

ANALYZING THE CAPABILITIES OF FRUGAL DIGITAL TWINS FOR SUSTAINABLE SMART CITY INFRASTRUCTURE DEVELOPMENT IN AFRICA: AN ESGS PERSPECTIVE FROM GHANA

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ABSTRACT

Digital twins, virtual replicas that mirror physical infrastructure through real-time data, have emerged as a pivotal technology for smart city development globally. However, their deployment in developing countries remains constrained by high costs, limited digital infrastructure, and insufficient local expertise. This paper analyses the capabilities of frugal digital twins as enablers of sustainable smart city infrastructure development in Africa, with Ghana as a case study. Grounded in the Environmental, Social, Governance, and Sustainability (ESGS) framework, the study examines how cost-effective digital twin solutions can be embedded within Africa's built environment to support climate-resilient infrastructure design, predictive urban management, and circular economy strategies. Adopting a mixed-methods approach that integrates a systematic literature review with stakeholder analysis, the research evaluates the technical functionality, scalability, and ESGS alignment of digital twin applications in resource-constrained urban settings. Results indicate that frugal digital twinning can enhance operational efficiency in waste management, environmental monitoring, and infrastructure maintenance while reducing implementation barriers through open-source platforms and low-cost IoT sensors. The study further identifies digital twin technology as a viable tool for training and capacity building among built-environment professionals. The study contributes to the growing discourse on integrating ESGS

principles into Africa's infrastructure planning and offers a replicable model for leveraging digital twin technology across developing nations.

Keywords: Frugal Digital Twinning, Smart Cities, ESGs, Built Environment, Developing Countries, Ghana, Digital Twin Training

Introduction

It is not until very recently that the concept of a Digital Twin (DT) came to the fore and gained momentum in the urban context within developing countries. This is owing to its innovative potential to transform how the physical systems of smart cities can be managed and planned to improve their environmental performance. A DT can be defined as a virtual representation of a physical system and its associated environment and processes, updated through the exchange of information between the physical and virtual systems (VanDerHorn & Mahadevan, 2021). The recent expansion of the Urban Digital Twin (UDT) concept is attributed to knowledge gained from the development of smart cities globally (Ferré-Bigorra et al., 2022; Weil et al., 2023). UDTs are being deployed in smart cities worldwide and becoming rich sources of information on physical urban systems (Ruohomäki et al., 2018), pertaining to power grids, energy demand, mobility, public transportation, water supply, waste management, and climatology (Ferré-Bigorra et al., 2022; Schrotter & Hürzeler, 2020). However, deploying these technologies in developing countries remains fraught with infrastructural, economic, and technical constraints (Graham, 2020; Teye et al., 2022). This research addresses this gap by exploring the potential of frugal digital twinning, a cost-effective adaptation of digital twins for resource-limited environments. The study focuses on Ghana as a case study, with the research objective of analysing the capabilities of digital twins in smart city development within developing countries, viewed through the Environmental, Social, Governance, and Sustainability (ESGS) framework. Frugality in digital technology does not imply austerity alone; it denotes the strategic design and deployment of systems that maximise functionality per unit resource, foster local innovation, and ensure resilience against systemic shocks (Radjou et al., 2012; Bound & Thornton, 2012).

One widely accepted interpretation of a smart city pertains to innovation, focusing not exclusively on information and communication technology (ICT) but also on improving aspects of urban life, including governance, transportation, economy, environment, and quality of life (Anthopoulos et al., 2015). As a working definition, a sustainable smart city is one that uses ICT and other means to improve quality of life, efficiency of urban operations and services, and competitiveness while ensuring it meets the needs of present and future generations with respect to economic, social, and environmental aspects (ITU, 2016; Bibri et al., 2023). With urban areas in Ghana facing rapid growth, there is an urgent need to improve infrastructure and services efficiently. Digital twinning, if adapted to the needs and limitations of developing regions, can facilitate enhanced decision-making and real-time problem-solving (Deren et al., 2021; Canorea, 2023; Dani et al., 2023).

The co-generative relationship between infrastructure, information, and data is not a recent phenomenon; for thousands of years, cities have been made of information, data collecting and processing (Mattern, 2017). What is new is the intensity, speed, scale, and automation of the ways in which digital data transforms infrastructural processes. Traditional smart city approaches, dependent on advanced technology and extensive data infrastructure, are often unsustainable in resource-limited

environments (Tavmen, 2020; Kunkel & Tyfield, 2021). The development of UDT is still in its incipient stages, and the area of UDT is still in its infancy research, fragmented along disciplinary lines (Weil et al., 2023). Despite the recent increase of research on UDTs, there still is a paucity of knowledge when it comes to their adaptation for developing country contexts.

To fill this gap, this study provides a systematic literature review combined with stakeholder analysis on the capabilities of frugal digital twins in the context of sustainable smart cities in Africa. To the best of our knowledge, no review study has systematically synthesised the existing work on the capabilities, challenges, and ESGS alignment of frugal digital twinning for smart city development in the Global South. It is timely to investigate these capabilities to inform scholars, practitioners, and policymakers so that they can work collectively toward deploying frugal digital twins for sustainable urban development.

2. Research Methodology

To answer our research question investigating the capabilities of frugal digital twins for sustainable smart city infrastructure development in Africa, we conducted a mixed-methods study integrating a systematic literature review with a stakeholder survey.

2.1 Articles Identification Criteria

A systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach (Moher et al., 2010). The research criteria was based on the following keyword strings across three databases:

("Digitalization" OR "Intelligent Cities" OR "Digital Cities") AND ("Digital Twin" OR "Digital Twinning" OR "Digital Twining Technology") AND ("Frugality" OR "Frugal Digital Twinning") AND ("Smart Cities" OR "City Digital Twin") AND ("Developing Countries" OR "City Users")

A time constraint further refined the search to papers published between 2000 and 2025 to capture both foundational and contemporary knowledge. The systematic review traced the keywords "Digitalization", "Digital Twinning", "Frugality", "Smart Cities", and "Developing Countries".

2.2 Literature Platform Selection

Three major databases were utilised: Scopus, Science Direct, and Google Scholar. Scopus was selected for its wide inclusion of peer-reviewed scientific articles and advanced searching options. Science Direct was selected for full-text access to peer-reviewed articles, enhancing the transparency and reliability of the review. Google Scholar was selected for its largest coverage of published literature, including grey articles and other resources. Scopus and Science Direct results were exported via the Export function in RIS format, while Google Scholar results were exported with the Cite function in Endnote format. All results were imported into Endnote software and grouped by database. Table 1 presents the identification search results.

Table 1. Literature Identification Search Results

Database	Search Feature / Keywords	Results
Scopus	Advanced Search; Documents; All Fields; 2000–2025	679
Science Direct	Advanced Search; Articles; All Fields; 2000–2025	2,998

Google Scholar	Advanced Search; Articles; 2000–2025	249
Total	Combined initial results	3,926

Source: Author's Construct, 2025

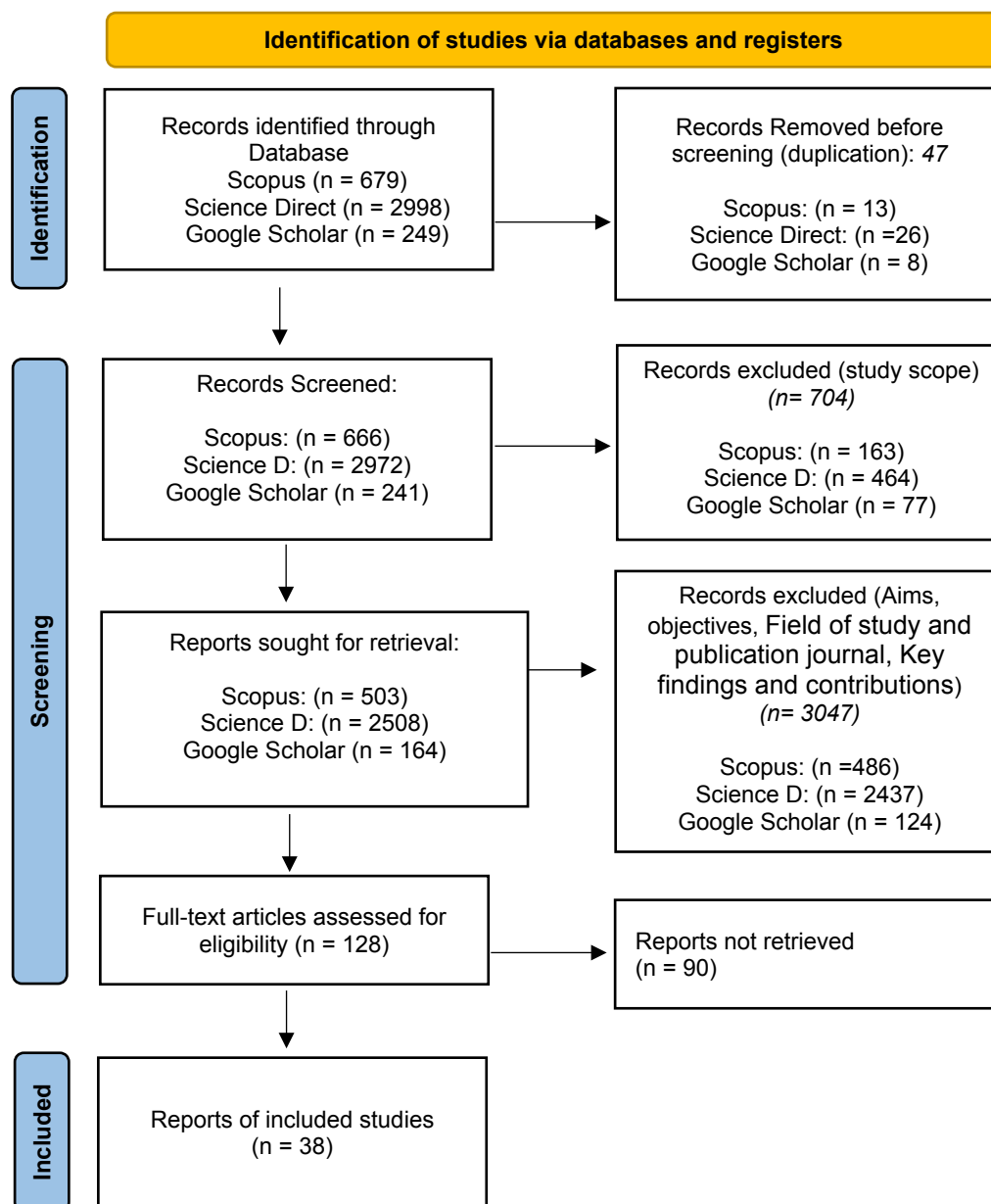


Figure 1: PRISMA protocol for the study
Source: Author's Construct

2.2.1 Screening and Eligibility Criteria

With the identification criteria applied, 3,926 records were identified. Following the PRISMA methodology, the screening and eligibility steps consisted of removing duplicates and articles that did not meet the scope, aims, field-of-study, or key-findings criteria. Table 2 presents the screening results.

Table 2. Literature Screening Results

Screening Criteria	Excluded	Remaining
Duplications	47	3,879
Study scope	704	3,175
Aim and objectives	1,115	2,060
Field of study and publication journal	923	1,137
Key findings and contributions	1,009	128
Final included studies (after eligibility)	—	38

Source: *Author's Construct, 2025*

2.3 Stakeholder Survey and Grouping of Findings

To complement the literature review, primary data was collected through a structured survey distributed to 58 professionals across Ghana. A Sequential Transformative Design was used, allowing the theoretical perspective of the researcher to guide the study and determine the order of data collection. The results from both methods are integrated during the interpretation phase. The sample comprised 24 architects, 12 urban planners, 8 civil engineers, 8 municipal officials, 3 academic researchers, 1 electrical engineer, 1 community leader, and 1 software engineer. Among respondents, 53% held master's degrees, 43% held bachelor's degrees, and 3% held doctoral degrees. Geographically, 58% of respondents were located in Accra and 42% in Kumasi. Findings are reported in four sections: (1) capabilities of digital twins in smart city development; (2) readiness and adaptability of Ghana's infrastructure; (3) urban health applications of frugal digital twinning; and (4) implementation framework and stakeholder engagement.

3. Results

In this section, we present and narrate the findings from both the systematic literature review and the stakeholder survey, organised thematically. The literature findings establish the conceptual and empirical foundations, while the survey data provides contextual validation from the Ghanaian setting.

3.1 Digitalization: Foundations and Urban Implications

Digitalization refers to the widespread integration of digital technologies into social, economic, and urban systems, reshaping how services are delivered, decisions are made, and institutions interact with citizens (Mohammadrezaei et al., 2024). The literature distinguishes between digitization (converting analogue data to digital), digitalization (integrating digital tools into processes), and digital transformation (systemic reinvention through digital means) (Gartner, 2021). Tools such as Geographic Information Systems (GIS), Internet of Things (IoT) sensors, and remote sensing technologies enable the collection and analysis of spatial and temporal data on phenomena from traffic congestion to energy consumption (Batty, 2018; Kitchin, 2014). Central to the smart city discourse is the conceptualisation of urban space as a cyber-physical system, where physical infrastructure, digital networks, and institutional processes operate as an interconnected system (Albino et al., 2015; Graham & Marvin, 2021). However, the adoption of these systems in resource-constrained geographies is hindered by infrastructural limitations, financial constraints, and concerns about technological sovereignty (Mohammadrezaei et al., 2024; Weil et al., 2023).

and virtual space enabling bidirectional mapping and interaction (Dani et al., 2023). However, the development of UDTs is still in its incipient stages, with challenges related to interoperability, data quality, modelling complexity, and governance being the most frequently cited in the literature (Weil et al., 2023; Lei et al., 2023).

3.3 Frugal Digital Twinning: Conceptual Framework

Applying frugal principles to digital twinning involves utilising low-cost sensors and open-source software, phased modular deployment, leveraging local data sources and community-generated data, and encouraging partnerships with universities, NGOs, and private sector actors (Bound & Thornton, 2012; Canorea, 2023). As indicated in figure 3, strategies include selective twin deployment prioritising high-impact assets such as water infrastructure and waste systems, contextual model calibration using local environmental data, participatory design engaging end-users, and open data standards avoiding proprietary lock-in (Radjou et al., 2012; Kunkel & Tyfield, 2021). Emerging evidence suggests that frugal deployments, although limited in scope, offer incremental bridges towards full-fledged smart city capabilities (Mohammadrezaei et al., 2024). Pilot programmes in waste management, flood monitoring, and health surveillance showcase feasibility in Sub-Saharan African settings (Canorea, 2023; Macaulay et al., 2019).

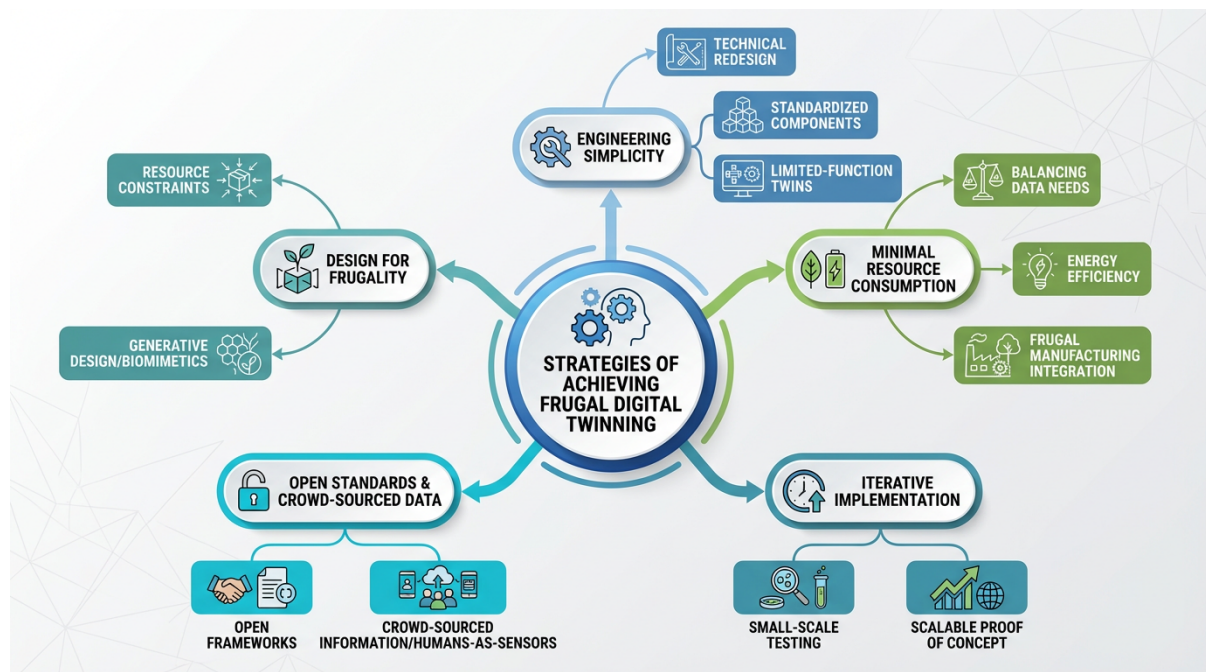


Figure 3: Frugal digital twinning strategies

Source: Author's construct, 2026

3.4 The ESGS Framework and Sustainable Infrastructure

The ESGS framework provides a structured lens for evaluating frugal digital twin deployments. The environmental dimension concerns climate-resilient infrastructure, energy efficiency, and pollution monitoring, areas where digital twins demonstrate strong capabilities through simulation and scenario planning (Hilty & Aebischer, 2015; Yigitcanlar et al., 2019). The social dimension encompasses equity, citizen engagement, and inclusive service delivery, aligning with frugal principles of community participation (Bibri & Krogstie, 2017; Allam & Dhunny, 2019). The governance dimension addresses data sovereignty, institutional collaboration, and

regulatory frameworks thus critical concerns where digital policies may lag behind technological adoption (Mohammadrezaei et al., 2024; Velikzhanin et al., 2022; Weil et al., 2023). The sustainability dimension integrates long-term viability, scalability, and alignment with SDGs 9, 11, and 13 (Sachs et al., 2019; Kunkel & Tyfield, 2021).

3.5 Digital Twin Technology for Training and Capacity Building

An emerging and increasingly recognised capability of digital twin technology lies in its application for training and capacity building within built-environment professions. Digital twins provide immersive, data-rich virtual environments as shown in figure 4, enabling architects, urban planners, engineers, and municipal officials to develop competencies in urban systems management without risks or costs of physical experimentation (Sepasgozar, 2020; Jiang et al., 2021). This is particularly relevant given that 13% of UDT studies identify skills and workforce shortages as a major concern (Weil et al., 2023), and that qualified human resources for digital twin projects remain rare in the construction and infrastructure industries (Gürdür Broo et al., 2022).

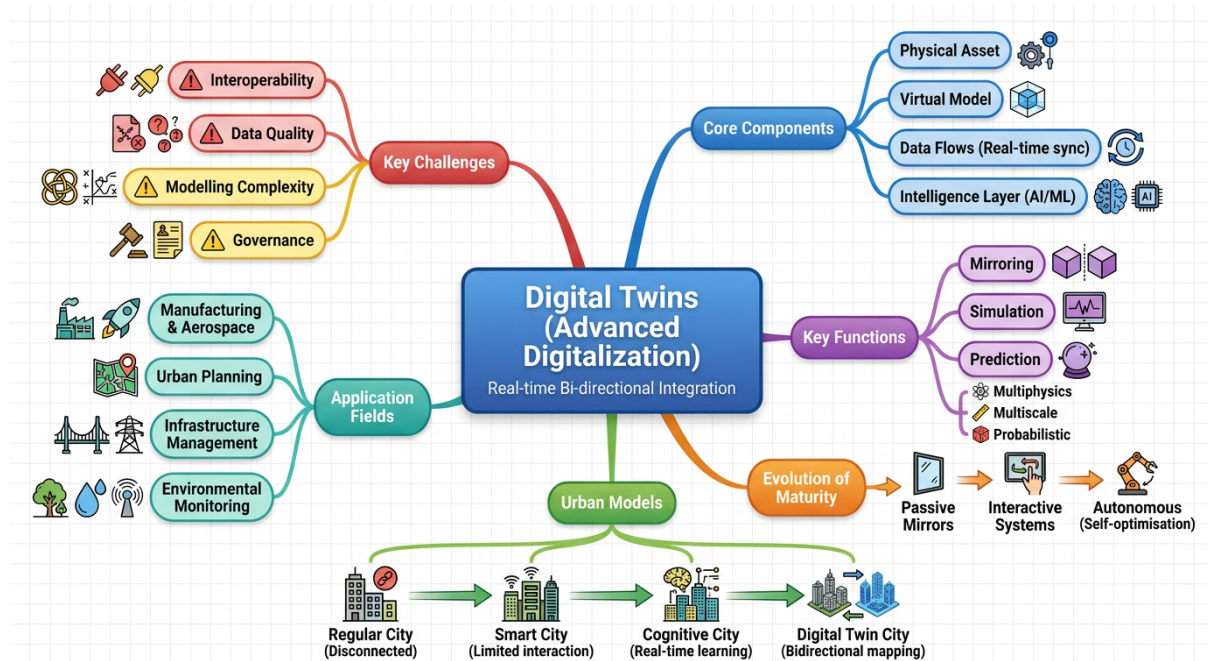


Figure 4: Digital twinning mind mapping

Source: Author's construct, 2026

In developing country contexts, frugal digital twin models built on open-source platforms can democratise access to training environments previously reserved for well-resourced institutions (Opoku et al., 2021; Fuller et al., 2020). A simplified digital twin of a waste management network or drainage system can serve as a training simulator for municipal planners. Jiang et al. (2021) demonstrated how digital twin-enabled learning environments enhance spatial reasoning and systems-thinking skills. Sepasgozar (2020) argued that integrating digital twin concepts into curricula bridges the gap between theoretical knowledge and practical competence. Lu et al. (2020) emphasised the potential for continuous professional development through evolving urban models. From an ESGs perspective, this training dimension contributes to the social pillar (equitable professional development), governance pillar (institutional

capacity for data-driven decision-making), and sustainability pillar (long-term human capital development) (Aghimien et al., 2020).

3.6 Smart Cities: Models and Urban Futures

Smart cities have evolved from early ICT-enablement experiments to integrated models focusing on sustainability, citizen-centricity, and adaptive learning (Caragliu et al., 2011; Angelidou, 2015). Classifications include technological smart cities, citizen-centric smart cities, and sustainable smart cities (Albino et al., 2015; Trindade et al., 2017). Key functions include mobility, utilities, health, and safety (Bibri & Krogstie, 2017; Ebadi & Sahafizadeh, 2023). Digital twins act as integrators situated at the intersection of physical assets, data platforms, and policy-making (Shahat et al., 2021; Dani et al., 2023). Smart city development underpinned by digital twins can foster urban resilience by enabling scenario planning and rapid response to shocks like capacities especially valued in developing contexts susceptible to climate extremes (Deren et al., 2021; Weil et al., 2023).

3.7 The Case of Ghana: Urbanisation and Digital Readiness

Ghana exemplifies the complex urban transition in developing countries, with a population exceeding 33 million, growing at over 2% annually (Ghana Statistical Service, 2022). Key urban centres face exponential growth outpacing local government capacities (Yeboah, 2003; Owusu & Afutu-Kotey, 2010). The Government has outlined a Smart Cities agenda including the National Digital Property Addressing System, e-governance portals, and GIS-based utility mapping (Ministry of Communications, 2020), but implementation is hampered by resource constraints and fragmented regulatory frameworks (Agyeman, 2020; Gyamfi et al., 2021). Ghana's legal framework includes the Data Protection Act (2012), Cyber Security Act (2020), and the National Digital Policy and Strategy (2020–2025), yet digital literacy remains a persistent challenge (Buabeng-Andoh, 2012; Asante & Opoku, 2021).

3.8 Stakeholder Survey Findings

3.8.1 Perceived Capabilities of Digital Twins

Of 58 respondents, 72% confirmed familiarity with digital twin technology. Waste management was identified as the urban system most likely to benefit (45 responses, 20%), followed by traffic and transport (44 responses, 19%), flood and disaster prediction (40, 17%), urban health monitoring (37, 16%), housing (32, 14%), and energy/water distribution (31, 14%). DTT was rated as having “very high” potential by 40% of respondents, with community participation identified as the most critical feature for successful deployment (24%).

Table 3. Urban Systems Perceived to Benefit Most from Digital Twinning (n=58)

Urban System	Responses	Percentage
Waste management	45	20%
Traffic and transport management	44	19%
Flood and disaster risk prediction	40	17%
Urban health monitoring	37	16%

Housing and infrastructure development	32	14%
Energy/water resource distribution	31	14%

Source: Author Field Survey, 2025

3.8.2 Infrastructure Readiness and Barriers

Regarding digital infrastructure readiness, 41% rated Ghana as “somewhat ready”, 29% as “very ready”, 28% as “not ready”, and 2% as “not sure”. Low digital literacy (42 responses, 20%) and high cost of advanced technology (41, 20%) emerged as the most critical challenges, followed by weak institutional collaboration (38, 18%), lack of awareness (36, 17%), limited internet access (30, 14%), and inconsistent data standards (23, 11%). A notable 64% affirmed that existing municipal digital platforms could be leveraged for digital twin initiation. The transport sector was rated most ready for digital transformation (34%).

3.8.3 Urban Health Applications

A strong majority (81%) affirmed the feasibility of digital twin implementation for urban health. Mapping healthcare access gaps was the highest-rated health application (25%), followed by real-time air quality monitoring (21%), managing urban sanitation (21%), predicting disease outbreaks (21%), and supporting maternal health programmes (11%). Community surveys (23%), mobile phone data (22%), and satellite imagery (21%) were identified as the most practical data sources for health-focused digital twins.

3.8.4 Implementation Framework and Stakeholder Engagement

National government was ranked as the most appropriate lead stakeholder, followed by municipal assemblies and universities. A centralised governance model received the highest endorsement (34%), followed by decentralised city-level leadership (29%) and public-private partnerships (28%). Most significantly, 74% rated community participation as “very important” in the design of digital twin systems.

4. Discussion

As this study indicates, frugal digital twins possess significant capabilities for advancing sustainable smart city development in Africa, provided implementation is context-sensitive, participatory, and aligned with the ESGs framework. This section analyses and interprets the results in relation to previous work, examines implications for urban management, and proposes future research directions.

4.1 Analysis and Interpretation of Results in Relation to Previous Work

The findings empirically validate several theoretical propositions. Professional familiarity with digital twin technology, whilst growing, remains uneven across Ghana’s urban centres, reflecting observations by Bound and Thornton (2012) that digital twinning applications in the Ghanaian context remain limited by knowledge diffusion and digital literacy. However, among those with familiarity, there is strong consensus on the potential of digital twins to enhance real-time monitoring, urban analytics, and predictive modelling, confirming that digital twins are not merely technological novelties but tools for addressing core urban inefficiencies when implemented frugally (Batty, 2018; Canorea, 2023).

The infrastructure readiness assessment reveals cautious optimism about Ghana's adaptability alongside recognition of significant barriers. This is consistent with the findings of Weil et al. (2023), who identified eight categories of challenges for UDT implementation, with interoperability, data quality, and modelling being most frequently cited. In the Ghanaian context, the prominence of low digital literacy and high technology costs as barriers mirrors the global pattern where technical challenges tend to overshadow social and legal issues (Lei et al., 2023). The identification of existing digital platforms (by 64% of respondents) as potential leverage points suggests a latent institutional readiness that could be unlocked through targeted investment, echoing Bibri and Krogstie (2017).

4.2 Implications for Urban Management and Planning

The strong endorsement of waste management (20%) and transport (19%) as the urban systems most likely to benefit from digital twinning has direct implications for urban management priorities. These align with Ghana's most pressing urban challenges like waste overflow and traffic congestion are daily realities in Accra and Kumasi (Amoako & Frimpong Boamah, 2017; Yigitcanlar et al., 2019). From an ESGs environmental perspective, deploying frugal digital twins for waste management and transport monitoring represents a high-impact, low-barrier entry point for sustainable smart city development.

The urban health findings expand the scope of digital twin utility beyond traditional infrastructure management. The identification of mobile data, community surveys, and satellite imagery as viable inputs for health-focused digital twins corroborates the frugal innovation paradigm of using locally available, low-cost data sources to generate actionable intelligence (Kunkel & Tyfield, 2021; Canorea, 2023). This aligns with the ESGs social pillar and contributes directly to SDGs 3 and 11.

4.3 The Training Dimension: Bridging the Capacity Gap

A critical finding of this study is the identification of digital twin technology as a viable tool for training and capacity building. The emphasis on low digital literacy (20%) as the leading barrier to implementation directly connects to the need for digital twin-based training programmes. Weil et al. (2023) similarly found that 13% of UDT studies cite skills and workforce shortages as a major concern, with researchers deploring the lack of professional community and training resources. For Africa's built-environment sector, investing in frugal digital twin-based training represents a strategic pathway to developing local expertise necessary for independent smart city implementation, reducing dependence on external consultants and proprietary systems (Sepasgozar, 2020; Aghimien et al., 2020). From an ESGs governance perspective, building institutional capacity for data-driven decision-making through training is essential for sustainable adoption.

4.4 Suggestions for Future Research

In the realm of sustainable smart cities in the Global South, there is a unique window of opportunity to advance frugal digital twinning. This requires strategic focus on addressing existing gaps, including the following. First, there is a need for longitudinal case studies of frugal digital twin pilot projects in African cities, documenting implementation processes, challenges, and outcomes over time. Second, cost-benefit analyses specific to developing country contexts would provide empirical evidence for the effectiveness and financial viability of frugal digital twin solutions compared to conventional urban management approaches. Third, the effectiveness of digital twin-

based training programmes for built-environment professionals in Africa deserves rigorous evaluation, including assessments of knowledge transfer, practical skill development, and institutional capacity outcomes. Fourth, holistic approaches to frugal digital twinning that simulate the environmental, social, and economic processes of sustainable smart cities and their functions would benefit from broader research on data privacy, sovereignty, inclusivity, transparency, and fairness within the ESG framework. Fifth, research should explore how frugal digital twins can be integrated with emerging AIoT technologies to enhance environmental performance in resource-constrained settings, building on the convergence identified by Bibri et al. (2023) and Weil et al. (2023).

5. Conclusion

Typical to new technologies, as there are new opportunities to embrace and unlock, there are new challenges to address and overcome. This paper analysed the capabilities of frugal digital twins for sustainable smart city infrastructure development in Africa, using Ghana as a case study and applying the ESG framework as an evaluative lens. The systematic literature review of 38 included studies, combined with a stakeholder survey of 58 professionals, revealed significant capabilities across multiple domains.

Key capabilities identified include the ability to optimise waste management and transport systems, support real-time environmental monitoring, enhance urban health surveillance, facilitate data-driven decision-making at municipal level, and serve as a platform for training and capacity building among built-environment professionals. All these capabilities, when viewed through the ESG framework, contribute to environmental sustainability, social equity, institutional governance, and long-term scalability.

However, the study also identifies significant barriers: low digital literacy, high technology costs, weak institutional collaboration, and inconsistent data standards. These findings, consistent with the eight categories of UDT challenges identified by Weil et al. (2023) in the global context, are compounded in the Ghanaian setting by uneven ICT infrastructure distribution and limited regulatory frameworks.

The study concludes that frugal digital twinning is not merely a technological adaptation but a strategic enabler for sustainable, inclusive, and resilient city-making in developing countries. The emphasis on community participation (identified by 74% of respondents as very important), the endorsement of open-source and affordable technologies, and the recognition of existing municipal digital platforms as leverage points collectively suggest that Ghana, and by extension other developing nations, possesses latent readiness for frugal digital twin adoption that can be activated through targeted investment, multi-stakeholder collaboration, and capacity building.

We hope our findings serve to inform practitioners about the capabilities and bottlenecks relevant to frugal digital twin implementation in the Global South and that this work will stimulate further debate and prospective research on devising innovative, context-sensitive approaches to digital twin deployment for sustainable African smart cities.

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