Natural Resources for Human Health

eISSN: 2583-1194

Original Research

**Received** 15 March 2026
**Revised** 20 April 2026
**Accepted** 10 May 2026

Natural Resources for Human Health 2026, Vol. 6 (1s): 513–528

**KEYWORDS**:
Digital Innovation; Sustainable Urban Infrastructure; Emerging Economies; Implementation Barriers; Environmental Sustainability

# Digital Innovation for Sustainable Urban Infrastructure in Emerging Economies: A Systematic Literature Review of Economic-Environmental Outcomes, Governance Mechanisms, and Implementation Barriers

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**ABSTRACT:** Rapidly advancing urbanisation and continuing infrastructure issues require that emerging economies improve essential services while avoiding carbon-intensive development, financial burdens and technological lock-in. This systematic literature review examines the role of digital innovation supports the economic and environmental sustainability of urban infrastructure, while also investigates the governance frameworks and implementation barriers that influence these outcomes. Following PRISMA 2020, the review synthesises 212 publications from 2021 to 2026 through descriptive evidence mapping and thematic synthesis. Artificial intelligence and machine learning were identified in 84 studies (39.6%), followed by Internet of Things and sensor systems in 64 (30.2%) and big-data analytics in 57 (26.9%). Energy and electricity systems constituted the leading infrastructure domain (69 studies; 32.5%), followed by transport and logistics (58; 27.4%). The principal value-creation mechanisms were automation and process integration (108; 50.9%), innovation and capability development (99; 46.7%), optimisation and resource allocation (75; 35.4%), and real-time monitoring (67; 31.6%). Ninety-nine studies (46.7%) considered economic and environmental outcomes jointly, while 65 (30.7%) explicitly examined emerging-economy contexts. However, implementation was constrained by scalability and context-transfer limitations (136; 64.2%), inadequate data and performance metrics (108; 50.9%), governance and regulatory deficiencies (103; 48.6%), limited organisational readiness (62; 29.2%), and cybersecurity, privacy and trust concerns (53; 25.0%). The synthesis develops a Digital Innovation–Infrastructure–Sustainability framework in which digital capabilities affect sustainability through monitoring, prediction, optimisation, automation and institutionalised decision-making. The review concludes that digitalisation is not intrinsically sustainable: durable economic–environmental value depends on interoperable standards, accountable data governance, institutional capacity, lifecycle cost and carbon measurement, inclusive service design, and locally appropriate financing.

## 1 INTRODUCTION

Urban infrastructure systems are simultaneously economic assets, environmental systems and public-service institutions. Energy infrastructures, transport routes, buildings, water supply systems, waste management services and digital networks shape productivity, household welfare, resource consumption and emissions over decades. Emerging economies face a particularly challenging investment problem: they must expand access and capacity rapidly while avoiding high-carbon path dependence, fiscal overextension and infrastructure that is unable to adapt to climate and technological change. Digital innovation including artificial intelligence (AI), Internet of Things (IoT) sensors, big-data analytics, digital twins, blockchain, cloud and edge computing, and advanced connectivity is increasingly proposed as a means of resolving this tension.

The optimistic argument is technically plausible. Sensors make infrastructure conditions visible; analytics convert data into forecasts; digital twins allow alternatives to be tested before physical intervention; and automated control can reduce energy use, downtime and material waste. In buildings, digital twins support lifecycle monitoring and safety management (Lauria and Azzalin, 2024). In smart grids, digital management improves demand coordination and integration of renewable resources (Khaleel et al., 2024). In transportation and logistics, the application of analytics and automation can reduce congestion, decrease fuel consumption, and lower greenhouse gas emission (Tsolakis et al., 2021; Fatorachian et al., 2025b). In water systems, digitally improved decision-making tools can improve resource allocation under uncertainty (Zhao et al., 2025). These mechanisms suggest that economic and environmental goals do not have be treated as automatic trade-offs.

However, the evidence does not support a simple technology-deterministic conclusion. Digital systems introduce capital and operating costs, cybersecurity exposure, dependence on vendors and data, additional electricity demand, and potential exclusion of citizens or organisations with limited digital access. Benefits that are demonstrated in a pilot, single city or high-capacity institution may not survive scaling or transfer to jurisdictions with fragmented governance, scarce technical skills, legacy assets and uncertain municipal finance. Analyses of sustainable construction and smart-city technologies consistently identify the same unresolved questions: implementation focused on specific lifecycle stage, there is lack of comparable performance metrics, and governance and institutional frameworks are often less attention than technical capabilities (Li et al., 2025; Pellegrino and Stasi, 2024; Sacoto-Cabrera et al., 2025).

The emerging-economy literature has sharpened this concern. Framework for emerging smart cities emphasise that the technology adoption should be paired with socioeconomic, legal, institutional changes (Mallik et al., 2025). A study conducted in India highlights digital literacy, cost, and inter-organizational collaboration as factors influencing the growth of smart public-service infrastructure (Choudhuri et al., 2022). Evidence from China suggests that digital innovation and digital infrastructure may improve urban energy efficiency and green productivity, however the impacts differ by regions, policy conditions and industrial structures (Xiao et al., 2025; Liu et al., 2025). Research on Saudi smart cities also emphasises the importance of capability enhancement, governance, and context relevant execution alongside advanced technology (Bahreldin et al., 2025).

Existing reviews are commonly organised around one technology, one sector or a general smart-city agenda. This creates three forms of fragmentation. First, technology-centred reviews often catalogue applications without explaining the mechanisms connecting technology to outcomes. Second, sector-centred reviews make it difficult to compare value pathways across infrastructure systems. Third, sustainability is frequently represented by environmental indicators alone or by broad claims that do not quantify economic viability. The present review addresses this fragmentation by integrating technologies, operational mechanisms, dual economic-environmental outcomes, governance conditions and implementation barriers in a single framework, with a specific analytical lens on emerging economies.

## 2 CONCEPTUAL BACKGROUNDS

### 2.1 Digital Innovation as an Infrastructure Capability

Digital innovation should not be reduced to the acquisition of discrete technologies. In infrastructure settings, its value lies in the organisational capacity to combine sensing, connectivity, data architecture, analytics, operational control and institutional decision-making. The same IoT device can generate no value when data remain isolated, modest value when used for monitoring, and substantial value when integrated with forecasting, maintenance and resource-allocation decisions. Digital capability is therefore a socio-technical configuration rather than a hardware inventory.

The reviewed studies suggest a progression from datafication to operational intelligence. The IoT and sensors monitor asset and environmental conditions. Cloud and edge infrastructures transmit and process information. AI and big-data analysis identify trends, forecast demand and failure, and enhance decision-making. Digital twins provide an evolving representation of tangible resources or systems, whereas blockchain and associated distributed technologies can enhance traceability and transaction confidence in multi-actor environments (Almulhim, 2025; Matei and Cocosatu, 2024; Lukić et al., 2025). The value of this architecture depends on its interoperability and the ability to integrate outputs into operational practices.

### 2.2 Dual Economic-Environmental Sustainability

Economic sustainability refers here to the capacity of infrastructure to deliver reliable services and long-term value within viable cost, productivity and financing conditions. It includes operating-cost reduction, avoided downtime, asset-life extension, service productivity, investment efficiency and wider economic value. Environmental sustainability includes energy and carbon performance, renewable-energy integration, resource efficiency, waste reduction, circularity and reduced ecological pressure. Treating these outcomes jointly is essential because an environmentally beneficial digital system may be financially unscalable, while a cost-saving system may shift rather than reduce environmental burdens.

The dual-outcome perspective also requires attention to timing and system boundaries. Predictive maintenance may increase short-term expenditure but it also reduces lifecycle cost and material replacement. Cloud migration may lower local energy use while increasing electricity demand elsewhere. Smart mobility may improve vehicle efficiency yet stimulate additional travel. Consequently, credible sustainability claims require total-cost-of-ownership analysis, lifecycle assessment, explicit baselines and reporting of rebound or displacement effects.

### 2.3 Governance as a Conversion Mechanism

Governance is not an external backdrop to digital infrastructure; it determines whether technical potential becomes public and environmental value. Data rules will shape access, privacy, security and accountability. Procurement may determine whether suppliers are rewarded for equipment delivery or verified outcomes. Regulation and tariffs affect investment incentives. Institutional coordination determines whether transport, energy, building and land-use decisions reinforce or undermine one another. Citizen participation affects legitimacy and the distribution of benefits.

This role is especially pronounced in emerging economies, where fiscal constraints, uneven digital access, informal service provision, rapid urban growth and overlapping authorities may change both the feasibility and consequences of digitalisation. The relevant question is therefore not whether a technology works in the abstract, but under which institutional, financial and infrastructural conditions it produces measurable, inclusive and durable economic-environmental performance.

### 2.4 Research Questions

RQ1: Which digital technologies and infrastructure domains dominate the evidence base?

RQ2: Through which operational mechanisms do digital innovation influence infrastructure performance?

RQ3: What economic and environmental outcomes are reported, and how often are they assessed jointly?

RQ4: Which governance mechanisms and implementation barriers condition the reported outcomes?

RQ5: How does the evidence from emerging economies differ from, or remain underrepresented within, the wider literature?

RQ6: Which theoretical, methodological and policy priorities should guide the next generation of research?

## 3 RESEARCH METHODOLOGY

### 3.1 Research Review Design

The study uses a systematic, matrix-based evidence-synthesis design. Reporting was structured with reference to PRISMA 2020, which specifies transparent reporting of identification, selection, synthesis and limitations in systematic reviews (Page et al., 2021), and to thematic-synthesis principles that move from descriptive coding to analytical themes (Thomas and Harden, 2008). The unit of analysis was the individual publication record.

The authors confirmed that PRISMA identification, deduplication, title-and-abstract screening and full-text eligibility assessment produced a final included set of 212 publications. The matrix supports transparent analysis of the included evidence but does not itself contain the upstream Scopus/Web of Science field codes, complete Boolean strings, duplicate-removal totals, stage-specific exclusion counts or reviewer-agreement statistics. Those items should therefore be transferred from the original review log into the final journal submission rather than reconstructed from the included set.

### 3.2 Source Pool and Eligibility Criteria

The post-screening matrix contained 212 populated records. All records had non-empty titles, outlet names, findings, research gaps and references. Normalised-title and DOI checks found no duplicate titles or duplicate DOI strings within the included set. Publication years ranged from 2021 to 2026 as shown in Table 1 below.

| Publication Years | Article Published |
|---|---|
| 2021 | 3 |
| 2022 | 7 |
| 2023 | 5 |
| 2024 | 51 |
| 2025 | 91 |
| 2026 | 55 |
| **TOTAL** | **212** |

Table 1: Publication Years ranged from 2021 to 2026

Eligibility was organised around four intersecting concept blocks:

- Digital Innovation or named Digital Technologies;
- Urban Infrastructure or an enabling infrastructure-related system;
- Economic and/or Environmental Sustainability Outcomes;
- Governance, Implementation or contextual relevance.

Direct urban applications were combined with enabling evidence from energy, logistics, industry, construction, finance, public services and digital infrastructure because these systems shape urban service delivery and implementation capacity. No study was excluded from the final synthesis on geographical grounds. Emerging-economy context was coded explicitly when the record named an emerging/developing-economy frame or an identifiable country context within that analytical category. This yielded 65 explicitly contextualised studies and 147 global, developed-economy or geographically non-specific comparators. Table 2 below show the eligibility criteria.

| ***Dimension*** | **Included** | **Excluded from focal synthesis** |
|---|---|---|
| *Phenomenon* | Digital innovation, transformation or named technology | No digital component |
| *Application* | Direct urban or infrastructure system application | Firm-level digitalisation without an infrastructure application |

| | | |
|---|---|---|
| *Outcome* | Environmental sustainability, resource/energy performance, resilience or related sustainable outcome | Purely technical performance without a sustainability connection |
| *Document type* | Journal article | Conference paper or preprint |
| *Language/data* | English-language record with complete structured extraction | Incomplete or non-English record |
| *Context* | All contexts for comparison; emerging-economy evidence coded separately | No exclusion solely by geography |

Table 2: Eligibility Criteria

**3.3 Coding Framework**

Coding was deductive and inductive. Deductive categories reflected the review questions: digital technology, infrastructure domain, operational mechanism, economic outcome, environmental outcome, governance mechanism, implementation barrier and geographical context. Inductive refinement was used when repeated concepts appeared in the findings or gaps, such as context transfer, institutional coordination, cybersecurity, legacy-system integration and lifecycle measurement. Categories were non-mutually exclusive because individual studies commonly examined multiple technologies, domains or barriers.

Dictionary-assisted coding standardised obvious terminology and reduced inconsistency across 212 records. Category assignments were then checked against titles, findings and gap narratives. Counts therefore represent the number of studies in which a category was identifiable from the structured extraction, not the frequency of individual words. Percentages are descriptive evidence-map indicators and should not be interpreted as effect sizes.

| Construct | Operational meaning | Illustrative indicators |
|---|---|---|
| Digital capability | Technology or integrated digital architecture applied to infrastructure | AI/ML; IoT; analytics; digital twin; cloud/edge; blockchain; 5G; BIM |
| Infrastructure domain | Physical or digital system delivering urban services | Energy; transport; buildings; water; waste; ICT; public services |
| Mechanism | Process through which technology changes infrastructure operation | Monitoring; prediction; optimisation; automation; coordination; lifecycle management |
| Economic outcome | Financial, operational or wider value outcome | Cost; productivity; downtime; asset life; competitiveness; investment |
| Environmental outcome | Resource or ecological performance outcome | Energy; carbon; emissions; renewables; waste; circularity |
| Governance | Institutional arrangement shaping adoption and accountability | Policy; standards; data governance; procurement; stakeholder coordination |
| Barrier | Condition constraining implementation or transferability | Cost; skills; cybersecurity; legacy assets; weak metrics; context specificity |
| Context | Geographical or institutional setting | Country; emerging/developing-economy label; global/non-specific |

Table 3: Analytical Codebook

**3.4 Synthesis and Quality Safeguard**

Analysis combined descriptive mapping with thematic synthesis. Descriptive counts established the technological, sectoral and contextual profile. Thematic synthesis then connected technologies to mechanisms, outcomes and enabling conditions. Negative and cautionary evidence - including cybersecurity, rebound effects, data quality, vendor dependence, finance and exclusion - was retained rather than treating digital adoption as a proxy for sustainability.

Four safeguards were applied to avoid overclaiming. First, all 212 author-confirmed included studies were retained and the narrower infrastructure and contextual subsets were treated as descriptive strata, not as unreported exclusions. Second, emerging-economy evidence was identified only when the record contained an explicit contextual signal rather than being inferred from a general study. Third, category counts were treated as non-exclusive evidence-map signals, not causal estimates. Fourth, the paper distinguishes study-level information available in the matrix from the authors' integrative interpretation. Because method and quality indicators were not available consistently for all records, study-level critical appraisal must be reconciled with the review team's appraisal file before submission.

## 4 FINDINGS

### 4.1 Corpus Profile

The final synthesis contains 212 included studies. The evidence is highly recent: 91 studies were published in 2025 and 55 in 2026, compared with 51 in 2024, 5 in 2023, 7 in 2022 and 3 in 2021. In total, 197 studies (92.9%) appeared during 2024-2026. This recency reflects accelerating interest but also limits longitudinal inference because many infrastructure impacts unfold over asset lifecycles far longer than the observation windows represented.

Energy and electricity systems were the most common infrastructure domain (69 studies; 32.5%), followed by transport and logistics (58; 27.4%), smart cities and urban public services (41; 19.3%), industrial infrastructure (39; 18.4%), waste and circular-resource systems (34; 16.0%), digital or ICT infrastructure (27; 12.7%), buildings and construction (20; 9.4%), and water or wastewater (9; 4.2%). Categories overlap because individual studies frequently span multiple systems. The distribution shows clustering around data-intensive and operationally observable systems, while water and integrated resource systems receive comparatively limited attention.

| Characteristic | Count | Share of included set |
|---|---|---|
| Included studies/publications | 212 | 100.0% |
| Explicit emerging-economy context | 65 | 30.7% |
| Global/non-specific comparator evidence | 147 | 69.3% |
| Explicit dual economic-environmental outcomes | 99 | 46.7% |
| Published in 2024-2026 | 197 | 92.9% |
| Broad urban-infrastructure nexus | 94 | 44.3% |
| Direct infrastructure application | 55 | 25.9% |
| Smart-city / urban-public-service domain | 41 | 19.3% |
| Energy / electricity domain | 69 | 32.5% |
| Transport / logistics domain | 58 | 27.4% |

Table 4: Profile of the final included evidence matrix

### 4.2 Technology Portfolio: Convergence rather than Substitution

AI and machine learning were identified in 84 studies (39.6%), followed by IoT and sensor systems in 64 (30.2%) and big-data or advanced analytics in 57 (26.9%). Industry 4.0/5.0 umbrella concepts appeared in 41 (19.3%), blockchain in 33 (15.6%), cloud or edge computing in 31 (14.6%), digital twins in 29 (13.7%), advanced connectivity in 28 (13.2%) and robotics or automation in 26 (12.3%). These frequencies do not imply that one technology is universally superior. Instead, the literature increasingly describes technology stacks: sensors acquire data, networks and cloud platforms move or store them, analytics generate insight, and digital twins or automated controls connect insight to physical operations.

This convergence is most visible in smart cities. Reviews describe IoT, AI and digital twins as interdependent components of urban intelligence, although they also identify inconsistencies in data exchange, protection of sensitive information, and a lack of outcome metrics (Sacoto-Cabrera et al., 2025). Integrated IoT-blockchain frameworks emphasise transparency and coordination yet large-scale validation remains limited (Almulhim, 2025). Digital-twin applications cover areas such as building safety and lifecycle management to water allocation, emergency resilience and logistics (Lauria and Azzalin, 2024; Zhao et al., 2025; Fatorachian et al., 2025c). The technological frontier is therefore architectural integration, not simply higher adoption counts.

The evidence also warns against platform-centric lock-in. Interoperability limitations can prevent cities from connecting legacy assets and departmental systems; insufficient governance can transform data integration into privacy and cybersecurity risk; and cloud or AI workloads can generate environmental burdens outside the local boundary. A sustainable technology portfolio must consequently be modular, standards-based and assessed across its full digital and physical lifecycle.

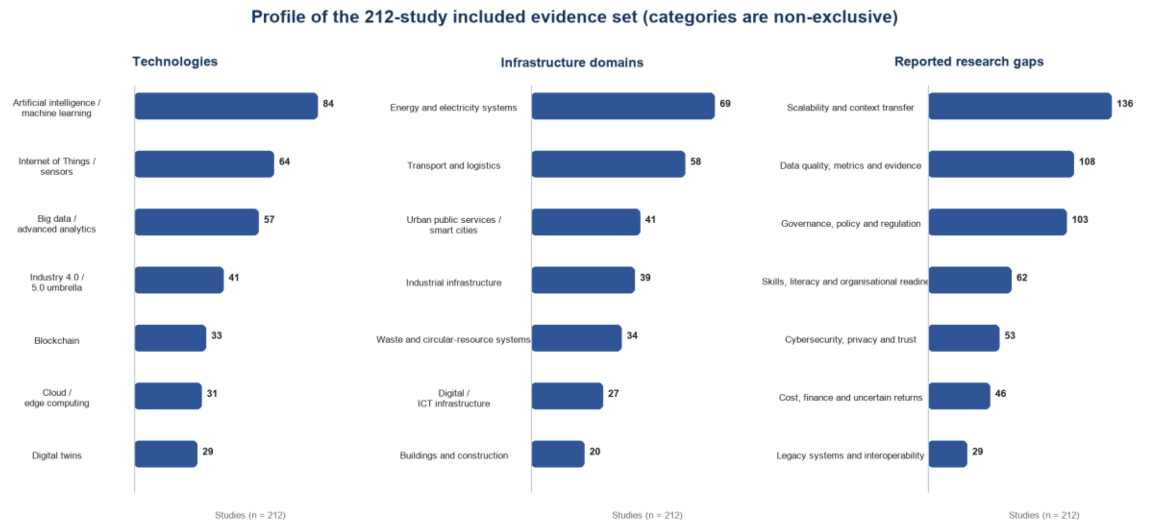


Figure 1: Technology, infrastructure-domain and implementation-barrier profile of the included evidence

### 4.3 Operational Mechanism linking Technology to Performance

Automation and process integration formed the most common mechanism, appearing in 108 studies (50.9%). Innovation and capability development appeared in 99 (46.7%), optimisation or resource allocation in 75 (35.4%), real-time monitoring and visibility in 67 (31.6%), predictive analytics or maintenance in 54 (25.5%), data-driven decision-making in 49 (23.1%), multi-actor coordination or platform effects in 46 (21.7%), and circularity or lifecycle management in 27 (12.7%). These results reveal a recurring causal chain.

The first stage is visibility. Sensors and connected platforms reduce information latency about asset condition, demand, environmental quality and resource flows. The second stage is anticipation, in which forecasting and anomaly detection support maintenance, congestion management, load balancing or risk identification. The third is optimisation, where resources, schedules and control settings are adjusted. The fourth is institutionalisation: digital recommendations become part of procurement, maintenance, planning and service-delivery routines. Economic and environmental benefits depend on completing the chain. Monitoring without decision rights, interoperable systems or implementation capacity creates dashboards rather than sustainable performance.

Infrastructure examples illustrate the chain. IoT sensors in the construction sector can identify hazards and improve equipment utilisation, but costs, integration and user adoption hinder their implementation (Anjum and Luz, 2024). Digital twins can support seismic safety and lifecycle maintenance, but their value depends on reliable data and integration with asset-management decisions (Lauria and Azzalin, 2024). Automated logistics at ports might improve environmental performance through coordinated operational decisions rather than relying on AI alone (Tsolakis et al., 2021). Energy-asset digitalisation similarly creates value through predictive maintenance, legacy-system integration and workforce capability, all of which are organisational mechanisms as much as technical ones (Erhueh et al., 2024).

### 4.4 Economic Outcomes

The economic case for digital infrastructure is organised around avoided cost and improved asset productivity. Sixty-three studies (29.7%) explicitly addressed economic efficiency or cost reduction, while 65 (30.7%) addressed innovation or competitiveness and 41 (19.3%) addressed reliability, resilience or safety with economic implications. Common benefit channels include lower energy and maintenance expenditure, reduced unplanned downtime, improved capacity utilisation, longer asset life, faster service delivery and better targeting of capital interventions.

However, cost saving is more frequently asserted than evaluated through comprehensive investment analysis. The gap coding identified cost, finance or uncertainty returns in 46 studies (21.7%). Capital requirements, specialist skills, data infrastructure, integration and ongoing software costs can be significant, especially for governments and utilities with limited financial capacity. Several studies advocate for cost-benefit analysis, sustainable financing and investment frameworks instead of only recording technical visibility (Khaleel et al., 2024; Pellegrino and Stasi, 2024). The relevant economic metric is therefore not the purchase price or short-run efficiency gain, but risk-adjusted lifecycle value including avoided failures, resilience benefits, cybersecurity costs, capability development and vendor-transition costs.

Evidence that links digital innovation to firm-level economic and environmental performance hence suggests that the two outcomes can be mutually beneficial (Ajmal et al., 2026). Yet firm-level findings cannot automatically be transferred to public infrastructure because benefits and costs accrue to different actors. A transport platform may generate social time savings while leaving the operator without a direct revenue stream; a smart grid may reduce system emissions but require tariff reform; and open urban data can create external innovation benefits that procurement models do not capture. Economic sustainability therefore requires an explicit value-allocation and financing model.

### 4.5 Environmental Outcomes and Unresolved Rebound Effects

Environmental findings concentrate on emissions or environmental performance (45 studies; 21.2%), energy efficiency or renewable integration (44; 20.8%), and resource efficiency or circularity (27; 12.7%). Smart grids, AI-enabled energy management and urban analytics can improve the match of supply and demand, integrate variable renewable generation and identify inefficient assets (Khaleel et al., 2024; Xiao et al., 2025). Transport analytics can further reduce routing inefficiency, congestion and fuel consumption, while waste management can improve inventory and material-flow coordination (Fatorachian et al., 2025a; Fatorachian et al., 2025b). Building and infrastructure digital twins can improve maintenance timing and reduce avoidable material replacement.

The evidence is less developed on net environmental impact. Digital devices, data centres and AI models consume energy and materials; device replacement contributes to electronic waste; and efficiency improvements can be offset by increased demand. Green clouding management and data-centre studies will recognise the need for energy-aware computing, but system boundaries often remain narrow (Deshmukh et al., 2025; Feng et al., 2026). Environmental claims should therefore include the footprint of digital infrastructure itself, not only savings in the managed physical system.

Furthermore, 96 studies (46.7%) explicitly brought economic and environmental outcomes together. Even within this substantial subgroup, metrics differ considerably. Carbon, energy, waste, productivity, cost and service outcomes are measured at different organisational and geographical scales. This inconsistency prevents robust comparison and makes it difficult to determine whether a digital intervention is genuinely eco-efficient, merely shifts burdens, or remains economically dependent on temporary project funding.

### 4.6 Governance Mechanisms

Public policy and regulation were identifiable in 67 studies (31.6%), data governance or cybersecurity in 53 (25.0%), standards and interoperability in 48 (22.6%), finance and procurement in 41 (19.3%), multi-stakeholder coordination in 34 (16.0%), and institutional capacity or leadership in 31 (14.6%). These patterns confirm that governance is multi-layered.

Technical governance establishes data models, interface standards, system architecture and cybersecurity controls. Organisational governance defines ownership, decision rights, skills and accountability. Inter-organisational governance coordinates utilities, municipal departments, private vendors, financiers and citizens. Policy governance aligns regulation, tariffs, procurement and environmental goals. Weakness at any layer can interrupt the mechanism from digital capability to performance.

Data governance deserves particular emphasis. Urban infrastructure data may reveal individual behaviour, critical-asset vulnerabilities or commercially sensitive operations. Cybersecurity cannot be treated as a late-stage technical add-on; it must be embedded in system architecture, procurement, workforce training and incident governance. At the same time, overly closed systems can inhibit interoperability and public-value innovation. The governance challenge is to establish proportionate access, security, accountability and portability

Procurement also shapes sustainability. Traditional technology procurement promotes the delivery of components, while sustainable infrastructure requires verified service, lifecycle and environmental outcomes. Outcome-based specifications, open standards, staged scaling, total-cost evaluation and auditable data rights can align vendor incentives with public value. Research on smart grids and emerging smart cities further indicates that financing and policy coordination must be designed together (Khaleel et al., 2024; Mallik et al., 2025).

### 4.7 Implementation Barriers

The most frequently coded implementation barrier was scalability and context transfer, found in 136 studies (64.2%). Data quality, metrics and limited evidence followed in 108 (50.9%), governance, policy and regulation in 103 (48.6%), skills and organisational readiness in 62 (29.2%), cybersecurity, privacy or trust in 53 (25.0%), cost and uncertain finance in 46 (21.7%), legacy-system interoperability in 29 (13.7%), and infrastructure or connectivity constraints in 22 (10.4%).

These barriers are interdependent. Limited finance encourages small pilots, but pilots produce weak longitudinal evidence; weak evidence makes financing more difficult. Legacy systems make integration costly; custom integration increases the reliance on vendor; reliance of vendor makes standards and exit strategies more important. Skill shortages increase dependence on consultants, but insufficient internal ownership reduces the likelihood that digital results will change operations. Cybersecurity failures can damage trust and delay adoption, although security investment further affects the business case.

The pattern explains why pilot success is not equivalent to system transformation. Scaling requires stable governance, interoperable architecture, operational ownership, recurring budgets, workforce development and measurement systems. The literature is rich in technical opportunity but thinner on the institutional work needed to maintain digital infrastructure over time. This imbalance is especially consequential in emerging economies, where externally financed pilots may not include sustainable operating models.

### 4.8 Emerging-Economy Evidence

65 of the 212 included studies (30.7%) explicitly addressed an emerging economy or developing-economy frame. Coding labels were non-exclusive: 29 studies used a general emerging/developing-economy frame, while India

appeared in 16, China in 14, Indonesia in 6 and Malaysia in 5; Saudi Arabia and other Middle Eastern contexts were much less frequent, and Africa was represented only sporadically. The broader contextual base is valuable, but its geographical concentration remains a central result and limits confident generalisation across diverse institutional, fiscal and urban conditions.

India-focused evidence highlights both application potential and constraints. Smart-home and smart-city studies describe energy and service opportunities, while research on public-service infrastructure identifies cost, digital literacy, coordination and context-specific rollout as critical (Prasad, 2025; Choudhuri et al., 2022). Chinese city-level studies provide stronger quantitative evidence that digital innovation, fintech-green-finance synergies and digital infrastructure can improve urban energy efficiency or green productivity, but also show different regional and policy effects (Xiao et al., 2025; Zhang and Sun, 2025; Liu et al., 2025). The Saudi evidence stresses strategic pathways, institutional capability and governance for advanced smart-city technologies (Bahreldin et al., 2025).

Three cross-cutting propositions emerge. First, foundational capacity matters: electricity reliability, connectivity, data quality and skilled personnel determine whether advanced applications are feasible. Second, institutions mediate technology effects: fragmented authority, procurement rigidity, unclear data ownership and weak local maintenance capacity can neutralise technical benefits. Third, distribution matters: digital systems may improve aggregate efficiency while excluding informal settlements, small firms or citizens without connectivity and digital literacy. Emerging-economy research should therefore assess service access and distributional outcomes alongside efficiency and carbon.

| Context | Dominant emphasis | Recurring gaps |
|---|---|---|
| India | Smart homes, public services, sustainable IT and smart-city missions | Digital literacy; cost; rollout coordination; service effectiveness |
| China | Urban energy efficiency, green finance and industrial upgrading | Regional heterogeneity; causal pathways; policy thresholds; current-period validation |
| Indonesia | SME digitalisation, supply-chain capability and operational sustainability | Infrastructure readiness; firm heterogeneity; finance; transfer beyond pilot samples |
| Malaysia | Digital transformation, manufacturing and sustainable performance | Capability gaps; measurement consistency; sector and city-level generalisation |
| Saudi Arabia | Advanced smart-city technologies and strategic pathways | Institutional readiness; governance; scaling and capability development |
| General emerging economies | Integrated smart-city and development frameworks | Finance; legal and regulatory change; stakeholder collaboration; transferability |
| Africa and Latin America | Sparse and fragmented coverage in the included set | Country-comparative evidence; informal systems; affordability; distributional outcomes |

Table 5: Emerging-economy evidence and recurring concerns

## 5 DISCUSSIONS

### 5.1 Digital Innovation-Infrastructure-Sustainability Framework

The synthesis supports a four-layer Digital Innovation-Infrastructure-Sustainability (DIIS) framework. The first layer comprises digital capabilities: connected sensing, data architecture, analytics, AI, digital twins, distributed trust and connectivity. The second comprises operational mechanisms: visibility, prediction, optimisation, automation, coordination and lifecycle management. The third comprises infrastructure performance: reliability, utilisation, service quality, resource productivity and adaptive capacity. The fourth contains economic and environmental outcomes. Governance and emerging-economy contingencies operate across all layers rather than as a final implementation variable.

The framework as shown in Figure 2 below clarifies that digital technologies do not directly cause sustainability. Their effects are mediated by operational and organisational change. A sensor creates information, not emissions reduction. A predictive model creates a recommendation, not maintenance performance. A digital twin creates a representation, not a capital-allocation decision. Value emerges when information is trusted, integrated into decision rights, supported by resources, and connected to measurable outcomes.

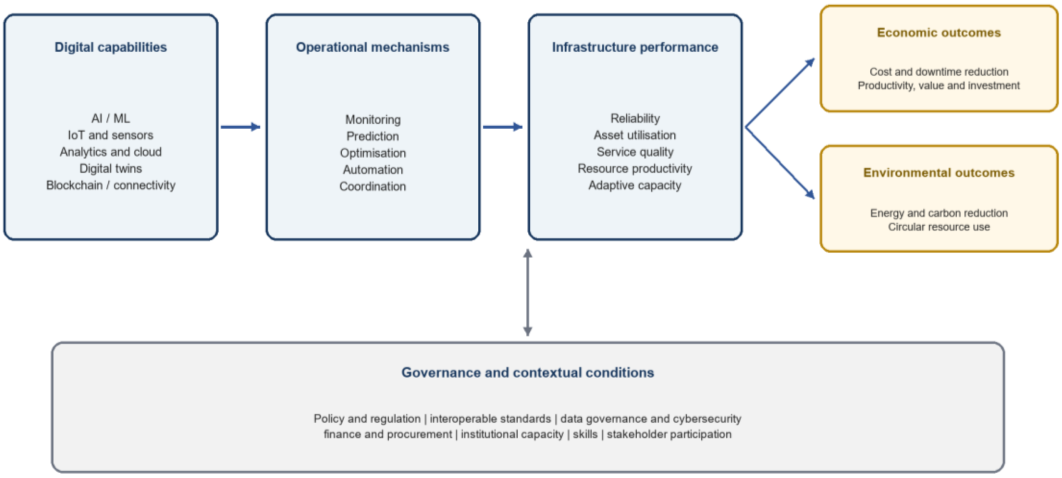


Figure 2: Digital Innovation-Infrastructure-Sustainability framework

### 5.2 Theoretical Contributions

The first theoretical contribution is mechanism specification. Much of the literature uses digital transformation as a composite antecedent. The DIIS framework decomposes this construct and specifies a sequence from technology architecture to operational mechanisms and outcomes. This permits clearer hypotheses about mediation and failure. For example, IoT adoption should improve environmental performance only when data visibility changes optimisation or maintenance decisions.

The second contribution is outcome complementarity with constraints. Economic and environmental outcomes can be mutually reinforcing when both arise from reduced waste, energy, failure and idle capacity. Complementarity is not guaranteed when digital operating costs are high, environmental burdens are displaced, or benefits accrue to actors who do not finance the system. The relevant theoretical construct is therefore governed complementarity: the alignment of incentives, system boundaries and measurement that allows dual value to persist.

The third contribution is contextual contingency. Institutional capacity, standards, finance, connectivity, skills and legitimacy moderate every stage of the pathway. Emerging economies should not be represented as a homogeneous moderator. Different combinations of fiscal space, urban form, energy mix, governance structure and digital capability generate distinct adoption configurations. Configuration-based and comparative institutional approaches may therefore explain more than single-variable models.

The fourth contribution is a shift from adoption to institutionalisation. Adoption measures whether technology is present; institutionalisation measures whether it is integrated into budgets, roles, routines, standards, maintenance and accountability. The recurrent evidence gaps indicate that sustainable performance depends more on the latter.

### 5.3 Interpreting the Economic-Environmental Relationship

The review indicates three possible relationships between economic and environmental outcomes. In a synergy configuration, reduced energy, waste and downtime simultaneously lower cost and environmental pressure. In a sequencing configuration, environmental benefits require upfront investment and appear only after capability development or asset renewal. In a tension configuration, digitalisation improves operational or commercial performance while increasing energy demand, electronic waste, surveillance risk or inequality.

This typology helps reconcile apparently inconsistent findings. Studies that use short observation windows may record investment cost without later savings. Studies with narrow boundaries may count local energy savings but omit cloud-computing emissions. Studies focused on operators may miss user or citywide benefits. Future research should therefore report the outcome configuration, time horizon, system boundary and distribution of value.

### 5.4 Why Emerging Economies require a Distinct Analytical Lens

Emerging economies are not merely lower-resource versions of developed contexts. Rapid growth, informal systems and infrastructure deficits can increase the marginal value of digital coordination, but they also make implementation more sensitive to institutional and distributional conditions. Digital systems can enable leapfrogging where legacy assets are limited, yet imported platforms may create dependence when local maintenance, data governance and procurement capability are weak.

A sequencing principle follows. Foundational reliability and data governance should precede highly complex optimisation. Interoperable sensor and asset registries may create more durable value than high-profile AI pilots when data quality is low. Pilot selection should prioritise problems with clear service baselines, operational ownership and measurable dual outcomes. Scaling should be conditional on verified performance, cybersecurity readiness, financing for recurrent costs and transferability across neighbourhoods or agencies.

### 5.5 Research Agenda

The next generation of research should move beyond technology inventories and cross-sectional adoption models. Priority is given to designs that identify mechanisms, measure net outcomes, explain contextual heterogeneity and support decision-making under real implementation constraints.

| Theme | Priority question | Recommended design |
|---|---|---|
| Causal mechanisms | Which operational changes mediate the effect of each technology on cost, carbon and service outcomes? | Panel studies; event studies; quasi-experiments; mediation analysis |
| Lifecycle dual performance | When do environmental benefits exceed the digital system's own lifecycle footprint and total cost? | Integrated lifecycle assessment and total-cost-of-ownership models |
| Long-term institutionalization | Which pilots remain operational and valuable five or more years after implementation? | Longitudinal case studies; asset-level performance tracking |
| Governance configurations | Which combinations of standards, data governance, procurement and institutional capacity enable scaling? | Comparative institutional analysis; qualitative comparative analysis |
| Emerging-economy heterogeneity | How do fiscal space, informality, energy mix, urban form and digital access change outcomes? | Multi-country comparative designs; multilevel models |

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|---|---|---|
| Equity and inclusion | Who gains, who pays and who is excluded from digital infrastructure services? | Distributional impact assessment; participatory and spatial analysis |
| Cyber-resilience | How do security controls affect reliability, trust, cost and interoperability? | Cyber-resilience maturity models; incident and stress-test evidence |
| Rebound and displacement | Do efficiency gains increase demand or shift emissions, waste and risk across boundaries? | System dynamics; consumption-based carbon accounting; scenario analysis |
| Finance and value allocation | Which revenue, tariff and blended-finance models align beneficiaries with cost bearers? | Real-options analysis; public-value and financing case studies |
| Cross-system integration | When does integration across energy, transport, buildings, water and waste create net value? | Urban digital twins; systems modelling; controlled implementation pilots |

Table 6 Priority Research Agenda

## 6 IMPLICATIONS

### 6.1 Implications for Urban Governments and Regulators

Urban governments should begin with service and sustainability outcomes rather than a list of technologies. Each proposed investment should specify the problem, baseline, operational mechanism, beneficiary, cost bearer, environmental boundary and decision that will change. Technology-neutral procurement can then require open interfaces, data portability, cybersecurity-by-design, lifecycle support and independently auditable performance.

Governments should establish a minimum urban digital-infrastructure governance stack: asset and data standards; role-based access and privacy rules; cybersecurity requirements; procurement and vendor-exit provisions; outcome definitions; and a cross-agency decision forum. Regulatory sandboxes can be useful where existing rules block experimentation, but they should include evaluation and transition criteria rather than becoming permanent exemptions.

Distributional safeguards are essential. Impact assessment should examine affordability, accessibility, coverage, displacement, surveillance exposure and the participation of informal or underserved communities. Public legitimacy is a performance condition because infrastructure technologies depend on data sharing, behavioural response and long-term institutional support.

### 6.2 Implications for Infrastructure Owners and Operators

Operators should develop digital capability as a portfolio. Priority investments are those that connect reliable data to high-value operational decisions, such as critical-asset maintenance, energy dispatch, leakage control, routing or safety. Architecture should be modular and interoperable, with clear ownership of data quality and model performance. Workforce development should combine technical training with process redesign and decision accountability.

Business cases should use total cost of ownership and lifecycle value. They should include integration, cybersecurity, connectivity, data management, model monitoring, retraining, vendor transition and decommissioning, as well as expected savings. Environmental assessment should include the digital system's own energy and material footprint. Benefits should be tracked against a pre-specified counterfactual and reported long enough to distinguish learning effects from sustained performance.

### 6.3 Implications for Investors and Development Partners

Financiers should avoid funding isolated demonstrations without recurrent-cost and institutionalisation plans. Stage-gated finance can link disbursement to data quality, interoperability, capability transfer and verified economic-environmental milestones. Blended finance may be justified where public environmental or resilience benefits are not captured by operator revenues, but subsidy design should make the value gap explicit.

Development partners can reduce fragmentation by funding shared standards, local technical capability, open reference architectures and cross-city learning. Evaluation requirements should favour comparable measures while allowing context-specific outcomes. Project documentation should include failure and adaptation, not only successful implementation narratives.

## 7 CONCLUSION

Digital innovation can support sustainable urban infrastructure by making assets visible, anticipating failure and demand, optimising resources, automating control and coordinating decisions across organisations. The evidence is strongest for IoT, AI, analytics and integrated digital architectures in smart-city, energy, transport and building applications. Economic and environmental benefits are most likely to align when digitalisation reduces energy, waste, downtime and underutilised capacity.

Yet the review's central conclusion is conditional: digitalisation is not intrinsically sustainable. Context transfer, governance, weak metrics, cybersecurity, finance, skills and interoperability repeatedly interrupt the pathway from technology to value. Emerging economies face additional constraints but may also capture large benefits where digital systems improve scarce-resource allocation and enable infrastructure leapfrogging.

Across the 212 included studies, the DIIS framework locates governance at the centre of this relationship. Sustainable outcomes require interoperable standards, accountable data practices, institutional capacity, lifecycle cost and carbon measurement, locally viable finance, and inclusive service design. Research and policy should therefore move from asking which technology to adopt toward asking which governed configuration produces verified, durable and equitably distributed economic-environmental performance.

### 7.1 Limitation

This review has important limitations. First, the present analysis begins from the authors' finalized 212-study included-set matrix rather than raw Scopus and Web of Science exports. The workbook does not preserve original search dates, database field codes, full Boolean strings, deduplication counts, stage-specific exclusion reasons or reviewer-agreement statistics. These elements should be transferred from the original PRISMA review log and archived with the submission; if that log is incomplete, the searches must be rerun reproducibly.

Secondly, the matrix contains structured summaries rather than attached full texts. The synthesis can reliably analyse the supplied findings and gaps, but it cannot independently verify every statistical estimate, method, sampling decision or interpretation. Full-text eligibility and data extraction should be independently checked by at least two reviewers, with disagreements resolved and reported.

Thirdly, outlet indexing and peer-review status were not verified record by record. Automated metadata checks indicate that the author-confirmed included set contains 198 records presented as journal outlets, nine conference-proceedings records and five records marked as preprints. All 212 were retained because the authors identified them as the finalized PRISMA set; nevertheless, document type, peer-review status and current Scopus indexing should be verified against the stated protocol before submission.

Next, coding is non-exclusive and dictionary-assisted. Counts describe the structure of the extracted evidence and are not affect sizes. A second-reviewer coding check and an article-level critical-appraisal instrument appropriate to mixed evidence should be completed or reconciled with the review team's existing appraisal file.

Lastly, the evidence base is temporally concentrated and geographically uneven. Sixty-five studies explicitly concern emerging-economy settings, but country-specific evidence is concentrated in India and China. Conclusions for Africa, Latin America, smaller states and lower-income urban systems remain provisional. Finally, the review does not conduct meta-analysis because outcome constructs, measures, study designs and units of analysis are too heterogeneous.

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