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Enhancing Environmental Sustainability through AI-Driven Digital Twin Systems for Net-Zero Carbon Smart Construction

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Abstract: The construction sector significantly contributes to global greenhouse gas (GHG) emissions, accounting for up to 20% of total global emissions while playing a major role in climate change. Rapid urbanization alongside resource-intensive building practices exacerbates environmental challenges, which highlight the urgent need for net-zero carbon and sustainable solutions. The study aims to critically examine how Digital Twin (DT) systems and Artificial Intelligence (AI) can enhance environmental sustainability and support net-zero carbon goals in smart construction. Based on a comprehensive literature review and recent scholarly works on sustainability, AI integration in the built environment, and digital twin applications, findings show that AI-driven digital twin systems provide significant benefits ranging from predictive energy optimization, real-time carbon monitoring, improved decision-making regarding material selection, logistics, and waste reduction. Altogether, these systems facilitate resilience in smart cities through Internet of Things (IoT), Building Information Modelling (BIM), and machine learning integration to optimize resource efficiency. Meanwhile, challenges including data integration, cybersecurity, high costs of implementation, and ethical concerns are major barriers. Despite this, the study contributes to the academic domain by advancing digital transformation knowledge in sustainable construction and providing industry insights on practical ways to achieve zero-carbon goals. It highlights the need for future research to focus on standardization, policy frameworks, and the use of scalable adoption strategies.

Keywords: *Environmental Sustainability, AI-Driven Digital Twin Systems, Net-Zero Carbon, Smart Construction, Artificial Intelligence, Internet of Things.*

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I. INTRODUCTION

The construction industry significantly contributes to climate change, accounting for approximately 19% of global greenhouse gas (GHG) emissions (Labaran et al., 2021). Urbanization has also played a major role, as urban cities consume 75% of natural resources while producing 80% of global emissions (Kryvomaz & Savchenko, 2021). By 2024, Yilmaz (2024) noted that the construction sector is responsible for 75% of annual global greenhouse gas emissions, with concrete alone accounting for 7% of carbon emissions. To address this menace, the implementation of green building principles and innovative technologies has been found to reduce carbon emissions and environmental impact in the sector (Kryvomaz & Savchenko, 2021).

Environmental sustainability in the built environment is essential for addressing climate change and facilitating long-term quality of life (QoL). Studies have shown the importance of considering the life cycle in sustainable building design, focusing on social, economic, and environmental performance (Janjua, Sarker, & Biswas, 2019). To achieve sustainability Datta et al. (2023) wrote that the 4Es (Effectiveness, Economic, Efficiency, and Ethics) and 4 Poles (Social, Economic, Environmental, and Technology) model are important, especially as environmental comfort and sustainability principles in architecture help to preserve comfort and address climate crisis (Yilmazer & Onay, 2019).

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Sanchez-Silva et al. (2024) observed that since resilience is a critical part of sustainable infrastructure, which ensures recovery from damaging events while minimising functionality disruptions, a systems-thinking approach to making risk-informed decisions is requisite for responsible evolution of the built environment.

Digital twin (DT) systems augmented by artificial intelligence (AI) have shown potential in reducing smart building construction by 25-40%, minimizing carbon emissions by 20% in transportation, and improving renewable energy usage in smart grids by 20% (Li, 2025). Integrating AI and IoT (Internet of Things) with digital twins facilitates energy optimization for zero-energy constructions while enhancing urban resilience (Alnaser et al., 2024). AI-powered digital twin systems offer improved sustainability in the construction sector, including the use of machine learning (ML) for automated monitoring and tracking equivalent CO2 emissions from existing buildings (Arsiwala et al., 2023), and enhanced productivity (Olanrewaju et al., 2024). Nonetheless, challenges including security, data integration, and workforce skill gaps persist, and further research is needed to fully exploit the system's potential (Zhang et al., 2024).

➢ *Aim and Objectives*

This study aims to evaluate the effectiveness and limitations of machine learning-driven anomaly detection systems for mitigating cyber threats in digital financial and crypto-asset ecosystems.

➢ *The Objectives are:*

- To explore current cybersecurity challenges affecting digital finance and crypto-assets.
- To review and compare machine learning (ML) techniques used in anomaly detection within the digital finance and crypto-asset sectors.
- To analyze real-world case studies where ML-driven anomaly detection systems were used for mitigating cyber threats.
- To identify implementation challenges and propose recommendations for enhancing real-time threat detection in high-risk financial environments.

II. ENVIRONMENTAL SUSTAINABILITY USING AI-DRIVEN DIGITAL TWIN SYSTEMS

➢ *Environmental Sustainability in Construction*

AI-driven digital twin systems are used for enhancing environmental sustainability in construction. The systems integrate data fusion approaches, IoT sensors, and AI to optimize energy efficiency, improve indoor environmental quality across a building's lifecycle, and reduce carbon emissions (Alnaser et al., 2024). Digital twin systems enable fault detection, monitoring, and predictive maintenance for more sustainable management and operations (Yitmen et al., 2025). Meanwhile, the technology has various applications across individual smart buildings to smart cities, providing opportunities for urban resilience and improved energy management (Zahedi et al., 2024). Although the technology can be applied to wider areas to ensure and meet broader sustainability goals, challenges remain in the full exploitation of digital twin systems for sustainability, including cybersecurity, data integration, and the need for standardised frameworks (Zhang et al., 2024).

➢ *Digital Twin Technology in Construction*

Digital twin technology in construction is rapidly evolving, which involves the creation of virtual replicas of systems, physical assets, or processes (Sargiotis, 2025) by integrating different technologies like Building Information Modelling (BIM), AI, IoT, and machine learning to improve efficiency and decision-making (Su et al., 2023). Digital twins provide several applications, including facility management, lifecycle analysis, structural health monitoring, and energy optimization (Khallaf et al., 2022). Meanwhile, digital twins are applied across the construction lifecycle from design to planning, construction management, and facility management (Su et al., 2023).

The integration of digital twin technology with building information modelling (BIM) helps to address construction project challenges through real-time data and analysis of physical assets (Nguyen & Adhikari, 2023). Sustainable construction is achievable through evolution from BIM to DT with various applications in simulation, smart systems, and technology integration (Zahedi et al., 2024).

➢ *AI-Driven Solutions for Smart Construction*

Artificial intelligence (AI) is transforming the construction industry through enhanced sustainability, efficiency, and cost-effectiveness. AI-driven solutions such as predictive analytics facilitate improved decision-making and risk assessment (Ajayi, 2025), optimization of resource management (Ghani, 2025), and automation of labor-intensive tasks. Alghusni et al. (2025) observed that machine learning algorithms and IoT-based monitoring systems are used to optimize the process of selecting and applying smart materials, which leads to significant cost reductions while improving energy efficiency. Integrating AI in construction management enhances project planning, risk management, and scheduling (Obiuto et al., 2024).

These solutions also help in facilitating carbon tracking and sorting waste, especially as generative design powered by AI and other relevant technology-bound solutions help to create energy-efficient and sustainable structures while contributing to the circularity of building life cycles for a greener built environment (Dagadkar et al., 2025).

However, despite recent research showing the potential of integrating AI, IoT, and digital twins' technologies to enhance sustainability in smart construction, researchers have identified a lack of comprehensive studies that combine these technologies, and thus, necessitating increased focus on related challenges while exploring their collective impact on sustainable development and the built environment (Bibri et al., 2024).

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III. CONCEPTUAL FRAMEWORK

This study is underpinned by the framework integrating Artificial Intelligence (AI) and Digital Twin (DT) systems to foster environmental sustainability and net-zero carbon goals in construction and the built environment. Digital Twins, which imply dynamic digital replicas of physical assets, enable real-time simulation, monitoring, and optimization across the lifecycle of a building (Omrany et al., 2023).

The integration of Digital Twin technology with AI techniques, including predictive analytics, machine learning, and optimization algorithms, provides insights that drive waste reduction, resource efficiency, and mitigation of carbon emissions (Enyejo et al., 2024).

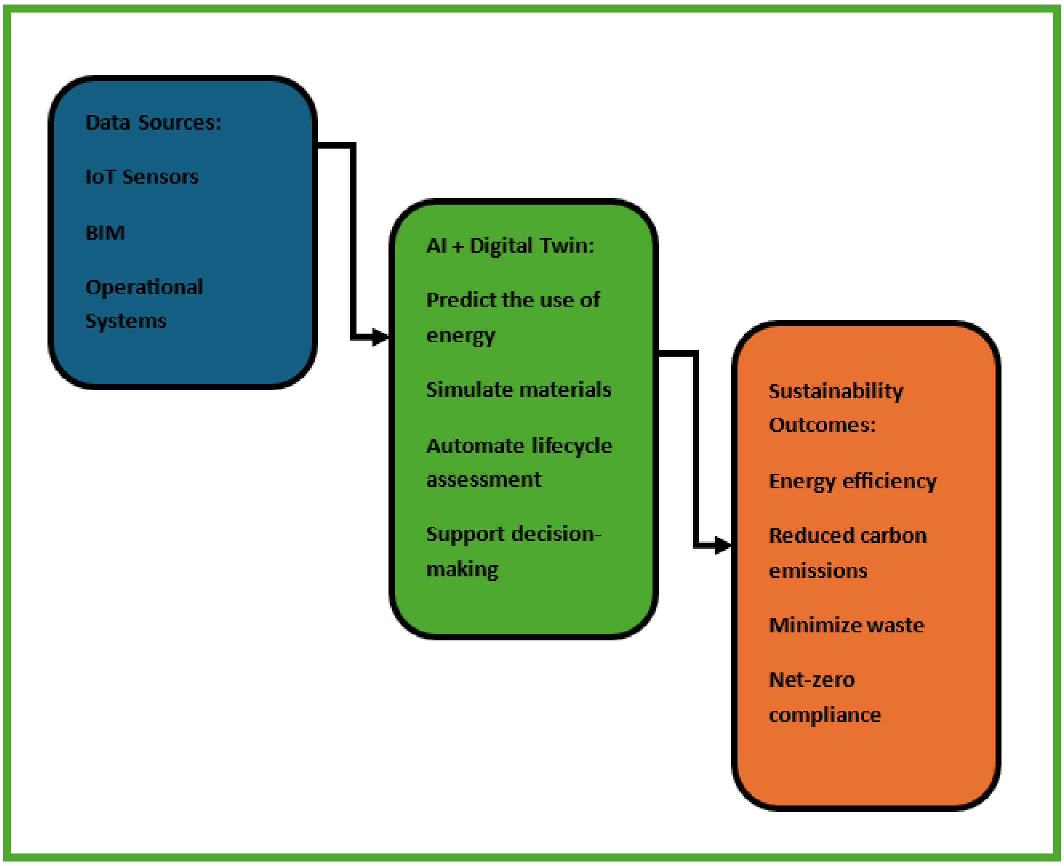

Fig 1: Conceptual Framework: AI-Driven Digital Twin Systems for Net-Zero Carbon Smart Construction

The framework depicts construction projects as cyber-physical ecosystems, where data from Building Information Modelling (BIM), Internet of Things (IOT) sensors, and operational systems are fed into a central digital twin platform. The large data streams are modelled by AI to predict and optimize energy consumption across the lifecycle of the building, simulate the use of materials (Mehmood et al., 2019), and supply chain logistics to reduce embodied carbon, automate carbon footprint tracking using lifecycle assessment (LCA), and support decision-making via sustainability scenarios to builders, project managers, designers, and policymakers.

Also, the integration is guided by three fundamental elements, including technological enablers such as IoT, AI, Digital Twins, and BIM; sustainability indicators comprising waste reduction, energy efficiency, and carbon emissions; and net-zero outcomes, including resilience, carbon neutrality, and compliance with climate policies. The conceptualisation of AI-driven DT systems. The conceptualization of AI-driven Digital Twin systems serves as a gap between environmental responsibility and digital smartness, providing a pathway for efficient transition towards sustainable, smart, and carbon-neutral operations [See Figure 1 above].

- *AI-Driven Digital Twins for Carbon Monitoring*

AI-driven digital twins are powerful tools for monitoring carbon in different domains, including construction. In smart cities, these tools are critical for reducing energy usage in buildings by 25-30% while decreasing transportation-induced carbon emissions by 20% (Li, 2025). In existing buildings, digital twins integrating other technologies such as AI, BIM, and IoT can automate the monitoring and prediction of carbon equivalent emissions, which enable data-driven retrofitting strategies (Arsiwala et al., 2023). Across urban infrastructures, AI-driven digital twins can potentially help in reducing energy consumption and carbon emissions, while the combined effect enables data-driven decision-making and predictive analysis for implementing retrofitting strategies and enhancing sustainability through the lifecycle of a building (Zhang et al., 2024). These insights facilitate low-carbon design choices, enhance building operations, and optimize construction logistics while ultimately reducing environmental impact, accelerating the transition to zero-carbon construction, and improving compliance (Royan, 2021).

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➢ *Enhancing Lifecycle Sustainability*

AI-driven digital twins are useful in enhancing sustainability in construction by reducing carbon emissions while improving energy efficiency throughout the lifecycle of a building (Zhang et al., 2024). These tools have demonstrated substantial ability to save energy in smart buildings, power grids, and transportation networks, contributing to global sustainability goals (Li, 2025). In smart building systems and the built environment, AI-driven digital twins improve energy efficiency and indoor environmental quality, while enabling decision-making for detecting and maintaining infrastructure (Yitmen et al., 2025). AI optimization of smart materials, including phase-change materials and self-healing concrete, also promises in sustainable construction, helping to reduce costs, decrease material waste, and improve energy efficiency compared to traditional methods (Alghusni et al., 2025).

➢ *Benefits for Net-Zero Construction Projects*

AI-driven digital twin systems provide significant benefits for net-zero construction projects by enhancing sustainability through virtual representations of physical assets and processes for effective and faster decision-making, increased productivity, and improved communication (Olanrewaju et al., 2024). The systems foster decision-making through accurate insights into operational and embodied carbon, which supports the selection of energy-efficient designs and sustainable materials. During construction, these systems optimize logistics, minimize equipment idling, and reduce waste, while in operations, predictive analytics services the purpose of improving energy management while lowering carbon footprints. The integration of data from IoT, BIM, and supply chains consolidates the potential of digital twins for assured compliance with sustainability standards to reduce costs and fast-track progress toward net-zero targets in smart construction domains (Nemati, Aminnejad, & Lork, 2025).

➢ *Challenges and Risks*

Despite the benefits of AI-driven digital twin systems for net-zero construction, some challenges and risks persist. Technically, the integration of diverse data sources, including IoT, BIM, and supply chains, demands high accuracy (Li et al., 2022). Also, cybersecurity threats, sensor errors, and model drift can compromise the system's reliability. In terms of ethics, concerns regarding data privacy, potential bias, and workers' surveillance arise in AI-driven design decisions. In addition, high upfront costs for training, system maintenance, and digital infrastructure may discourage adoption, especially for smaller construction firms (Rasheed et al., 2024). Financing may be complicated by uncertain return on investment (ROI) and regulatory compliance. Therefore, these risks must be addressed using transparent use of AI, alignment of long-term value with sustainability goals, and strong governance (Omopariola & Aboaba, 2019).

IV. FUTURE PROSPECTS AND POLICY IMPLICATIONS

The future of construction is bright with AI-driven digital twin systems, especially with prospects in advancing net-zero construction and seamless integration into smart cities. On the one hand, these systems hold the potential to enable real-time carbon monitoring, lifecycle planning, predictive energy optimization, and create buildings that can smartly interact with urban infrastructure. Therefore, adoption of the digital twin systems enhanced by artificial intelligence can be accelerated through policy recommendations, emphasizing the inclusion of government incentives such as green financing, tax breaks, and public-private partnerships that lower firms' entry barriers (Xu & Wudi, 2024).

Similarly, capacity-building initiatives ranging from workforce training to digital literacy programs are crucial for widespread use. In addition, standardization and regulations are required, establishing unified data protocols, AI governance guidelines, and carbon accounting frameworks to ensure reliability, accountability, and interoperability across construction projects (Tettey et al., 2025). Trust in AI-driven systems can be enhanced through clear policies that mandate lifecycle carbon reporting, cybersecurity safeguards, and verified digital product passports. Essentially, aligning regulatory frameworks with sustainability goals will reduce environmental risks, foster innovation, and position digital twins as the core of future zero-carbon, intelligent, and resilient urban ecosystems (Woods & Freas, 2019; Bibri, Huang, & Omar, 2025).

V. CONCLUSION

This study aimed to examine how AI-driven digital twin (DT) systems can enhance environmental sustainability while supporting net-zero carbon goals in smart construction. The study showed that the construction sector is a major contributor to global greenhouse gas (GHG) emissions, yet digital transformation using AI-integrated DT systems offers immense opportunities for lifecycle optimization, carbon reduction, and improved decision-making. According to key findings, digital twins facilitate energy optimization, carbon monitoring, and predictive analytics, while artificial intelligence facilitates accurate carbon tracking, generative design, and resource management. These technologies enable waste reduction, sustainable material selection, and improved operational efficiency, and thus accelerate the transition to zero-carbon smart construction.

This research contributes to existing knowledge regarding the integration of AI, BIM, IoT, and digital twin systems in advancing resilience and sustainability in the built environment. In industrial practice, the study also provides practical insights into the role of digital technologies for reducing costs, improving compliance, and aligning construction practices with climate goals across the globe.

However, challenges persist regarding cybersecurity, data integration, high financial costs, and ethical implications. The potential of the systems to achieve sustainable, zero-carbon, and resilient urban built environments can be realized through standardized frameworks, exploring scalable models, and enhancing AI governance.

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AUTHORS' CONTRIBUTION

- Oluwatumininu A. Abayomi: Conceptualized the study, developed the research framework, and drafted the initial manuscript.
- Jemima O. Odiete: Conducted the literature review, synthesized related works, and contributed to writing the introduction and policy implications.
- Cosby O. Oni: Analyzed environmental sustainability perspectives, refined methodological insights, and contributed to drafting the discussion and conclusion.
- Brenda Togo: Reviewed the manuscript for coherence, provided critical revisions, and aligned the study with sustainability management perspectives.

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