, AI bridge maintenance, BrIM, anomaly detection and predictive maintenance. The second phase identified sustainability and resilience literature using terms such as lifecycle assessment, low-carbon bridge, circular materials, resilient infrastructure, climate adaptation and sustainable asset management. The third phase connected the technical evidence to Saudi Arabia through terms such as Vision 2030, smart cities, transport infrastructure, logistics corridors, giga-projects and sustainable urban development.

Literature was included when it offered conceptual, technological, methodological, governance or applied insight relevant to smart bridge systems. Sources were excluded when they were outdated, promotional, unrelated to bridges or infrastructure assets, or lacked sufficient methodological clarity. The selected evidence was synthesised into five analytical themes: sensing and monitoring, digital representation, predictive analytics, sustainability performance and governance. These themes were then translated into the framework, maturity model, roadmap and implementation matrix presented in this paper.

III. LITERATURE REVIEW: SMART BRIDGE TECHNOLOGIES

Structural health monitoring is the foundation of smart bridge systems. SHM uses sensors to measure strain, displacement, acceleration, inclination, temperature, humidity, corrosion potential, scour depth, acoustic emissions, traffic loading and environmental exposure. Compared with periodic inspection alone, SHM provides continuous or near-real-time visibility of structural behaviour. IoT-based monitoring can transmit these data streams to edge devices, cloud platforms or owner dashboards where they can be filtered, stored and interpreted (Bhatta et al., 2024; Kang X. et al., 2025).

Digital twins extend SHM by connecting live or periodic data with digital models of the asset. A bridge digital twin may include BrIM/BIM geometry, finite element models, inspection history, maintenance records, sensor feeds, drone imagery, traffic data, weather exposure and deterioration models. Costin et al. (2024) and Sun et al. (2025) show that digital twins can improve asset knowledge continuity and scenario analysis by linking measured condition with engineering models. For Saudi bridge owners, this is significant because rapid infrastructure development can create long-term maintenance risk if as-built information, material data and inspection records are not standardised from project handover.

Artificial intelligence and machine learning are increasingly used for crack detection, anomaly screening, vibration interpretation, missing-data estimation, deterioration forecasting and maintenance prioritisation. Vision-based AI can process drone and camera images of hard-to-access bridge elements, while data-driven models can recognise unusual structural responses that may not be obvious during normal inspections (Plevris, 2024; Prakash et al., 2025). However, AI should support professional engineering judgement rather than replace it. Safety-critical decisions require explainability, local calibration, quality-controlled training data and audit trails.

Sustainability technologies are equally important. Low-carbon concrete, supplementary cementitious materials, recycled aggregates, corrosion-resistant reinforcement, fibre-reinforced polymers, modular construction and material passports can reduce lifecycle impact when selected carefully. Lifecycle assessment is necessary because the material with the lowest initial embodied carbon may not be the best option if it shortens service life or increases maintenance frequency. Under Saudi environmental conditions, durability, maintainability and exposure resistance should be evaluated alongside carbon reduction.

Communication and energy systems determine whether monitoring can be maintained over time. Solar-powered gateways, LPWAN, 5G connectivity, edge computing and energy harvesting can reduce monitoring cost and improve resilience. Edge computing is particularly useful because raw sensor data are often noisy and high-volume. Local filtering can identify relevant events before sending information to central platforms. Cybersecurity must also be treated as a bridge safety issue because connected infrastructure dashboards, maintenance systems and transport networks may create new vulnerabilities if not governed properly.

IV. SAUDI VISION 2030 ALIGNMENT

Vision 2030 creates a clear policy and investment context for smart bridge systems. The Kingdom is developing smart cities, logistics hubs, tourism destinations, industrial zones and integrated transport networks. Bridges within these systems must support safe movement, economic diversification, environmental responsibility and digital transformation. Sustainable smart bridges can contribute directly by improving mobility, reducing unexpected closures, supporting tourism access and strengthening logistics reliability. They can also contribute indirectly by reducing emissions associated with emergency repairs, traffic delays and premature replacement.

Saudi mega-projects and regional infrastructure programmes provide an opportunity to embed smart bridge requirements from the beginning rather than retrofit them later. Sensor-ready design, digital handover standards, material passports, cyber-secure data architecture and lifecycle performance indicators can be written into contracts at planning and design stages. This approach aligns with the model-based engineering logic discussed by Gbran and Alzamil (2025), where sustainable urban development depends on data, modelling, governance and measurable outcomes.

The local capability dimension is also important. Smart bridge programmes require civil engineers, data analysts, digital twin specialists, inspection professionals, material scientists, cybersecurity experts and maintenance planners. This creates opportunities for Saudi universities, consultancies, contractors and public agencies to establish living laboratories, pilot projects and professional development programmes. Therefore, smart bridge implementation should be framed not only as infrastructure technology but also as research, innovation and human-capital development.

V. CONCEPTUAL FRAMEWORK FOR SUSTAINABLE SMART BRIDGES

The proposed framework contains four connected layers: physical asset sustainability, sensing and communication, digital intelligence and decision governance. The physical asset sustainability layer includes bridge foundations, bearings, joints, deck systems, drainage, barriers, lighting, utilities and the surrounding transport context. Sustainability begins at this layer through durable design, climate resilience, maintainability, low-carbon material selection, corrosion resistance and efficient inspection access. A bridge cannot become sustainable merely through later digital additions if the physical design is weak or difficult to maintain.

The sensing and communication layer captures information about structural condition, traffic loading and environmental exposure. Sensor selection should be risk-based and decision-based. Coastal bridges may require chloride, humidity and corrosion monitoring; long-span bridges may require vibration, displacement, wind and cable-force monitoring; bridges crossing wadis may require water-level and scour sensors; high-volume urban bridges may require axle-load, fatigue and deck-condition monitoring. Communication infrastructure must consider reliability, power consumption, redundancy, cybersecurity and maintenance access.

The digital intelligence layer converts data into engineering insight. It includes BrIM/BIM models, finite element analysis, digital twins, AI algorithms, deterioration models, geospatial data and lifecycle cost-carbon tools. Outputs should be understandable to engineers and decision makers: risk scores, warning thresholds, remaining useful life estimates, maintenance priorities and scenario comparisons. Scenario analysis is essential in Saudi Arabia because traffic growth, high temperatures, coastal corrosion and rapid urban expansion may change bridge performance assumptions over time.

The decision governance layer converts technical outputs into action. It defines owner responsibilities, data standards, maintenance thresholds, cyber rules, procurement requirements, audit trails, contractor performance indicators and budget prioritisation. Without governance, monitoring systems can become unused dashboards. Effective governance should connect alerts to inspection procedures, maintenance work orders, sustainability reports and executive asset decisions.

Figure 1. Sustainable smart bridge system framework for Saudi Vision 2030 infrastructure development. Source: Author.

VI. FINDINGS FROM THE LITERATURE AND THEMATIC SYNTHESIS

The literature reveals five key findings. First, smart bridge benefits depend on integration rather than technology quantity. Sensors, digital twins and AI tools produce value only when they are linked to maintenance decisions, risk thresholds and lifecycle objectives. Second, SHM data are most useful when bridge-specific baseline behaviour is established. Temperature, traffic and environmental effects can create changes that are not damage-related, so local calibration is necessary before automated warnings are trusted.

Third, digital twins are becoming the central platform for bridge asset knowledge. They can join design information, inspection records, sensor data, drone imagery and maintenance history in one continuously updated model. However, the literature also shows that digital twins fail when data formats, ownership responsibilities and update processes are not defined. For Saudi projects, this means digital handover requirements should be included in procurement and not left to post-construction interpretation.

Fourth, sustainability should be measured across the full lifecycle. Low-carbon materials, longer service life, reduced emergency repairs, fewer traffic disruptions and improved reusability all affect sustainability outcomes. Predictive maintenance can reduce waste by targeting interventions and avoiding unnecessary replacement. However, sustainability metrics must be defined at owner level, otherwise the environmental benefits of smart bridge systems remain theoretical.

Fifth, governance and skills are recurring limitations. Many papers emphasise technical capability, but fewer explain who will operate the system, verify AI outputs, maintain sensors, protect data, approve thresholds and fund interventions. Saudi implementation should therefore combine technology adoption with local training, data governance and performance-based maintenance contracts.

The main gap emerging from the synthesis is the lack of Saudi-specific empirical evidence. Future studies should test sensors under desert heat and dust, compare monitoring performance in coastal and inland bridges, validate AI defect detection on Saudi bridge images, and quantify lifecycle cost and carbon savings from predictive maintenance. Until these studies are conducted, the framework in this paper should be treated as a structured implementation model rather than a validated field system.

Table 1. Smart bridge technology domains and Saudi implementation considerations

Technology domain	Typical bridge application	Expected benefit	Saudi implementation consideration
IoT sensor networks	Strain, vibration, temperature, corrosion, scour and traffic monitoring	Continuous condition visibility and early warning	Select sensors according to desert heat, dust, coastal corrosion, flood exposure and maintenance access
Bridge digital twins	Integration of BrIM/BIM, finite element models,	Scenario testing, asset knowledge continuity	Require standardised digital handover and model updating

	inspection records and live SHM data	and better maintenance planning	protocols in contracts
AI and machine learning	Crack detection, anomaly screening, deterioration forecasting and missing-data estimation	Faster inspection processing and risk-based prioritisation	Validate models locally and keep engineers accountable for safety-critical decisions
Low-carbon materials	Durable concrete, recycled materials, corrosion-resistant reinforcement and modular elements	Lower lifecycle carbon and longer service life	Use lifecycle assessment rather than initial embodied carbon alone
Governance platforms	Dashboards, thresholds, audit trails, cybersecurity and performance reporting	Transparent asset management and improved coordination	Create owner-side data standards, cyber rules and performance-based maintenance KPIs

VII. SMART BRIDGE MATURITY INDEX AND QUANTITATIVE SCORING MODEL

To strengthen decision usefulness, this paper proposes a review-derived Smart Bridge Maturity Index (SSBMI). The index is not intended to replace engineering assessment; instead, it provides a simple screening tool for classifying the readiness of bridge assets for smart lifecycle management. The proposed formula is:

$$SSBMI = 0.20D + 0.20S + 0.20T + 0.15A + 0.15G + 0.10C$$

where D represents documentation and digital handover readiness, S represents sensor and SHM readiness, T represents digital twin and model integration, A represents AI and predictive analytics readiness, G represents governance and cybersecurity readiness, and C represents lifecycle carbon and circularity readiness. Each component can be scored from 0 to 100 using owner-defined criteria. A bridge scoring below 40 may require basic documentation and inspection improvements; 40-59 indicates early smart readiness; 60-79 indicates integrated asset management potential; and 80 or above indicates readiness for advanced predictive maintenance and network-level reporting.

This quantitative model is intentionally transparent. It allows bridge owners to prioritise critical assets without pretending that all bridges require the same level of digital sophistication. A small rural bridge may need accurate documentation and periodic inspection, while a critical logistics bridge, coastal crossing or urban interchange may justify high-level digital twin and AI monitoring. Future empirical research can refine the weights through expert surveys, analytic hierarchy process modelling, pilot data and lifecycle cost-benefit analysis.

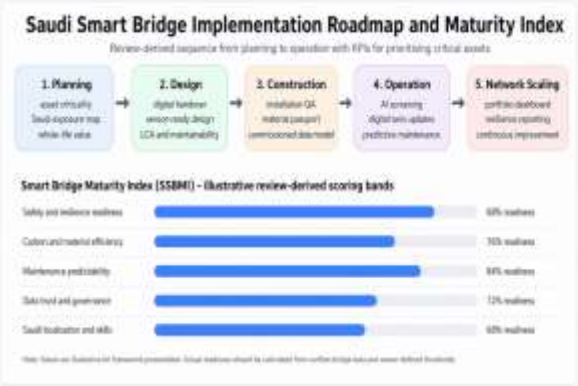

Figure 2. Review-derived smart bridge roadmap and maturity index. Source: Author.

Table 2. Smart Bridge Maturity Index scoring bands

Maturity level	Score range	Core capability	Recommended action
Level 1 - Documentation readiness	0-39	Basic inspection records, asset registry and lifecycle documentation	Complete digital handover, inspection zoning and sustainability baseline
Level 2 - Targeted monitoring	40-59	Risk-based sensors for critical components or exposure conditions	Pilot SHM on high-risk assets and define alert thresholds
Level 3 - Integrated asset data	60-69	BrIM/BIM, SHM and maintenance records connected	Establish digital twin workflows and owner data standards
Level 4 - Predictive management	70-84	Calibrated digital twin with AI-supported anomaly detection	Use predictive maintenance and lifecycle cost-carbon optimisation
Level 5 - Network intelligence	85-100	Portfolio dashboard connected to mobility, resilience and sustainability reporting	Scale across critical corridors and continuously update governance rules

VIII. SAUDI IMPLEMENTATION OPPORTUNITIES

Saudi Arabia can implement sustainable smart bridges through phased deployment. The first opportunity is to prioritise critical bridges based on traffic importance, logistics value, exposure condition, failure consequence and maintenance difficulty. The second opportunity is to introduce smart bridge requirements into design and construction contracts. These requirements should include sensor-ready design, naming conventions, BrIM/BIM handover, material passports, data ownership rules, cybersecurity obligations and maintenance interfaces.

The third opportunity is to create pilot testbeds with Saudi universities, public authorities, consultants and technology vendors. Pilot bridges can test sensor durability under heat and dust, corrosion monitoring near coastal areas, drone inspection workflows, digital twin updating and AI anomaly detection. The fourth opportunity is to connect smart bridge outputs to sustainability reporting. KPIs can include lifecycle carbon intensity, unplanned closure hours, sensor availability, maintenance response time, structural risk index, percentage of reusable materials and service-life extension.

The fifth opportunity is to develop local professional capability. Engineers and inspectors must understand how to verify alerts, calibrate models, maintain sensors and interpret dashboards. Human-centred implementation is essential because smart bridge systems will fail if the users do not trust or understand them. Training, standard operating procedures and accountability structures should therefore be developed alongside technology procurement.

Table 3. Vision 2030 alignment matrix for sustainable smart bridge systems

Vision 2030 priority	Smart bridge function	Measurable KPI	Expected national value
Infrastructure resilience	SHM, exposure monitoring and predictive maintenance	Structural risk index, unplanned closure hours, response time	Safer bridges and improved continuity of transport services
Environmental sustainability	Lifecycle assessment and circular	Lifecycle carbon intensity, recycling	Reduced material waste and better

	material tracking	rate, service-life extension	carbon performance
Logistics and mobility	Digital twin scenario planning and maintenance scheduling	Traffic disruption hours, asset availability, corridor reliability	Improved movement of people, goods and emergency services
Digital transformation	BrIM/BIM handover, dashboards and AI analytics	Digital handover completeness, sensor uptime, model update frequency	Data-driven infrastructure governance and smart city integration
Local capability	Pilot projects, university partnerships and professional training	Number of trained specialists, local research outputs, Saudi testbeds	Growth of national engineering and innovation capacity

IX. DISCUSSION

The main implication of this review is that sustainable smart bridges should be treated as part of national infrastructure systems rather than isolated engineering projects. Saudi Arabia has the opportunity to avoid fragmented data systems by establishing common bridge data standards, a unified maturity model, procurement templates and owner dashboards across major infrastructure programmes. This would support consistency while allowing each bridge to be monitored according to its risk profile.

The proposed framework also has relevance for exceptional talent and research profiles because it demonstrates a clear link between engineering innovation and national development. A researcher working on smart bridge systems can contribute to Vision 2030 by improving infrastructure resilience, reducing lifecycle environmental impact, supporting digital transformation and enabling local knowledge development. The contribution becomes stronger when the paper moves beyond general review and presents a framework, maturity model, implementation roadmap and gap analysis.

However, limitations remain. This paper is based on literature synthesis and does not include field measurements, a Saudi case study or statistical validation. It therefore provides a conceptual foundation rather than final proof of performance. The next stage should involve one or more Saudi bridge case studies where sensor data, inspection findings, environmental exposure, traffic loading, lifecycle cost and carbon metrics are collected over time. Such empirical work would make the research stronger for high-impact journals and for Premium Residency evidence because it would demonstrate measurable innovation and implementation relevance.

X. CONCLUSION

This review examined sustainable smart bridge systems for Saudi Vision 2030 infrastructure development. The analysis shows that bridge sustainability and intelligence should be integrated through physical asset durability, SHM and IoT sensing, digital twin modelling, AI-supported analytics and governance-based decision making. The greatest value is created when data are converted into maintenance actions, lifecycle planning, carbon reduction and resilience outcomes.

The paper addressed the main weaknesses of a conventional review by adding a research gap, original contribution statement, thematic synthesis, Smart Bridge Maturity Index, Saudi roadmap and Vision 2030 alignment matrix. These elements make the paper more suitable for academic review and for exceptional talent evidence because they show a defined contribution rather than only a descriptive summary of literature.

Future research should validate the framework through Saudi bridge pilots. Priority studies should measure sensor performance under desert and coastal exposure, test AI defect detection using local image datasets, compare low-carbon and durable material options, quantify lifecycle carbon savings from predictive maintenance, and evaluate the economic value of reduced closures. With empirical validation, sustainable smart bridge systems can become a practical pillar of Saudi Arabia's next-generation infrastructure strategy.

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