Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: https://www.science-gate.com/IJAAS.html

AI-enabled circular economy framework for quantum-smart cities: Strategic pathways for Saudi Arabia's Vision 2030

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ARTICLE INFO

Article history:
Received 18 December 2025
Received in revised form
16 June 2026
Accepted 4 July 2026

Keywords:
Circular economy
Smart cities
Artificial intelligence
Internet of Things
Quantum computing

ABSTRACT

The shift from linear "take–make–dispose" models to regenerative Circular Economy (CE) systems is important for sustainable urban development. Artificial Intelligence (AI) and the Internet of Things (IoT) are widely recognized as key technologies for supporting CE in smart cities; however, few frameworks combine these technologies with emerging quantum computing capabilities. This study proposes a multi-layered, AI-enabled CE framework for quantum-smart cities in the context of Saudi Arabia's Vision 2030. A multiphase methodology is applied, including a systematic literature review, benchmarking of global CE initiatives, and adaptation to Saudi urban conditions. The proposed framework includes six functional layers, ranging from data collection to citizen engagement. The findings show that interoperability standards, ESG dashboards, and gradual integration of quantum technologies can improve predictive maintenance, resource efficiency, and citizen participation. Unlike existing CE models that treat digital technologies separately, this study introduces an integrated and quantum-ready architecture capable of addressing complex optimization problems in large-scale urban systems. By linking CE domains to Vision 2030 Key Performance Indicators (KPIs) in major projects such as NEOM and Riyadh Sustainability Strategy, the framework provides policymakers with a clear roadmap for embedding CE principles into the national innovation system. It also offers practical guidance for cross-sector implementation, governance alignment, and long-term scalability, while highlighting future research directions in quantum optimization and citizen-centered innovation.

1. Introduction

The Circular Economy (CE) represents a paradigmatic shift from the linear "take–make–dispose" industrial model to regenerative systems that prioritize the retention of material and product value through reuse, repair, and high-quality recycling (Geissdoerfer et al., 2017). As global urbanization accelerates, metropolitan centers face mounting pressure to decouple economic growth from resource consumption and environmental impact (Bibri et al., 2023). Digital technologies are increasingly recognized as central enablers of this transition, offering the capabilities to optimize complex resource flows, predict systemic inefficiencies, and enable adaptive urban planning. Specifically, Artificial Intelligence (AI), the Internet of Things (IoT), and emerging Quantum Computing (QC) are poised to provide the transformative analytical power required for truly regenerative urban systems (Ramadoss et al., 2018; Sacco et al., 2023). This convergence marks a critical evolution in CE research, shifting the discourse from isolated digital interventions to integrated, multi-layered smart city architecture.

Recent systematic literature reviews confirm that IoT-enabled decision support systems (DSS) are instrumental in operationalizing CE principles. These systems demonstrate improved economic efficiency through reduced operational expenses, predictive maintenance, and material optimization, while simultaneously advancing environmental sustainability via the real-time monitoring of emissions, smart water reuse, and enhanced energy efficiency (Bibri et al., 2023; Ramadoss et al., 2018). These findings underscore the dual economic and ecological value of digital enablers for CE

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deployment. Nevertheless, current implementations are still mainly sector-specific and lack the systemic integration needed to facilitate megacity-scale CE transformations.

Saudi Arabia's Vision 2030 initiative provides a strategic framework for embedding these advanced technologies. The Kingdom is making substantial investments in next-generation urban infrastructure, with flagship projects such as NEOM, the Riyadh Sustainability Strategy, and the Red Sea Development serving as modular testbeds for global innovation in sustainable digital transformation (Alyami, 2025; Yigitcanlar et al., 2019). These projects are also directly aligned with the Saudi Green Initiative and the National Data and AI Strategy (SDAIA), ensuring that CE adoption is embedded in broader national sustainability and digital governance agendas (Sacco et al., 2023). This alignment positions Saudi Arabia as one of the few nations capable of deploying CE frameworks on an unprecedented scale, supported by strong political will, financial capacity, and a rapidly evolving digital ecosystem that supports CE implementation.

However, the rapid deployment of technology must be reconciled with local conditions. Ethnographic studies of Saudi cities reveal nuanced challenges, including infrastructure gaps, resource strain, and the imperative for precise governance. While public willingness to embrace green practices is strong, successful adoption necessitates not only technological innovation but also robust, citizen-centric policy scaffolding and engagement mechanisms that embed CE principles into everyday urban life (Alyami, 2025). This highlights the need for CE frameworks that integrate behavioral, cultural, and governance dimensions as well as technical components.

Despite growing academic and practical interest in the convergence of AI, IoT, and CE, the existing literature remains fragmented across siloed disciplines, such as operations management, industrial ecology, and information systems (Bibri et al., 2023; Sacco et al., 2023). This fragmentation leads to two critical deficiencies: First, the lack of holistic frameworks that integrate governance and citizen engagement; and second, the failure to address the exponential computational complexity (NP-hard optimization barrier) faced by classical systems attempting to manage dynamic resource flows at the megacity scale. These gaps underscore the need for a unified, quantum-ready CE architecture capable of supporting real-time cross-sectoral decision-making.

Critically, few comprehensive frameworks rigorously integrate next-generation smart computing technologies, especially quantum readiness, within national innovation ecosystems to define the architecture of a "quantum-smart city." Furthermore, existing research lacks longitudinal studies assessing CE performance over time, stakeholder-inclusive approaches incorporating citizen perception and governance dynamics (Alyami, 2025), exploration of non-industrial applications such as healthcare, education, and tourism (Sacco et al., 2023), and defined interoperability standards to ensure seamless integration across diverse data systems. Global policy frameworks, such as the EU Circular Economy Action Plan and the UN Sustainable Development Goals, further highlight the urgency of overcoming these deficiencies, positioning Saudi Arabia's Vision 2030 as a unique opportunity to lead quantum-enabled CE innovations. To date, no study has proposed a CE framework that simultaneously integrates AI, IoT, digital twins, blockchain, and phased quantum computing into a policy-aligned national transformation agenda.

This study addresses these critical gaps by proposing a modular, scalable, and policy-aligned framework tailored to Saudi Arabia's strategic priorities and urban transformation agendas. The core contributions of this study are as follows: First, it introduces a multilayered architectural framework for the AI-enabled circular economy in quantum smart cities, systematically integrating AI, IoT, digital twins, blockchain, and phased quantum computing capabilities across core CE domains. Second, it provides a multi-dimensional strategic roadmap by conducting a comparative benchmarking of global CE pilots and explicitly mapping the six-layer architecture to Saudi Arabia's Vision 2030 pillars, specific deployment zones, and Key Performance Indicators (KPIs). Third, it bridges conceptual models with practical deployment by defining governance and citizen engagement mechanisms necessary to ensure institutional readiness and behavioral adoption, providing a complete, end-to-end blueprint for policymakers. Collectively, these contributions establish a novel theoretical and practical foundation for quantum-smart CE systems, advancing both academic discourse and national policy implementation.

2. Literature review

A robust and rigorous foundation is essential for any advanced framework. This section systematically reviews convergent academic literature across three core domains: the evolution and operationalization of the Circular Economy (CE), the role of digital transformation, specifically AI and IoT, in enabling CE, and the emerging relevance of quantum computing for urban sustainability. It concludes with a comparative benchmarking of international smart city pilots to contextualize global best practices. Together, these strands establish a conceptual and technological basis for the proposed quantum-smart CE architecture.

2.1. The circular economy: From concept to practice

CE is a multidisciplinary concept defined by three primary objectives: Designing waste and pollution, maintaining products and materials for use, and regenerating natural systems (MacArthur, 2013).

This model, which contrasts sharply with the dominant linear paradigm, has evolved through several iterations. Early approaches emphasized industrial ecology and cradle-to-cradle design (Braungart and McDonough, 2019), whereas contemporary definitions highlight systemic change and business model innovation, encapsulated by the 'R' principle of reduce, reuse, recycle, repair, refurbish, and remanufacture (Geissdoerfer et al., 2017; Reike et al., 2018).

Scholarly work increasingly addresses the challenges of CE transition, noting barriers such as technological complexity, regulatory fragmentation, market acceptance, and the need for significant supply chain reconfiguration (Kusi-Sarpong et al., 2019). In urban environments, operationalizing the CE requires sophisticated, interconnected systems capable of managing decentralized material flows and effectively monitoring product lifecycles. These insights underscore the necessity of embedding CE principles into smart city infrastructure. Recent studies also emphasize the importance of embedding CE principles into national innovation strategies, linking CE adoption to broader sustainability agendas, such as the EU Circular Economy Action Plan and the UN Sustainable Development Goals. Despite this progress, CE implementation remains uneven globally, with limited integration of digital governance, citizen engagement, and cross-sectoral data interoperability; these gaps are particularly pronounced in rapidly urbanizing regions.

This subsection highlights that while CE principles are conceptually mature, their operationalization in smart cities remains fragmented, requiring integrated digital and governance frameworks to overcome the systemic barriers to their implementation. This fragmentation provides a compelling rationale for developing multi-layered CE architectures capable of supporting real-time, data-driven decision-making across diverse urban domains.

2.2. Digital transformation and circular economy enablers

The digital revolution, driven by Artificial Intelligence (AI), the Internet of Things (IoT), and blockchain, provides the infrastructure required for CE operationalization, particularly in smart city contexts. These technologies enable real-time monitoring, predictive analytics, and adaptive governance, thereby closing resource loops and enhancing sustainability outcomes. Thus, digital transformation acts as the connective tissue linking CE theory to its practical implementation.

2.2.1. The Internet of Things (IoT) and data acquisition

IoT devices form the foundational Data Acquisition Layer for CE by providing real-time data on resource consumption, waste generation, asset utilization, and product condition (Mahmud, 2025). Applications include smart waste management, where sensor data optimizes collection routes and sorting to reduce energy consumption and increase recycling rates (Ramadoss et al., 2018). The IoT also supports predictive maintenance by monitoring asset health to extend product lifespans and shift business models from product sales to performance-as-a-service. Additionally, the IoT enables resource monitoring through real-time tracking of water and energy flows, helping to identify and mitigate leakage and inefficiencies. This subsection shows that IoT provides essential sensing capabilities but requires advanced analytics and governance integration to translate raw data into a systemic CE value. Without such integration, IoT deployments risk becoming isolated data silos rather than enablers of circular transformations.

2.2.2. Artificial intelligence (AI) and decision support systems (DSS)

AI functions as an analytical layer that transforms raw IoT data into actionable intelligence. AI algorithms underpin IoT-enabled DSS that drive CE performance (Yigitcanlar et al., 2019). Machine learning models can solve complex optimization problems, such as material matching for remanufacturing, logistics routing, and dynamic pricing for secondary materials. AI also powers digital twin simulations and virtual replicas of urban systems that allow scenario planning, product redesign for circularity, and infrastructure management without real-world risk (Bibri et al., 2023). Furthermore, AI supports predictive policy design by forecasting the environmental and economic impacts of interventions, thereby enabling urban planners to dynamically adjust regulations to achieve sustainability targets. Recent frameworks also highlight the role of AI in ESG compliance dashboards, enabling transparent monitoring of sustainability metrics across sectors. This subsection emphasizes that AI enables predictive and adaptive CE governance; however, current models remain limited without quantum-level optimization for complex urban systems. As urban systems scale, classical AI increasingly struggles with NP-hard optimization challenges, reinforcing the need for quantum-ready analytics.

2.2.3. The emergence of quantum computing in sustainable systems

Although AI and IoT provide near-term solutions, quantum computing is the next frontier for CE optimization. Quantum technologies offer the potential to solve computational problems, such as materials science optimization, financial modelling for resource scarcity, and large-scale logistical scheduling, which remain intractable for classical systems (Yigitcanlar et al., 2019). Quantum annealing and quantum machine learning are particularly relevant, enabling precise, high-speed calculations of complex material mixing ratios in sustainable construction or dynamic routing of resources across vast smart city networks (Hernandez et al., 2025). The introduction of quantum capabilities signals a shift toward "quantum-smart cities," where decisions are based on globally optimal solutions rather than locally optimized approximations. This capability is essential for managing the complexity of fully interconnected, resource-aware urban CE systems (Alyami, 2025). Recent contributions further demonstrate how quantum algorithms can accelerate CE applications in energy optimization, logistics, and multi-actor governance, underscoring the urgency of preparing Saudi cities for quantum readiness. Despite this potential, quantum integration remains largely absent from CE frameworks, representing a major theoretical and practical gap that is directly addressed in this study.

This subsection identifies quantum computing as a critical enabler for overcoming NP-hard optimization barriers; however, current CE frameworks lack the integration of quantum readiness into national innovation strategies. By embedding quantum-ready components into the CE architecture, this study advances the field toward next-generation circular urban systems. In practical CE applications, quantum optimization can be implemented using algorithms such as the Quantum Approximate Optimization Algorithm (QAOA) for routing and scheduling, and the Variational Quantum Eigensolver (VQE) for materials science optimization. Current hardware limitations—including qubit decoherence, gate-depth constraints, and noise sensitivity—necessitate hybrid quantum–classical architectures, where quantum subroutines solve NP-hard subproblems while classical systems manage large-scale orchestration.

2.2.4. Comparative benchmarking and policy alignment

Benchmarking international smart city pilots is critical for translating theory into practice. Amsterdam exemplifies a policy-driven approach, emphasizing governance frameworks and citizen buy-in to reduce virgin resource consumption. Singapore represents a technology-driven model, focusing on smart grid infrastructure, integrated utility management, and digital identity systems (Pappas et al., 2018). Tokyo and Seoul have successfully integrated smart mobility with CE principles, particularly waste reduction and efficient logistics.

These global case studies highlight that successful CE transitions require a blend of technology, policy and stakeholder engagement (Sacco et al., 2023). For Saudi Arabia, any framework aligned with Vision 2030 must therefore be highly policy-responsive, technologically advanced, and citizen-centric (Alyami, 2025). NEOM and the Riyadh Sustainability Strategy can serve as living laboratories for adapting global best practices, ensuring that Saudi pilots are benchmarked against international leaders while remaining tailored to local governance and cultural contexts. This synthesis of global benchmarking and national priorities provides a foundation for the proposed AI-enabled CE framework. Importantly, benchmarking also reveals the limitations of global pilots, such as fragmented KPIs, limited interoperability, and insufficient quantum readiness, which indicates the need for a more integrated, future-proof architecture.

This subsection underscores that while global pilots provide valuable lessons, Saudi Arabia requires a uniquely tailored framework that integrates benchmarking insights with Vision 2030 priorities and citizen engagement. By aligning global best practices with national transformation agendas, this study ensured contextual relevance and international comparability.

3. Methodology

The research design adopted a rigorous multi-phase methodology combining conceptual development with contextual adaptation, structured into three distinct phases to ensure that the proposed framework is both theoretically sound and policy-aligned with Saudi Arabia's Vision 2030. Phase I established foundational requirements and identified gaps through a systematic literature synthesis. In Phase II, global best practices were extracted through a comparative case analysis of smart city pilots. Phase III synthesizes these findings into a six-layer architectural framework and checks its applicability through strategic alignment and scenario development (Sacco et al., 2023; Yigitcanlar et al., 2019). This structured, sequential approach ensured methodological transparency, triangulation of insights, and strong alignment between the research questions, analytical procedures, and final framework design.

Fig. 1 illustrates the methodological flow, showing the progression from Phase I (Systematic Literature Synthesis) to Phase II (Comparative Case Analysis), and Phase III (Framework Conceptualization). This visual roadmap enhances clarity for reviewers and demonstrates the logical sequence of the research activities. Fig. 1 also highlights the iterative feedback loops between phases, reflecting the adaptive refinement process used to ensure contextual relevance to Saudi Arabia's urban transformation agenda.

3.1. Phase I: Systematic literature synthesis (SLS)

The initial phase established the theoretical foundation through a Systematic Literature Synthesis (SLS). The primary objective was to map the state-of-the-art digital technologies enabling the Circular Economy (CE) and identify existing conceptual gaps concerning quantum computing integration and national policy alignment. The search focused on peer-reviewed articles published between 2018 and the present in Scopus, Web of Science, and Google Scholar. The core Boolean search string targeted the convergence of (Circular Economy OR Urban Metabolism) AND (AI OR Digital Twin OR IoT OR Blockchain) AND (Quantum Computing). The final refined corpus was subjected to thematic analysis across three clusters (CE Transition Models, Digital Enablers, and Quantum Computing for Sustainability), which produced a functional requirement matrix and identified the need for a holistic, policy-aligned architectural design (Bibri et al., 2023; Montanaro, 2016; Ramadoss et al., 2018). This phase concludes with the identification of the absence of integrated quantum-ready CE frameworks, establishing the foundation for Phase II benchmarking. Inclusion and exclusion criteria were applied to ensure relevance, focusing on studies with explicit CE operationalization, digital integration or quantum applicability. This strengthened the reliability and replicability of our literature review.

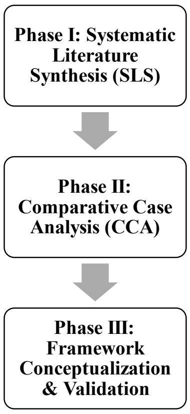

Fig. 1: Overall methodology

3.2. Phase II: Comparative case analysis (CCA)

The comparative case analysis (CCA) examined six leading global smart city initiatives–Amsterdam, Singapore, Tokyo, Seoul, Dublin, and Barcelona–through purposive sampling and cross-case synthesis. This phase benchmarks global best practices, focusing on key variables such as existing CE performance indicators, the integration of real-time AI/IoT decision-making, interoperability standards, governance models, and citizen engagement strategies. The findings informed the development of the framework's deployment pathways and ensured that global best practices were rigorously adapted to the contextual demands of the Saudi urban environment (Geissdoerfer et al., 2017; Pappas et al., 2018; Yadav et al., 2020). This phase highlights both transferable lessons and limitations of global pilots, ensuring that Saudi adaptation is context-sensitive rather than purely imitative. These cities were selected based on their diverse CE maturity, technological sophistication, and governance models, which enabled a comprehensive understanding of global CE implementation pathways. To enhance analytical rigor, a structured coding scheme was applied to extract patterns across cases, including governance mechanisms, technological enablers, and Key Performance Indicator (KPI) frameworks. This systematic comparison ensured that the resulting framework reflected both global best practices and region-specific requirements.

3.3. Phase III: Framework conceptualization

The final phase involved synthesizing the findings into a six-layer architectural framework (Data Acquisition, Processing, AI Analytics, Integration, Governance, and User Interface). CE domains, such as smart waste management, circular supply chains, and water reuse, were embedded for holistic coverage. A phased quantum integration roadmap was developed, encompassing near-term quantum-inspired algorithms and long-term deployment of Quantum Machine Learning (QML) (Montanaro, 2016; Sacco et al., 2023). This phase also detailed a multi-actor ecosystem to ensure collaborative governance, citizen inclusivity via gamified applications, and private sector engagement (Alyami, 2025). This structured validation process demonstrates methodological rigor and provides transparency for reviewers assessing the framework's credibility. Expert consultations included practitioners from digital governance, CE policy, and smart city planning, ensuring that the framework aligned with real-world implementation constraints and opportunities.

Scenario-based validation using digital twin concepts allowed the testing of hypothetical CE interventions (e.g., waste-to-resource routing and water reuse optimization), demonstrating the operational feasibility of the framework and highlighting areas that require further empirical refinement.

3.4. Limitations and evaluation

It is important to note that this study relies primarily on secondary data and conceptual modelling, which limits immediate empirical validation. Performance was evaluated using multidimensional indicators, including the Circularity Index, carbon reduction metrics, citizen engagement KPIs, and economic efficiency indicators. Pilot deployment in Saudi smart city zones, as identified in the strategic roadmap, remains a research priority for the future. Future empirical validation will require longitudinal data collection, citizen surveys, and real-time monitoring of CE KPIs to strengthen the practical applicability of the framework (Sacco et al., 2023; Yadav et al., 2020). In addition, the integration of quantum-ready components remains contingent on global advancements in quantum hardware and algorithmic scalability. These limitations do not diminish the conceptual contribution but indicate the importance of phased and adaptive implementation strategies in future studies. Although the framework is conceptually robust, the study does not include empirical testing or pilot deployment. To address this limitation, future research will implement the framework in selected Vision 2030 zones—particularly NEOM and Riyadh—using longitudinal CE performance indicators, citizen engagement metrics, and real-time operational data. This empirical phase will enable quantitative validation of the framework's predictive accuracy, operational feasibility, and cross-sectoral impact.

4. Results

The results section presents a comprehensive synthesis of the study's analytical outputs, demonstrating how global benchmarking, national policy alignment, and multi-layered technological integration converge to form the proposed AI-enabled Circular Economy Framework for Quantum-Smart Cities. It begins by contextualizing Saudi Arabia's Vision 2030 megaprojects as living laboratories for CE innovation, followed by a comparative assessment of international smart city pilot projects to extract the best transferable practices. This section details the strategic alignment between the six-layer CE architecture and Vision 2030 pillars, highlighting how each technological layer supports measurable sustainability outcomes across key deployment zones, such as NEOM, Riyadh, and the Red Sea. The subsequent subsections elaborate on policy integration, technological readiness, citizen engagement mechanisms, and private sector participation, collectively demonstrating the framework's operational feasibility and national relevance. Together, these results validate the framework's capacity to drive systemic, data-driven circular transformation at the megacity scale.

4.1. Case study: Saudi Arabia's urban innovation agenda

Saudi Arabia's urban innovation agenda, anchored in the transformative Vision 2030 program, presents unique and fertile ground for the accelerated deployment of AI-enabled circular economy models. The Kingdom's substantial investments in flagship megaprojects, such as NEOM, the Riyadh Sustainability Strategy, and the Red Sea Development, exemplify its commitment to advanced smart infrastructure and comprehensive environmental stewardship. These projects are designed as modular testbeds for digital innovation, providing an ideal environment for the large-scale, integrated deployment of the proposed quantum-smart CE architecture.

They also serve as living laboratories for testing interoperability standards, ESG dashboards, and citizen engagement platforms, ensuring that Saudi pilots are benchmarked against global leaders while remaining tailored to local governance and cultural contexts. This strategic approach allows Saudi Arabia to implement circular economy principles on a larger scale than most other countries, supported by consistent policies and rapid digital changes.

4.2. Comparative benchmarking of global CE pilots

The comparative analysis of global quantum smart-city pilots, as detailed in Table 1, highlights diverse yet effective approaches to integrating AI and advanced smart computing technologies within the operational CE framework. Cities such as Amsterdam (MacArthur, 2013; Reike et al., 2018), Singapore (Ramadoss et al., 2018), Dublin (Pappas et al., 2018; Yadav et al., 2020), and Tokyo (Kusi-Sarpong et al., 2019), Seoul (Lee et al., 2003), and Barcelona (Cavallo, 2022) demonstrate how digital infrastructure, ranging from IoT and blockchain to quantum simulation, can be strategically deployed to address complex urban sustainability challenges.

These global pilots offer critical lessons for Saudi Arabia. By adapting proven technologies and governance models, such as integrated Decision Support Systems (DSS) for citizen engagement and resource tracking, to local contexts, Saudi cities can significantly accelerate their transition toward regenerative, data-driven urban ecosystems. Benchmarking also reveals persistent gaps in global CE pilots, including fragmented KPIs, limited interoperability, and insufficient quantum readiness, which the proposed framework directly addresses. These descriptive insights establish the empirical foundation for the framework; the broader implications and strategic interpretation of these findings are examined in the Discussion section.

4.3. Strategic framework alignment with Vision 2030

This section summarizes the strategic alignment between the six-layer CE architecture and Vision 2030 pillars, building on the detailed architectural description provided in Section 5.1. The proposed AI-driven circular economy framework offers a strategic and integrated pathway for operationalizing sustainability in urban systems. As shown in Table 2, each pillar of Vision 2030 has a corresponding technological and governance component within the framework to ensure strategic synergy.

Fig. 2 shows that the thriving economy pillar is supported by AI-based lifecycle analytics, which improve productivity and resource efficiency in important industries. The An Ambitious Nation pillar is strengthened through digital twin systems and ESG dashboards that support better planning and data-driven decision-making. In addition, the framework supports the National Industrial Strategy by using blockchain for traceability in circular supply chains.

It also aligns with the National Data and AI Strategy (SDAIA) by promoting ethical AI use and data sharing. Overall, the framework is technically reliable, aligned with national policies, and helps monitor progress toward the sustainability goals of Saudi Vision 2030 through measurable KPIs.

Table 1: Comparison of global quantum-smart city pilots

City	Technologies deployed	CE focus areas	Outcomes achieved	Saudi relevance	DSS integration	Limitations	KPI/Outcome metrics	Source
Amsterdam	AI IoT Blockchain Digital twins	Circular construction Smart waste	50% waste diversion Material passports	Model for NEOM's construction strategy	DSS dashboards for material tracking	Relies heavily on EU regulatory frameworks Scalability limited outside EU context	Percentage of construction waste diverted Number of material passports issued	MacArthur (2013) and Reike et al. (2018)
Singapore	AI Edge computing Autonomous systems	Water reuse E-waste Logistics	NEWater reuse >40% e-waste traceability	Red Sea Project's water reuse	DSS for predictive water treatment	Centralized governance may limit citizen participation High infrastructure costs	Percentage of reclaimed water Percentage of e-waste recycled	Ramadoss et al. (2018)
Dublin	AI Open data Citizen dashboards	Smart mobility Reuse platforms	20% modal shift Reuse marketplaces	Riyadh's mobility and reuse	DSS for citizen engagement	Limited scalability of reuse marketplaces Dependency on citizen engagement	Percentage of modal shift Citizen participation rate	Pappas et al. (2018) and Yadav et al. (2020)
Tokyo	Robotics Quantum simulation IoT	Energy optimization Recycling	15% energy savings AI-driven recycling	Quantum-ready energy grid modelling	DSS for energy forecasting	High deployment cost of robotics Quantum simulation still experimental	Percentage of energy savings Percentage of recycling efficiency	Kusi-Sarpong et al. (2019)
Seoul	AI IoT Industrial symbiosis	Smart mobility Industrial reuse	Integrated logistics hubs Reduced congestion	Riyadh's transport and industrial zones	DSS for logistics optimization	Data silos and interoperability challenges across industrial zones	Percentage of congestion reduction Percentage of industrial reuse efficiency	Lee et al. (2003)
Barcelona	AI IoT Citizen dashboards	Urban reuse Participatory governance	High citizen engagement Reuse platforms	Najran and Riyadh citizen dashboards	DSS for behavioral analytics	Fragmented KPI tracking Governance complexity in participatory models	Citizen engagement rate Percentage of reuse adoption	Cavallo (2022)

Table 2: Alignment of framework components with Vision 2030 pillars

Vision 2030 pillar	Framework component	Strategic fit	Implementation readiness	Stakeholder involvement	Circular economy relevance	Time horizon	Environmental impact	Risk factors
A thriving economy	AI-driven lifecycle analytics	Enhances productivity and resource efficiency across all sectors, promoting economic diversification	Pilot-ready in NEOM and Riyadh	Government (Ministry of Economy) Private sector Industry consortia	Supports material recovery Waste diversion Resource efficiency across industrial sectors	Medium-term (5–10 years)	Reduced landfill waste Improved resource efficiency	Interoperability gaps Resistance from legacy industries
An ambitious nation	Governance and digital twin systems	Supports data-driven policy, rigorous performance monitoring, and ESG compliance	Conceptual and pilot stages in megaprojects	Regulators (SDAIA, ministries) Academia, policy think-tanks	Enables systemic monitoring of CE loops and policy enforcement for regenerative practices	Short-term (2–5 years)	Improved ESG compliance Transparent governance	Regulatory inertia Institutional readiness challenges
A vibrant society	Smart tourism and citizen engagement	Promotes sustainable lifestyles, community participation, and well-being	Early pilot stage in Riyadh and the Red Sea	Citizens, municipalities Tourism authorities	Drives behavioral adoption of CE practices through citizen participation and lifestyle change	Short-term (2–5 years)	Increased citizen participation Reduced consumption footprint	Digital literacy gaps Citizen trust issues
National industrial strategy	Circular supply chains and blockchain	Enables sustainable manufacturing, material reuse, and export competitiveness	Pilot stage in industrial zones	Industry Trade bodies Ministry of Industry	Facilitates closed-loop manufacturing Material reuse Industrial symbiosis for CE adoption	Medium-term (5–10 years)	Reduced industrial waste Improved export competitiveness	Cybersecurity risks Blockchain scalability challenges
National data and AI strategy (SDAIA)	Ethical AI and data governance	Ensures responsible innovation, data interoperability, and system-wide trust	Conceptual stage, SDAIA initiatives	SDAIA Regulators Data governance councils	Provides trusted data infrastructure for CE tracking Interoperability Ethical AI deployment	Long-term (10+ years)	Enhanced data trust Reduced systemic inefficiencies	Data privacy concerns Cybersecurity vulnerabilities

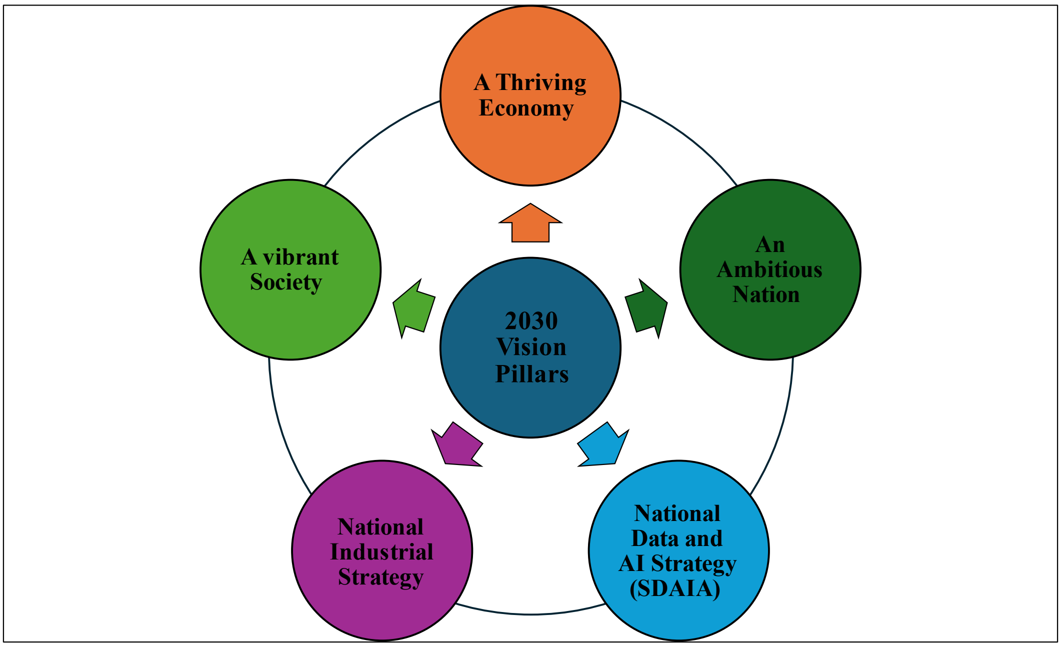

Fig. 2: Saudi Arabia's Vision 2030 pillars and circular economy domains

4.4. Policy integration

The proposed framework aligns directly with the Vision 2030 pillars of a Vibrant Society, Thriving Economy, and Ambitious Nation, embedding CE principles into national innovation ecosystems. By mapping CE domains, such as smart waste, water reuse, and circular supply chains, against Vision 2030 Key Performance Indicators (KPIs), the framework ensures a measurable impact on sustainability, economic diversification, and citizen well-being (Alyami, 2025). Governance mechanisms are reinforced through interoperability standards and ESG dashboards, enabling transparent monitoring of CE adoption across megaprojects such as NEOM and the Riyadh Sustainability Strategy (Sacco et al., 2023). This policy integration ensures that CE deployment is not only technologically feasible but also institutionally anchored and accountable.

4.5. Technological integration

The six-layer architecture integrates IoT for data acquisition, AI for analytics, and digital twins for scenario testing, ensuring that CE deployment is technologically robust and scalable. Blockchain traceability enhances supply chain transparency, whereas phased quantum integration provides computational power for complex optimization tasks, such as logistics routing and resource allocation (Bibri et al., 2023; Montanaro, 2016; Ramadoss et al., 2018). This technological roadmap positions Saudi Arabia as a global leader in quantum-enabled CE transitions, bridging near-term AI/IoT capabilities with long-term quantum readiness (Sacco et al., 2023). The layered design also ensures modularity, allowing cities with varying digital maturity levels to adopt this framework.

4.6. Citizen engagement

Vision 2030 emphasizes citizen participation in sustainability initiatives in Saudi Arabia. The framework embeds gamified mobile applications, dashboards, and reuse marketplaces to foster behavioral adoption of CE practices. Evidence from Barcelona and Dublin demonstrates that participatory governance and citizen dashboards significantly increase recycling rates and reduce virgin resource consumption (Sacco et al., 2023; Yadav et al., 2020). By adapting these models to the Saudi cultural context, the framework ensures inclusivity and long-term behavioral changes (Alyami, 2025). This citizen-centric approach strengthens social acceptance, a critical factor for CE adoption in culturally diverse urban environments.

4.7. Private sector and global benchmarking

The framework coincides with the Vision 2030 objective to diversify the economy by including the private sector in circular economy ideas. Insights from Amsterdam's material passports, Singapore's smart grid, and Seoul's industrial symbiosis demonstrate that public-private partnerships expedite the adoption of circular economy practices (Geissdoerfer et al., 2017; Kusi-Sarpong et al., 2019; Pappas et al., 2018). Saudi Arabia's megaprojects may utilize these ideas to attract investment, promote entrepreneurship, and develop worldwide leadership in circular economy innovation. This multi-actor alignment guarantees that circular economy implementation is economically feasible, technologically sophisticated, and socially inclusive. The insights from the Results section provide the empirical and strategic foundation for interpreting the broader implications of the framework, which are examined in the Discussion.

5. The AI-enabled circular economy framework for quantum-smart cities

Building on the benchmarking and alignment findings, this section presents the full architectural design of the proposed AI-enabled Circular Economy Framework. The findings from the systematic literature review and comparative case analysis culminate in the proposed AI-enabled Circular Economy Framework for Quantum Smart Cities. This modular, multi-layered architecture is designed to systematically conceptualize CE models with the practical, data-intensive deployment requirements of large-scale urban projects, such as those within Saudi Arabia's Vision 2030. It is explicitly designed to integrate technical innovation with governance and citizen engagement, ensuring that CE adoption is not only technologically feasible, but also socially inclusive and policy-aligned. By combining digital sensing, advanced analytics, interoperability mechanisms, and quantum-ready optimization, the framework provides a unified architecture capable of supporting real-time, cross-sectoral circularity at the megacity scale.

5.1. Conceptual architecture and CE domains

The framework is predicated on the vertical integration of smart technologies, spanning the physical urban environment to the final decision-making and citizen engagement interface. It comprises six sequential functional layers, ensuring seamless data flow from acquisition to actionable insights. The framework's functional layers are horizontally mapped against five critical Circular Economy Domains necessary for urban sustainability: Smart Waste Management, Circular Supply Chains (Water and Materials), Digital Twin Simulation, Energy Loop Closure, and Citizen Engagement (MacArthur, 2013; Reike et al., 2018). The goal is to enable dynamic, data-driven decision-making that shifts the urban ecosystem from localized optimization to globally optimal, regenerative resource management, a capability ultimately reliant on quantum computational power. Each domain is explicitly linked to Vision 2030 Key Performance Indicators (KPIs), enabling policymakers to measure CE progress in real time and make data-driven decisions accordingly. This dual vertical–horizontal mapping ensures that CE functions are not siloed but operate as interconnected subsystems within a unified architecture. To avoid repetition, this section focuses on the functional roles of each layer, while cross-referencing earlier descriptions where appropriate. The framework comprises the following layers.

- Layer 1: Data acquisition and sensing: This foundational layer is responsible for the real-time collection of physical, environmental, and operational data. IoT sensors, smart meters, and GIS systems provide the foundational monitoring of resource flows, waste levels, energy performance, and asset utilization. Edge computing ensures low-latency data capture, whereas standardized telemetry protocols (MQTT, CoAP) guarantee interoperability across diverse devices. This layer establishes the empirical backbone of the CE ecosystem, enabling accurate and continuous monitoring, which is essential for predictive analytics and policy enforcement.
- Layer 2: Data processing and storage: This layer provides a secure, scalable, and decentralized infrastructure for data management. Blockchain technology creates immutable records for material traceability, resource ownership, and verified circular supply chain transactions. Cloud and fog computing enable high-volume storage and processing for historical analysis and AI model training. Encryption and redundancy mechanisms ensure data integrity, aligning with Saudi Arabia's National Data and AI Strategy (SDAIA). By combining distributed ledgers with scalable cloud architectures, this layer ensures trusted, high-availability data pipelines across CE domains.
- Layer 3: AI analytics and digital twin simulation: This layer transforms raw data into predictive and prescriptive intelligence. Machine learning models (LSTM, XGBoost, and reinforcement learning) were used to forecast resource demand, asset failure, and optimal routing. Digital twins create high-fidelity simulations of urban systems, enabling scenario testing without real-world risk. Quantum readiness is embedded through the phased integration of quantum machine learning (QML) and quantum annealing, preparing Saudi smart cities for globally optimal resource management. This layer represents the analytical core of the framework, enabling both short-term operational optimization and long-term strategic planning.
- Layer 4: Integration and interoperability: This layer ensures that the outputs generated by AI and digital twins are seamlessly communicated across CE domains. Energy generation uses waste management data, whereas industrial symbiosis uses water reuse metrics. Interoperability standards (API gateways, open data protocols) are emphasized to align with Vision 2030's digital governance goals and enable cross-sector collaboration. This layer prevents the formation of isolated digital silos, ensuring that CE processes operate as interconnected loops rather than independent systems.
- Layer 5: Governance and policy alignment: This layer formalizes regulatory, ethical, and strategic oversight. Governance dashboards integrate ESG metrics, enabling policymakers to monitor CE performance in relation to Vision 2030 targets. Ethical AI deployment and data governance frameworks (Nobre and Tavares, 2017) are embedded to ensure trust, transparency, and compliance with the objectives of the Saudi Green Initiative. By linking CE operations to national policy instruments, this layer ensures institutional accountability and long-term sustainability.

- Layer 6: User interface and citizen engagement: This layer ensures that framework intelligence is consumable by diverse user groups, from city administrators to individual citizens. Gamified apps, citizen dashboards, and participatory governance platforms drive behavioral changes and regulatory compliance. This layer explicitly supports Vision 2030's "Vibrant Society" pillar by embedding CE principles into everyday urban life and fostering citizen-centric innovation ecosystems. This final layer operationalizes the social dimension of CE, ensuring that technological innovation translates into behavioral adoption and community participation.

As shown in Table 3, the AI-Enabled Circular Economy Framework is structured as a comprehensive six-layer architecture designed to move urban systems from raw data acquisition to high-level strategic governance. It begins with the Data Acquisition and IoT Sensing Layer, which serves as the foundational "nervous system" of the city, capturing real-time resource flows. The Communication and Connectivity Layer then manages these data, ensuring seamless interoperability across diverse urban subsystems. The Edge and Cloud Data Management Layer follows, providing the necessary computational backbone for storage and initial processing, while the AI and Quantum-Enhanced Analytics Layer represents the intelligence hub, where complex optimization and predictive modelling occur to drive circularity. The results are translated into citizen-centric services via the Service Orchestration and Citizen Engagement Layer, culminating in the Strategic Governance and Policy Layer. This top-tier layer ensures that all technological outputs are aligned with national sustainability mandates, such as Saudi Vision 2030, through rigorous ESG reporting and ethical oversight.

Fig. 3 presents a six-layer architecture for quantum smart circular economy systems. Each concentric ring represents a functional layer, progressing from core sensing (Layer 1) to citizen engagement (Layer 6). The components, enabling technologies, and roles in the CE are modularly mapped to each layer. This radial representation highlights the cyclical and regenerative logic of the CE, visually aligning the framework's structure with its underlying sustainability principles.

Table 3: The AI-enabled circular economy framework architecture

Layer	Component	Technology	Role in circular economy (CE)
	Physical infrastructure	IoT sensors Smart meters GIS	Real-time monitoring of resource flows Waste level tracking Energy performance measurement Asset utilization analysis
Layer 1: Data acquisition and sensing	Data filtering	Edge computing Micro-processing units	Reduce data latency Optimize bandwidth Enable localized analytics
	Data standardization	Telemetry MQTT CoAP	Ensure data consistency Maintain format integrity Support interoperability
	Distributed ledger	Blockchain technology	Track material ownership Verify transactions Enable supply chain traceability
Layer 2: Data processing and storage	Cloud/Fog computing	Scalable data warehousing Data lakes	Store historical data Train AI models Scale analytics
	Data integrity	Encryption Automated redundancy	Secure data Ensure reliability Guarantee availability
	Predictive modelling	Machine learning (ML) Deep learning	Forecast demand Predict maintenance Optimize routing
Layer 3: AI analytics and digital twin	Digital twin (DT)	High-fidelity simulation Physics-based modelling	Replicate urban systems Test policies virtually Reduce real-world risk
	Quantum readiness	Quantum machine learning (QML) Quantum annealing	Solve complex optimization Support multi-city logistics Advance materials science
	API gateway	RESTful APIs Service-oriented architecture (SOA)	Facilitate cross-domain exchange Enable modular applications
Layer 4: Integration and interoperability	Interoperability standards	Semantic web standards City-to-city protocols	Define formats Ensure scalability Guarantee coherence
	Automated workflows	Business process management (BPM) tools	Execute analytics decisions Automate CE operations
	Strategic alignment	Vision 2030 KPI mapping National digitization policy	Align CE with national goals Ensure measurability Support digitization policy
Layer 5: Governance and policy alignment	ESG performance dashboards	AI-driven monitoring Real-time reporting	Track ESG impact Provide transparency Enable accountability
	Decision support	Scenario modelling tools Policy simulators	Evaluate trade-offs Support evidence-based policy Include stakeholders
	Citizen interfaces	Mobile applications Public dashboards	Incentivize circular behavior Provide personalized feedback
Layer 6: User interface and citizen engagement	Administrator console	Integrated command center displays	Monitor CE performance Enable operational control
	Stakeholder collaboration	Digital platforms Integrated feedback loops	Facilitate public input Support iterative refinement

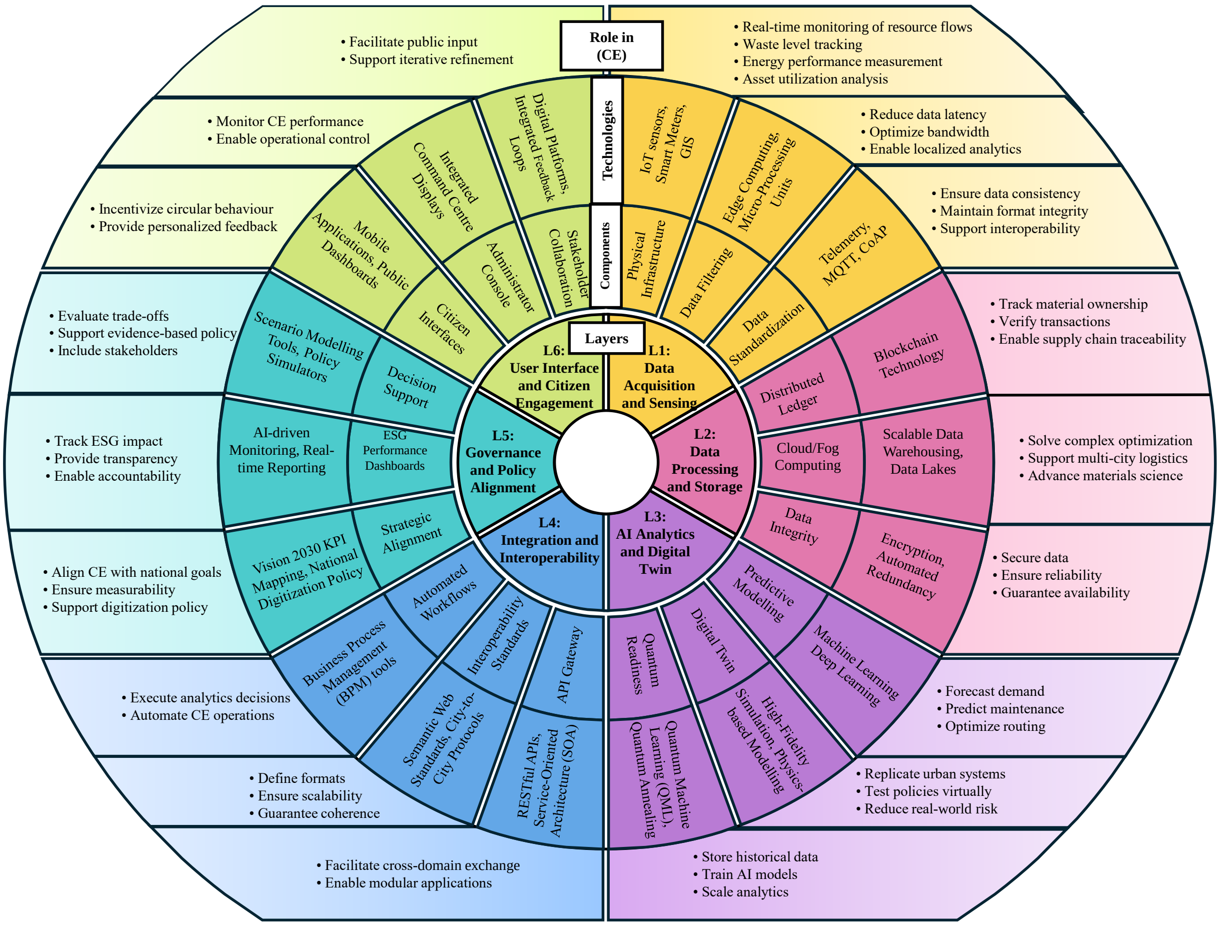

Fig. 3: The multi-layered architectural framework

5.2. CE domains and cross-domain synergies

The framework embeds specific CE domains across all six layers, ensuring holistic integration rather than siloed deployment. Smart Waste Management is enhanced through AI-driven bin fill prediction, contamination detection, and dynamic route optimization. Circular Supply Chains are strengthened through blockchain-enabled traceability, demand forecasting, and material recovery analytics. Smart Water Reuse is supported by IoT sensors and DSS platforms for quality monitoring and reuse optimization. Digital Twin Simulation provides urban system modelling capabilities for energy flows, logistics, and sustainable tourism. Construction applications focus on material banks, modular design, and CE procurement strategies, which are crucial for the NEOM project. The healthcare and education sectors benefit from improved medical waste management and CE literacy platforms. These domains interact dynamically; for instance, smart waste outputs feed directly into circular supply chains, and smart water reuse supports eco-tourism, demonstrating the framework's capacity for systemic synergy. This cross-domain integration ensures that CE interventions reinforce each other, amplifying the environmental and economic benefits across urban ecosystems. For example, in smart waste management, a quantum-inspired QAOA model can optimize multi-zone waste collection routes by simultaneously evaluating millions of routing permutations that classical solvers approximate heuristically. This capability becomes critical in megacity environments such as NEOM, where dynamic routing must account for real-time bin fill levels, traffic patterns, and energy constraints.

5.3. Operational mechanisms and resilience

To ensure practical and scalable deployment, the framework incorporates robust operational mechanisms. Interoperability standards, such as ISO 14001, OPC UA, and MQTT, ensure seamless sensor and data integration across municipal and project boundaries. Resilience protocols, including cybersecurity safeguards, redundancy strategies, and disaster recovery simulations, ensure system security and continuous operation against cyber and climate-related shocks. Policy integration aligns the framework’s metrics and objectives with the Saudi Green Initiative and SDAIA’s National AI Strategy. Performance metrics, including the Circularity Index, carbon reduction targets, citizen engagement rates, and economic efficiency indicators, provide measurable benchmarks for evaluating CE progress in the construction industry. Collectively, these mechanisms ensure that the framework is technologically advanced, secure, adaptable, and aligned with national sustainability mandates. Given the sensitivity of cross-sectoral data flows, the framework emphasizes cybersecurity hardening, including encryption, zero-trust architectures, and continuous threat monitoring to reduce exposure to system-level vulnerabilities.

5.4. Phased quantum integration roadmap

Quantum Computing is deliberately positioned as a phased integration strategy, ensuring that the framework is future-proof while remaining deployable with current technology. In the near term (2025–2030), the focus will be on quantum-inspired algorithms running on classical hardware to achieve immediate gains in logistics and resource optimization. In the mid-term (2030–2040), the introduction of the Quantum Approximate Optimization Algorithm (QAOA) enables real-time optimization challenges in smart grid resilience and water network balancing. In the long term (2040+), the full deployment of Quantum Machine Learning (QML) will support the predictive modelling of highly complex urban flows and comprehensive CE ecosystems, leveraging true quantum computational power. The roadmap also accounts for hardware constraints, noting that early deployments will rely on noisy intermediate-scale quantum (NISQ) devices with limited qubit counts. As hardware matures, deeper circuits and fault-tolerant qubits will enable full-scale QML models capable of modelling multi-actor CE ecosystems with significantly higher fidelity. This phased roadmap acknowledges the evolving maturity of quantum hardware while enabling immediate gains through quantum-inspired algorithms.

5.5. Stakeholder ecosystem and governance

The framework maps multi-actor roles to ensure inclusive governance. Citizens are positioned as active participants engaged through dashboards, gamified applications, and participatory budgeting mechanisms. The private sector drives industrial symbiosis, CE supply chains, and product-as-a-service models. Regulators enforce ESG compliance, data governance, and CE policies. Academia contributes to research pilots, longitudinal studies, and quantum algorithm development. This ecosystem approach ensures that CE transformation is collaborative, resilient, and supported across all segments of Saudi Arabia's innovation landscape.

5.6. Framework architecture and deployment context

Table 4 provides the definitive multidimensional alignment map of the proposed Six-Layer AI-Enabled Circular Economy Framework with the national development priorities outlined in Saudi Arabia's Vision 2030 and its related strategies. This integration demonstrates the strategic relevance of the conceptual framework, moving beyond theoretical design to practical implementation and measurement. Table 4 is structured to establish clear causality links between the high-level national mandates (Vision 2030 Pillars) and the specific framework layer and application area (CE Domain) through the system's core alignment rationale and strategic fit. Critically, it details the granular, operational strategic outcomes (e.g., infrastructure optimization, predictive reuse) realized through specific enabling technologies (e.g., Blockchain, QML, LSTM). Finally, this operational chain is anchored to measurable results using concrete Key Performance Indicators (KPIs). By specifying deployment zones such as NEOM, The Line, and Riyadh, Table 4 acts as a contextualized roadmap, checking the framework's scalability and relevance across Saudi Arabia's diverse and ambitious megaprojects.

Fig. 4 presents a multi-layered strategic framework that aligns Circular Economy (CE) domains with Saudi Arabia's Vision 2030 transformation pillars. Organized across six core layers, ranging from data acquisition to the user interface, the framework systematically integrates enabling technologies, strategic outcomes, and key performance indicators (KPIs) to support national development goals. Each CE domain, such as smart waste management and circular supply chain multi-layered twin simulation, is mapped to specific technologies, including IoT sensors, blockchain, predictive AI models, and semantic web standards. These technologies underpin outcomes such as real-time monitoring, scalable logistics, infrastructure optimization, and citizen engagement. The framework also incorporates cross-domain governance mechanisms, emphasizing ethical AI and quantum readiness to ensure system-wide trust and data interoperability. KPIs, such as landfill waste reduction, reclaimed water percentage, ESG dashboard compliance, and citizen participation rates, provide measurable benchmarks for progress. By aligning CE functions with Vision 2030 pillars, which are "A Thriving Economy, An Ambitious Nation, A Vibrant Society, and the National Data and AI Strategy," Fig. 4 offers a modular, policy-relevant roadmap for operationalizing circular innovation across Saudi megaprojects.

6. Discussion

The Discussion section moves beyond the descriptive synthesis presented in the Results to interpret the strategic, technological, and governance implications of the proposed framework. Whereas the Results section establishes what the benchmarking and alignment analyses reveal, this section examines what these findings mean for CE transitions, institutional readiness, and long-term quantum-enabled urban sustainability. The proposed AI-enabled circular economy framework for quantum-smart cities provides a critical theoretical and practical advancement by systematically addressing the complex and multi-dimensional requirements for urban resource regeneration.

Table 4: Multi-dimensional alignment of AI-enabled circular economy framework with Saudi Vision 2030

Vision 2030 pillar/national strategy	Strategic fit (alignment premise)	Framework layer	CE domain	Enabling technologies	Strategic outcome	KPIs	Deployment zones (KSA)
A thriving economy	Alignment with economic diversification and resource optimization	Layer 1: Data acquisition	Smart waste management	IoT sensors RFID Satellite imagery	Real-time monitoring Waste volume reduction	Percentage of reduction in landfill waste Recycling rate improvement	NEOM Riyadh
		Layer 2: Data processing	Circular supply chains	Blockchain Edge–cloud Pipelines Quantum APIs	Scalable logistics Optimized material recovery	Material recovery rate Blockchain traceability compliance	NEOM The line
		Layer 3: AI analytics	Water reuse systems	LSTM XGBoost Predictive models	Predictive reuse Integrated eco-tourism support	Percentage of increase in reclaimed water Predictive maintenance accuracy	Red Sea project
An ambitious nation	Alignment with data-driven policy and rigorous performance monitoring	Layer 4: Integration	Digital twin simulation	Digital twins RESTful APIs Semantic web standards	Infrastructure optimization Resource traceability	Number of operational digital twins Policy simulation accuracy	NEOM The line
		Layer 4: Integration	Construction materials	Material passports BIM Modular design	Sustainable building Circular procurement strategies	Percentage of adoption of material passports Circular procurement ratio	NEOM The line
		Layer 5: Governance	Smart mobility	ESG dashboards DSS Risk resilience tools	Emissions reduction Transport efficiency	CO_2 emissions reduction ESG dashboard compliance score	Riyadh NEOM
A vibrant society	Alignment with sustainable lifestyles and community participation	Layer 6: User interface	Citizen engagement	Gamified apps Feedback loops Behavioral dashboards	Participation Behavioral incentives	Citizen participation rate App engagement metrics	All zones
		Layer 6: User interface	Healthcare and education	Citizen dashboards Mobile apps Portals	Public health improvement Enhanced CE literacy	CE literacy index Health outcome indicators	Riyadh
National industrial strategy	Alignment with sustainable manufacturing and export competitiveness	Layer 2 and 4	Circular supply chains, industrial symbiosis	Blockchain IoT Digital twins Edge–cloud	Closed-loop manufacturing Export traceability	Material reuse rate Export traceability index	Industrial zones Riyadh NEOM
National data and AI strategy (SDAIA)	Alignment with responsible innovation and system-wide trust	Layer 3 and 5: Cross-domain governance	Cross-domain AI governance	Quantum readiness (QML/QA) Ethical AI governance	Responsible innovation Data interoperability System-wide trust	AI ethics compliance index Data interoperability success rate	All zones

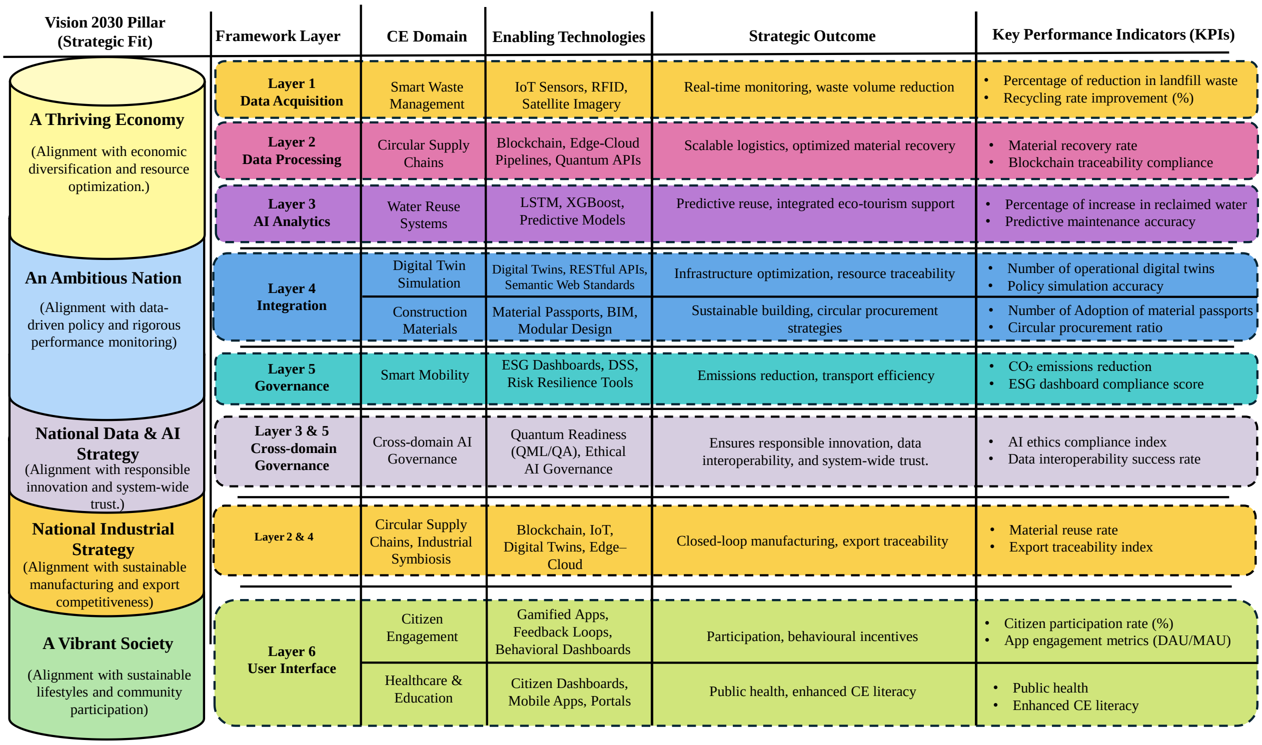

Fig. 4: Strategic mapping of circular economy framework to Vision 2030 pillars

The six-layered functional architecture serves as the interpretative core of this study, moving the scholarly discourse on digital CE from descriptive concepts to a prescriptive, action-oriented system. Specifically, the integration of AI-driven analytics with the foundational IoT sensing infrastructure fundamentally enhances economic efficiency through capabilities such as predictive maintenance, lifecycle analytics, and resource optimization (Kusi-Sarpong et al., 2019). Concurrently, this digital platform advances environmental sustainability through real-time monitoring of emissions, smart water reuse, and efficient energy flows, all of which are essential components of robust CE implementation (Ramadoss et al., 2018). Furthermore, the inclusion of Digital Twin Simulation within the Analytics Layer is key, enabling planners to conduct rigorous "what-if" scenario testing for circular design and policy interventions on urban systems. Compared to prior CE studies that emphasize digital enablers in isolation (Bibri et al., 2023; Ramadoss et al., 2018), this framework uniquely integrates analytics, governance, and citizen engagement into a unified architecture. This holistic integration represents a significant conceptual contribution, demonstrating that CE transitions require not only technological sophistication but also coordinated institutional, behavioral, and policy mechanisms. This interpretive lens clarifies how the framework not only consolidates existing CE enablers but also restructures them into a coherent, future-oriented system capable of addressing multi-scalar urban challenges.

The primary strategic significance of this framework lies in its direct alignment and contextualization within Saudi Arabia's Vision 2030 megaprojects. This detailed strategic and operational roadmap is comprehensively mapped out in Table 4, which links Vision 2030 Pillars to specific technological implementations, Deployment Zones, and Key Performance Indicators (KPIs). These ambitious urban developments necessitate technologically advanced, scalable, and future-proof solutions. The framework's emphasis on interoperability standards is designed to mitigate the risks associated with creating fragmented technological silos across diverse municipal and economic zones (Pappas et al., 2018). Crucially, the phased capability for Quantum Readiness is the most significant strategic differentiator, guaranteeing the long-term viability of the framework. While current AI excels at local optimization, the vast, dynamic scale of future Saudi smart cities will generate NP-hard logistical and resource-matching problems that only quantum computing can solve optimally, ensuring the transition to a truly globally optimized circular ecosystem. This novelty distinguishes the framework from existing AI/IoT-focused CE models, which lack quantum readiness and policy-anchored deployment pathways (Gyongyosi and Imre, 2019). By embedding quantum-ready components into the CE architecture, the framework anticipates future computational demands and positions Saudi Arabia at the forefront of next-generation smart city innovation.

However, successful deployment depends on rigorously bridging the gap between technological capacity and institutional readiness. Ethnographic insights from Saudi Arabia's urban contexts highlight that successful adoption requires robust governance alignment and careful consideration of public perception and infrastructure readiness (Alyami, 2025). The framework addresses this by embedding a dedicated governance and policy alignment layer, which requires the creation of flexible regulatory sandboxes and the mandatory use of ESG Dashboards to ensure transparency and accountability to Vision 2030 targets. Finally, the user interface and citizen engagement layer operationalizes the principle of stakeholder-inclusive decision support, which is vital for securing the public buy-in necessary to shift entrenched linear consumption behaviors toward a regenerative, circular model (Sacco et al., 2023; Yadav et al., 2020). Relative to global pilots that emphasize dashboards without KPI coupling (Pappas et al., 2018; Yadav et al., 2020), this framework advances citizen engagement by linking behavioral adoption to measurable CE outcomes. This integration of behavioral analytics and KPI-driven engagement ensures that citizen participation becomes a measurable strategic lever, rather than a peripheral component of CE transitions.

Beyond Vision 2030, the framework incorporates CE principles into larger sustainability agendas by directly supporting regional projects like the Middle East Green Initiative and Saudi Green Initiative. Policymakers can obtain transparent tools for tracking CE progress, guaranteeing accountability, and facilitating international benchmarking against the UN SDG targets and the EU CE action plan by including ESG dashboards and interoperability standards. This policy contextualization expands on earlier research that highlights trust and governance in Saudi Smart Cities (Alyami, 2025; Nobre and Tavares, 2017). Thus, the framework supports Saudi Arabia's growing position as a leader in climate-aligned digital innovation while simultaneously promoting national transformation and regional and global sustainability leadership.

Despite its strengths, several risks must be considered when using the model. The expansion of blockchain and IoT technologies has heightened data privacy and cybersecurity challenges. Citizen adoption barriers, including digital literacy and trust in AI systems, may slow down uptake. Quantum readiness also presents uncertainty because hardware maturity and algorithmic scalability remain globally uneven. The cultural adaptation of citizen engagement tools and ethical governance of quantum algorithms further complicate deployment, requiring phased implementation and adaptive oversight. These limitations underscore the need for iterative, evidence-based deployment strategies and continuous capacity building across institutions, industries, and communities.

Future research should prioritize empirical validation through pilot projects in NEOM and Riyadh, longitudinal tracking of CE KPIs, and citizen engagement studies. Cross-sectoral applications in healthcare, education, and tourism represent promising extensions of CE principles. Quantum optimization for multi-actor governance, logistics routing, and energy loop closure offers particularly impactful avenues (Gyongyosi and Imre, 2019), positioning Saudi Arabia as a global leader in quantum smart sustainability. Further work should explore hybrid quantum-classical architectures, economic feasibility assessments, and governance models that ensure the ethical, transparent, and culturally aligned deployment of quantum-enabled CE systems.

While the proposed framework offers significant potential, its implementation introduces several risks that must be carefully managed. First, the expansion of IoT and blockchain infrastructures increases exposure to cybersecurity threats, including sensor spoofing, data tampering, and distributed denial-of-service attacks. Second, the collection of high-resolution urban data raises privacy concerns, particularly in citizen-facing applications where behavioral analytics are used to incentivize CE participation. Third, interoperability challenges may arise when integrating heterogeneous municipal systems, potentially leading to fragmented data flows or inconsistent KPI reporting. Fourth, citizen adoption may be hindered by digital literacy gaps and varying levels of trust in AI-mediated decision systems. Finally, quantum readiness introduces uncertainty due to the immaturity of current hardware, including qubit instability, noise sensitivity, and limited circuit depth.

To mitigate these risks, the framework incorporates regulatory sandboxes, ethical AI governance protocols, and mandatory ESG dashboards to ensure transparency and accountability. Hybrid quantum–classical architectures are recommended to manage computational uncertainty, while phased deployment strategies allow institutions to build capacity gradually. Collectively, these measures ensure that the framework remains resilient, secure, and socially acceptable during real-world implementation.

7. Conclusion and future work

This study successfully proposed and detailed a comprehensive AI-enabled circular economy framework for Quantum Smart Cities, providing a critical strategic roadmap for Saudi Arabia's urban transformation agenda under Vision 2030. The framework creates a multi-layered architecture that uses advanced digital technologies, such as Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twins, Blockchain, and phased Quantum Computing, to drive systemic, regenerative resource management in key urban areas. The primary conceptual contribution lies in defining the architectural requirements for the next generation of Quantum-Smart Cities, proactively addressing the computational complexity barrier that limits classical optimization across vast, interconnected urban systems. Furthermore, the modular, six-layered functional architecture (spanning data acquisition to user interface) directly bridges theoretical CE models with practical, data-intensive deployment requirements, endorsed through systematic literature synthesis and comparative benchmarking of global pilots. By explicitly embedding interoperability standards, ESG dashboards, and phased quantum readiness, the framework advances beyond existing AI/IoT-focused CE models to address NP-hard optimization challenges on a megacity scale. Collectively, these contributions establish a novel, future-proof foundation for CE-driven urban sustainability, positioning the framework as a significant advancement in both CE theory and smart city system design.

This study holds significant policy relevance by providing a contextually specific roadmap that aligns global CE best practices directly with the pillars and megaproject mandates of Saudi Arabia Vision 2030. Table 4 comprehensively maps the detailed strategic and operational roadmap. Crucially, the embedded governance and citizen engagement layers underscore the necessity of moving beyond purely technical solutions. A successful CE transition requires regulatory reform and active, technology-mediated stakeholder participation. Therefore, the framework serves as a powerful instrument for policymakers seeking a scalable and integrated strategy to achieve national sustainability goals. In addition, the framework explicitly supports regional initiatives, such as the Saudi Green Initiative and the Middle East Green Initiative, embedding CE adoption into broader sustainability agendas and reinforcing Saudi Arabia's leadership in global climate action. This policy contextualization ensures accountability while enabling international benchmarking against the EU CE Action Plan and the UN SDG targets. By linking CE operations to measurable KPIs and national transformation programs, the framework provides a transparent mechanism for evaluating progress and guiding adaptive policy refinement.

Although the framework is conceptually robust, its immediate validation relies on a systematic synthesis and comparative analysis. Future research should focus on empirical validation via longitudinal case studies, preferably incorporating pilot deployment within a specific Vision 2030 megaproject to measure the framework's influence on critical CE performance indicators (KPIs), including the material recovery rate and resource-use efficiency. This empirical validation must explicitly focus on quantifying the differences in KPIs achieved by layers leveraging quantum-inspired algorithms versus purely classical AI in the specified deployment zones. Additionally, focused work is required on the transition from quantum readiness to practical quantum implementation, including the development and testing of specific Quantum Optimization Algorithms (QOAs) tailored to complex CE challenges, such as dynamic material logistics. Finally, extending the framework's application to non-industrial sectors, such as circular healthcare logistics and sustainable tourism supply chains, and conducting detailed economic modelling to quantify the associated return on investment will solidify this strategic model as the definitive pathway for realizing genuinely regenerative and resilient urban environments in the era of quantum-smart computing. Further research should explore hybrid quantum-classical architectures, governance models for ethical quantum deployment, and capacity-building strategies to ensure institutional readiness for quantum-enabled CE modelling. A structured empirical validation plan—beginning with pilot deployment in NEOM and Riyadh—will be essential for quantifying the framework's operational performance and verifying its predictive and optimization capabilities.

In summary, this study contributes a multidimensional roadmap that bridges conceptual CE theory with practical deployment, explicitly aligning it with Saudi Arabia's Vision 2030 pillars and megaprojects. This study promotes both technical innovation and social adoption by incorporating quantum readiness, governance and citizen engagement into the framework. Future work will ensure that Saudi Arabia not only achieves its national sustainability goals but also positions itself as a global pioneer in quantum-enabled circular economy innovation. Thus, the framework represents a foundational step toward the realization of fully integrated, data-driven, and quantum-smart circular cities capable of shaping the next era of sustainable urban development. A risk-aware deployment strategy—incorporating cybersecurity safeguards, ethical AI governance, and phased quantum integration—will be essential to ensure that the framework remains both technically robust and socially trustworthy.

List of abbreviations

AI	Artificial intelligence
API	Application programming interface
BIM	Building information modelling
BPM	Business process management
CCA	Comparative case analysis
CE	Circular economy
CoAP	Constrained application protocol
CO_2	Carbon dioxide
DSS	Decision support systems
DT	Digital twin
ESG	Environmental, Social, and Governance
EU	European Union
GIS	Geographic information system
IoT	Internet of Things
KPI	Key performance indicator
KSA	Kingdom of Saudi Arabia
LSTM	Long short-term memory
ML	Machine learning
MQTT	Message queuing telemetry transport
NEOM	Strategic cognitive megacity project in northwestern Saudi Arabia
NISQ	Noisy intermediate-scale quantum
NP-hard	Non-deterministic polynomial-time hard
OPC UA	Open platform communications unified architecture
QA	Quantum annealing
QAOA	Quantum approximate optimization algorithm
QC	Quantum computing
QML	Quantum machine learning
QOA	Quantum optimization algorithm

REST	Representational State Transfer
RFID	Radio-frequency identification
SDAIA	Saudi data and AI authority
SDG	Sustainable development goal
SLS	Systematic literature synthesis
SOA	Service-oriented architecture
UN	United Nations
VQE	Variational quantum eigensolver
XGBoost	Extreme gradient boosting

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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