Energy & Buildings 333 (2025) 115484

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Synergistic integration of digital twins and zero energy buildings for climate change mitigation in sustainable smart cities: A systematic review and novel framework

Simon Elias Bibri [a,*], Jeffrey Huang [a], Osama Omar [b], Inji Kenawy [c]

[a] Swiss Federal Institute of Technology Lausanne (EPFL), Institute of Computer and Communication Sciences (IINFCOM), School of Architecture, Civil and Environmental Engineering (ENAC), Media and Design Laboratory (LDM), Lausanne, Switzerland

[b] Department of Architecture and Interior Design, College of Engineering, University of Bahrain, Manama P.O. Box 32038, Kingdom of Bahrain

[c] School of Computing, Engineering and the Built Environment, Edinburgh Napier University, Edinburgh, UK

A R T I C L E I N F O

Keywords:
Urban Digital Twins
Zero-Energy Buildings
Sustainable Smart Cities
Climate Change Mitigation
Artificial Intelligence

A B S T R A C T

Sustainable smart cities are increasingly turning to innovative technologies, such as Urban Digital Twins (UDTs) and Zero Energy Buildings (ZEBs), which offer transformative opportunities to enhance energy management and reduce environmental impacts. Despite significant progress, research on the integration of UDTs and ZEBs remains limited, and the lack of a unified framework hampers their potential to fully contribute to environmental goals in smart cities. Therefore, this study conducts a comprehensive systematic review of how UDTs and ZEBs can be integrated to strengthen climate change mitigation efforts in sustainable smart cities. It primarily aims to develop a novel framework that leverages their synergies for maximizing their combined potential to advance environmentally sustainable urban development. The study reveals key trends in the convergence of UDTs and ZEBs, emphasizing the growing role of Artificial Intelligence (AI), the Internet of Things (IoT), and Cyber-Physical Systems (CPS), while also highlighting specific research patterns related to their synergistic interplay and its contribution to enabling the convergence. Moreover, it underscores the role of UDTs in enhancing the energy management and performance capabilities of ZEBs by improving energy efficiency, boosting renewable energy integration, and reducing carbon emissions through real-time monitoring, advanced data analytics, predictive maintenance, and operational optimization. Conversely, ZEBs provide real-time data and performance metrics that enhance UDTs' analytical and predictive capabilities. Furthermore, the study introduces a comprehensive framework that integrates UDT technical and operational indicators with ZEB performance indicators. However, technical, ethical, environmental, financial, regulatory, and practical challenges must be addressed and overcome for large-scale implementation. The novelty and contribution of this study lies in the development of a unique integrated framework that bridges the gap between UDTs and ZEBs, highlighting their collective impact on sustainable urban development, an area that has not been explored in previous review research. Theoretical and practical insights are discussed to inform researchers, practitioners, and policymakers, showing how these findings can shape future research directions, guide technological implementation, and influence policy decisions in advancing sustainable smart cities.

1. Introduction

In light of the escalating global challenges posed by resource depletion, ecological degradation, and climate change, the urgency for innovative approaches to urban development has intensified, demanding immediate and innovative responses. These formidable challenges highlight the critical need for comprehensive sustainable development strategies, along with integrated frameworks. Consequently, sustainable smart cities have increasingly become a focal point as a sophisticated strategy for urban development, specifically designed to tackle the intricate challenges associated with environmental sustainability and climate change. Since the early 2020 s, these cities have extensively adopted the Internet of Things (IoT) and Big Data technologies, renewable energy systems, efficient and green infrastructure, and

* Corresponding author.
E-mail address: simon.bibri@epfl.ch (S.E. Bibri).

https://doi.org/10.1016/j.enbuild.2025.115484
Received 4 December 2024; Received in revised form 10 February 2025; Accepted 16 February 2025
Available online 20 February 2025

data-driven solutions to optimize urban systems, enhance resource management, improve energy efficiency, and reduce pollution (e.g., [1–8]). These innovations have fostered adaptive, resilient, and technologically advanced urban environments better equipped to mitigate the effects of urbanization and tackle the strain caused by resource scarcity.

Sustainable smart cities are merging latest digital innovations with established sustainability practices, paving the way for urban environments that are not only more intelligent but also well-equipped to face future challenges. In more recent years, sustainable smart cities have become particularly pivotal arenas for the implementation of emerging technologies, particularly Artificial Intelligence (AI) and Artificial Intelligence of Things (AIoT), and their applied solutions to further advance environmental sustainability and climate change mitigation goals [9–21]. AI enables the analysis of vast amounts of real-time data, improving decision-making and facilitating predictive modeling, while AIoT connects intelligent sensors and physical devices to computational processes or digital systems, optimizing resource utilization and enabling proactive energy management to reduce consumption and carbon emissions. These advancements have empowered sustainable smart cities to hasten environmental transitions and cultivate circular urban ecosystems, thereby promoting greater resource efficiency and resilience [22].

Furthermore, at the heart of the transformative shift characterizing sustainable smart cities are Urban Digital Twins (UDTs) (e.g., [23–27]), and Zero Energy Buildings (ZEBs) (e.g., [28–30]), which are becoming essential components of modern urban ecosystems. These technology solutions play a critical role in optimizing resource management, enhancing energy efficiency, integrating renewable energy sources, reducing carbon footprints, and supporting climate strategies through real-time monitoring, predictive maintenance, and system optimization [23,31–38]. They contribute to the advancement of sustainable smart cities by providing innovative solutions that align with the environmental goals of sustainable development. In this rapidly evolving landscape, ZEBs offer sustainable solutions by integrating solar photovoltaics, wind turbines, and hybrid energy system [29,39,40] and playing an instrumental role in achieving climate goals by promoting energy independence and promoting decarbonization or carbon–neutral cities [41,42].

Similarly, UDTs contribute to optimizing energy consumption to reduce building energy use [43], improving building energy efficiency [44], forecasting energy consumption for better management [45], and enhancing buildings' operational optimization [46], all of which apply broadly to building energy systems. UDTs, as digital replicas of physical urban environments, integrate real-time data and simulation models to monitor and optimize urban systems. They enhance decision-making processes and forecasting capabilities by leveraging AI, AIoT, Building Information Management (BIM), and Cyber-Physical Systems (CPS). These technologies significantly improve energy performance, occupant and thermal comfort, and building operational management [23,33,47–53]; [157], b). In particular, CPS play a key role in UDTs by integrating physical urban systems with digital models, creating a feedback loop that enable real-time data collection, analysis, and optimization while leveraging AI and AIoT for enhancing decision-making processes and supporting sustainability efforts in smart cities and beyond (e.g., [54–59]). Overall, the integration of UDTs with ZEBs represents a transformative approach to system and infrastructure management and forecasting [38,60–62].

Despite significant progress in both UDT and ZEB technologies, their integration remains largely unexplored. Most review studies focus on each technology independently, creating a gap in understanding how their synergistic integration can enhance environmental sustainability in the context of emerging sustainable smart cities. Specifically, much of the existing review studies treat UDTs and ZEBs as isolated systems in the context of climate change mitigation in smart cities, focusing on their individual advancements, challenges, and impacts. Key topics include the innovations and barriers in ZEBs as a strategy for mitigating climate effects (e.g., [36,53,63–70]) and the role of UDTs in advancing energy efficiency, renewable energy integration, and sustainable urban development [33,43–47,60,62,71–77]. This gap limits their collective impact on environmentally sustainable development in smart cities environmentally sustianable development in smart cities. Nonetheless, the research and practice landscape has evolved in recent years to emphasize the critical importance of integrated approaches, which are increasingly being explored in non-review studies.

Furthermore, there is a lack of a unified framework to guide the integration of UDTs and ZEBs, which hampers the full realization of their potential to maximize their contributions to environmental goals in smart cities. This integration represents a burgeoning area of research with the potential to leverage their strengths, driving the environmental transformation of this rapidly evolving urban landscape. This gap emphasizes the need for a comprehensive framework that addresses the technological and operational integration of UDTs and ZEBs, as well as promotes their synergy that can yield a result or achieve an effect that is greater than the sum of their individual contributions. Through this synergy, they complement and enhance each other within the framework of sustainable smart cities.

To address the identified gaps, this study conducts a comprehensive systematic review of how UDTs and ZEBs can be effectively integrated to enhance climate change mitigation efforts in sustainable smart cities. It primarily aims to develop a novel framework that leverages their synergistic potential, optimizing their collective impact on environmentally sustainable urban development. This study is guided by the following main research questions:

RQ1: What are the key emerging trends and research patterns in UDTs and ZEBs in the context of sustainable smart cities?

RQ2: How do UDTs enhance the operational performance and energy management of ZEBs in sustainable smart cities?

RQ3: How can a framework be developed to effectively integrate UDTs and ZEBs for advancing climate change mitigation goals in sustainable smart cities, considering the synergy of their technical, operational, and performance indicators?

The primary contribution of this study lies in developing a novel framework for integrating UDTs and ZEBs to reduce carbon emissions, improve energy efficiency, and integrate renewable energy sources in urban environments. The integrated framework offers actionable insights into the future of urban energy systems, driving the development of environmentally sustainable and climate-resilient urban environments, and informing strategies for achieving long-term sustainability. It can guide future urban planning, policy-making, and technological innovations aimed at improving climate mitigation actions and fostering zero-energy and carbon–neutral urban ecosystems.

The study is structured as follows: Section 2 presents the conceptual background, outlining the theoretical and practical foundations of UDTs and ZEBs within the framework of sustainable smart cities. Section 3 provides a survey of related work in the field, identifying existing research trends and highlighting gaps in the integration of these technologies. Section 4 details and illustrates the systematic approach to literature review. Section 5 presents the results and introduces the novel integrated framework. Section 7 provides a comprehensive discussion, summarizing the findings in relation to the research questions, comparing them with existing studies, exploring their implications for research, practice, and policymaking, and addressing the identified challenges while offering suggestions for future research. Finally, Section 8 concludes the study by recapping the key insights and highlighting the contributions made, along with some final reflections on the implications for future developments in sustainable smart cities.

2. Theoretical and practical foundations

This section outlines the key theoretical and practical foundations underpinning this study, providing a comprehensive understanding of the critical components involved in advancing environmentally sustainable urban development. The rapid expansion of sustainable smart cities, alongside the urgent need to mitigate the effects of climate change, has highlighted the critical role of integrating innovative technologies and data-driven approaches to tackle pressing environmental challenges. Central to this transformation are UDTs, ZEBs, and the convergence of AI, IoT, and CPS, which work in synergy to optimize resource management, improve energy efficiency, and strengthen urban resilience. These interconnected technologies and strategies support sustainable development goals and lay the groundwork for sustainable smart cities to mitigate future climate-related challenges while maintaining ecological balance.

2.1. Sustainable smart cities: The recent shift towards environmental sustainability

Sustainable smart cities represent a vision for the future of urban development, where the integration of advanced technologies, innovative solutions, and efficient and resilient infrastructure systems work together to enhance the quality of life for urban residents. These cities leverage emerging technologies—such as AI, AIoT, UDTs, and CPS—to optimize urban systems and foster sustainable practices, with a particular focus on advancing environmental sustainability (e.g., [11,15,18–21,26,57,78]. As an emerging model for urban development, sustainable smart cities seek to balance environmental, economic, and social dimensions of sustainability (e.g., [79–82]). The environmental dimension emphasizes the reduction of carbon emissions, the promotion of energy efficiency, the optimization of resource use, the improvement of waste management systems, and the mitigation of environmental degradation. The economic dimension fosters growth by advancing green technologies and supporting the development of sustainable industries while promoting job creation, enhancing local economies through eco-friendly innovations, and driving energy cost savings for urban communities. Accordingly, it aims to create a resilient economy that thrives while maintaining environmental integrity [1], ensuring long-term prosperity without depleting natural resources. The social dimension focuses on improving the quality of life by providing equitable access to services, fostering community engagement, addressing inequalities, and enhancing social well-being. This holistic approach emphasizes the need for greener, more adaptive urban solutions capable of meeting the needs of current generations while ensuring that future generations inherit a sustainable, thriving urban environment.

In recent years, urban development has increasingly focused on tackling the urgent challenges of environmental sustainability and addressing the impacts of climate change, with sustainable smart cities at the forefront of this transformation (see [11] for a bibliometric analysis). Initially driven by the adoption of IoT and Big Data technologies, this evolution has expanded to incorporate green and energy efficiency technologies and data-driven innovative solutions and approaches, fostering more adaptive, efficient, and resilient urban environments (e.g., [2–8]). Since the early 2020 s, the integration of cutting-edge technologies such as AI, AIoT, UDTs, and CPS has played a critical role in enhancing energy efficiency, reducing resource consumption, mitigating carbon emissions, and strengthening climate resilience [12–15,18–20,22,25,57,83]. While these technologies are not the primary focus of this study, their potential is reshaping urban infrastructure and setting the stage for the future of sustainable urban development through sophisticated, data-driven solutions [10,16,17,56,84–87], including ZEBs and UDTs. As cities continue to embrace these innovations, they are addressing current challenges and laying the groundwork for a future where urban ecosystems are capable of adapting to and thriving in the face of environmental pressures and climate-related uncertainties.

2.2. Urban digital twins: opportunities and challenges in advancing environmental sustainability goals

UDTs are digital replicas of urban environments that integrate real-time data from sensors, IoT devices, satellite imagery, and other sources to model, simulate, analyze, and predict the behavior of physical city infrastructure and systems using AI models and algorithms. This virtual representation enables a deeper understanding of city dynamics and offers actionable insights for optimizing urban operational functioning and enhancing urban planning processes. In the context of sustainable smart cities, AI- and AIoT-driven UDTs play a critical role in advancing environmental sustainability goals by enhancing resource management, optimizing energy usage, mitigating pollution, and improving infrastructure resilience to climate change. By simulating various urban scenarios, UDTs enable decision-makers to anticipate environmental impacts and devise solutions that promote sustainability and resilience through innovative approaches to infrastructure management and strategic planning (e.g., [27,88–90]). These advanced computational models help monitor and manage emissions, identify inefficiencies in urban systems, and foster data-driven decision-making that guides cities towards more sustainable, climate-resilient practices.

The integration of AI, AIoT, and CPS into UDTs significantly enhances their functionality and performance, enabling data-driven approaches to urban management and planning [55,56,91–93]. AI algorithms allow for real-time data analysis and predictive modeling, improving decision-making processes related to various environmental domains. AIoT, combining the power of AI and IoT, enables seamless communication between devices and systems, allowing for more accurate monitoring and management of environmental factors such as energy usage, emissions, and waste [25]. CPS facilitates the interaction between the physical and digital worlds, optimizing processes and improving the responsiveness of urban systems. Furthermore, AI is increasingly integrated into CPS, enabling smarter, more efficient operation through real-time data processing and predictive analytics [29,94]. This convergence of AI and CPS, alongside IoT, is essential for optimizing complex systems and creating more adaptive, resilient infrastructures in modern urban settings [95–97]. Together, these technologies empower cities to adapt more quickly to environmental challenges and achieve their sustainability goals [57].

The development and implementation of UDTs encounter a variety of challenges that hinder their effectiveness and scalability. These challenges include limited scenario exploration, which restricts the potential for comprehensive decision-making, and the analysis and interpretation of unstructured data are cumbersome due to the intricacy of urban systems and the vast variety of data types involved, complicating decision support by offering limited alternatives for action [27,98–102]. Issues with data quality, such as inadequate data availability and data inconsistency across different sources, further exacerbate these challenges [100,103–106]. These data issues are compounded with computational constraints that necessitate the development of multilevel integrated models to effectively manage and process the data within UDT frameworks [107–109]. Moreover, current UDT frameworks struggle with the complexity of integrating and visualizing detailed and realistic urban models, often lacking robust validation mechanisms to ensure the accuracy and reliability of their outputs [101,102,105,110,111]. These issues underscore the need for advancements in UDT systems to enhance their capability to support sustainable development and environmental sustainability in smart cities [107].

The integration of UDTs with AI and AIoT involves several challenges, as identified and discussed by several studies (e.g., [112,113,25,26,85,92,93,174]. These challenges include:

Complex urban system management: Managing interconnected urban systems at scale is inherently complex. The integration of UDTs with AI and AIoT requires the coordination of multiple systems, technologies, and stakeholders, which can be difficult to manage, particularly when there are legacy systems and infrastructure that may not be compatible with newer technologies.

Data synchronization: Ensuring synchronization of data from various sources (e.g., sensors, devices, and IoT systems) is critical to ensure that the digital representation of urban systems (i.e., UDTs) accurately reflects real-world conditions. Mismatched or delayed data can undermine the accuracy and effectiveness of AI-driven decisions.

Real-time processing capabilities: UDTs, combined with AI and AIoT, must process large volumes of data in real-time, which requires high-performance computing resources. Real-time decision-making capabilities are essential, but data overload and system latency may hinder the efficiency of this process.

Data latency: The need to handle real-time data introduces issues around latency. In fast-moving urban environments, even minor delays in data processing can significantly impact the effectiveness of AI systems that rely on this data for predictions and optimizations.

Computational overhead: The integration of machine learning and deep learning algorithms requires substantial computational power, particularly when processing vast amounts of sensor and operational data. The computational overhead can strain system resources, requiring ongoing upgrades and optimization efforts.

Security concerns: The deployment of AI and IoT systems introduces security risks, particularly when sensitive data is involved. Privacy concerns and potential cyberattacks on integrated urban infrastructure systems remain significant challenges that need to be addressed.

Interoperability and scalability: Integrating diverse systems across different urban contexts and ensuring they can communicate effectively with one another is a major challenge. Moreover, as cities grow and evolve, scaling these solutions to accommodate new data sources, technologies, and demands becomes more difficult.

These challenges highlight the complexity and scope of integrating UDTs with AI and AIoT technologies in the context of sustainable smart cities, especially when seeking to optimize urban systems for energy efficiency, sustainability, and climate change mitigation. Addressing these challenges is crucial for realizing the full potential of UDTs and ZEBs in sustainable urban development.

Moreover, in the realm of ZEBs, the integration of UDTs has sometimes failed to optimize energy consumption as predicted due to inaccurate energy modeling or inadequate sensor data integration, impacting the buildings' ability to achieve net-zero energy status. AI-driven predictive models in UDT systems may provide inaccurate forecasts due to insufficient training data or overlooked variables. Moreover, ZEB projects have occasionally underperformed when real-time data integration from IoT devices did not align effectively with the UDT system, resulting in less than optimal energy management and higher operational costs. These integration challenges and failures highlight the need for improved system interoperability and scalability to fully leverage the potential of UDTs in enhancing urban infrastructure management (e.g., [27,54,99,114]), including the energy efficiency of buildings.

2.3. Zero energy buildings: Contributions to climate change mitigation strategies

ZEBs are structures designed to produce as much energy as they consume over a one-year period, primarily through renewable energy sources such as solar, wind, and geothermal energy. The key principle behind ZEBs is energy efficiency, with these buildings incorporating advanced insulation, high-efficiency HVAC systems, and smart technologies to minimize energy consumption. ZEBs contribute directly to climate change mitigation by reducing reliance on fossil fuels and lowering greenhouse gas emissions [36,64,68]. They help reduce the carbon footprint of buildings, which are significant contributors to global energy use and emissions [41,53,69]. ZEBs align with broader efforts to transition toward a low-carbon economy by demonstrating how buildings can function sustainably, producing renewable energy while minimizing waste and environmental impact [67,70].

The integration of AI and AIoT with ZEBs plays an essential role in enhancing their functionality. AI algorithms enable smart, sustainable energy management by optimizing energy performance based on real-time data and predictive analytics [53]. Leveraging the capabilities of AIoT, ZEBs continuously monitor and adjust energy usage, ensuring that energy production from renewable sources is maximized while minimizing consumption. For example, AIoT systems can predict energy demands, optimize heating, cooling, and lighting operations, and detect inefficiencies in building systems. This seamless integration ensures that ZEBs meet their energy goals and adapt to environmental changes, further strengthening their role in climate change mitigation and supporting sustainable urban development.

The integration of UDTs and ZEBs in the dynamic landscape of sustainable smart cities provides a comprehensive framework for advancing environmentally sustainable urban development. UDTs support ZEBs by providing real-time data that enhances building performance, optimizes energy usage, and supports predictive maintenance [38,61,62]. ZEBs, in turn, play a key role in mitigating climate change by reducing energy demand and incorporating renewable energy technologies. Furthermore, ZEBs and UDTs are key to optimizing energy management, particularly when integrated with AI, AIoT, and CPS. Building performance simulations, powered by AI and DTs, has the potential to significantly improve energy efficiency in buildings [115]. Expanding on this integration, Cali et al. [116] explore the combination of DTs with AI, IoT, and blockchain to enhance energy management in smart cities. They emphasize the potential of DTs as decision-support tools in urban energy systems, highlighting the need for further technological advancements to fully realize their potential. The application and integration of DTs, AI, IoT, and CPS in residential districts and buildings demonstrates how these technologies work together to optimize energy consumption while maintaining comfort in ZEBs, nZEBs, and building performance [23,47,51–53,55,117], b). The collaboration between these technologies contributes to achieving broader climate goals by optimizing energy flows, reducing carbon emissions, and fostering sustainable urban ecosystems. Together, UDTs and ZEBs, powered by AI, AIoT, and CPS, provide a powerful synergy, where digital innovation and energy efficiency intersect to promote climate resilience and reduce environmental footprints in urban areas. This integrated approach provides a roadmap for cities to mitigate climate change while advancing environmental sustainability.

3. Related work

UDT systems have garnered significant attention as a foundational technology in sustainable smart cities, offering functionalities such as real-time monitoring, control, and decision-making through a dynamic digital representation of physical city assets. Similarly, ZEBs are designed to function by significantly reducing the need for external energy sources, particularly through renewable energy systems. The convergence of UDT and ZEB technologies represents a transformative frontier in sustainable urban development, addressing challenges such as energy efficiency, performance optimization, system integration, and climate resilience. This section analyzes aims and findings from 25 review studies conducted in recent years, categorized into two themes: 1) advancements and challenges in ZEBs as a strategy for climate change mitigation and 2) the role of UDTs in enhancing energy efficiency, enabling predictive maintenance, and supporting sustainable urban management. The first theme focuses the evolution of ZEB concepts, technological innovations, and their implementation across diverse climatic and regulatory contexts. The second theme involves how UDTs enhance real-time monitoring, facilitate data-driven decision-making, and optimize energy flows in smart cities. Together, these studies showcase the catalytic impact of ZEBs and UDTs in advancing environmental sustainability and creating efficient, resilient urban ecosystems, as well as illuminate the collaborative potential of ZEBs and UDTs in advancing climate change mitigation goals.

3.1. Advancements and challenges in zero energy buildings as a strategy for climate change mitigation

ZEBs have emerged as a crucial solution to mitigate the impacts of climate change by reducing energy consumption and minimizing carbon emissions in urban settings. They involve advancements in technologies such as energy-efficient design principles, strategies for optimizing energy use, and the implementation of renewable energy systems. The studies reviewed revolve around the progress made in ZEB technologies, the challenges in achieving energy goals, and potential pathways for scaling their implementation across various urban contexts.

In the realm of technological advancements, Wang et al. [53] provide a comprehensive review of key technologies critical for achieving ZEBs. The study highlights the role of energy-efficient measures, renewable energy technologies, and building energy management systems, emphasizing the integration of AI to optimize energy performance. Similarly, Al Dakheel et al. [63] explore the evolution of smart retrofitting, proposing it as a pathway to achieving nZEB standards. This research underscores the importance of energy flexibility and renewable energy integration as key features of modern ZEBs.

Regarding the role of renewable energy, Senyonyi et al. [69] present a systematic review of solar energy techniques in ZEBs, identifying passive and active approaches as essential for optimizing building performance. The study emphasizes gaps in experimental research and workforce training, advocating for stronger collaborations between academia and industry to advance solar technology adoption in ZEBs. Expanding on this, concerning case studies and global practices, Mohammed et al. [36] review ZEB implementations in residential buildings worldwide, analyzing 40 case studies to identify effective technologies across climates. Solar PV systems dominate warmer climates, while advanced insulation and heat recovery systems are critical for colder regions. The study highlights regional disparities in adoption and stresses the importance of context-specific solutions.

As regards conceptual frameworks and regional adaptation, Jaysawal et al. [64] review foundational concepts of Net Zero Energy Buildings (NZEBs), focusing on their self-sustaining energy cycles and renewable energy utilization. The study emphasizes the importance of tailoring energy systems to climatic conditions and regional energy demands. Expanding on this, Mengaw et al. [67] investigate NZEBs in tropical climates, highlighting unique challenges such as high cooling demands and limited energy storage solutions. The study underscores the need for region-specific innovations to address climatic constraints and improve the feasibility of ZEBs in such environments.

In the domain of policy and global strategies, Labaran et al. [65] examine barriers and facilitators to adopting energy-efficient building practices, identifying key influences such as government oversight, design standards, and material availability. The study proposes leveraging IoT and building automation systems to address implementation challenges. Furthermore, Lou and Hsieh [66] emphasize the role of Life Cycle Assessments (LCA) in reducing both embodied and operational emissions of ZEBs. The study discusses multidisciplinary strategies to align energy efficiency with emissions reduction. Meanwhile, Wilberforce et al. [70] critically evaluate the commercialization challenges of ZEBs, identifying cost barriers, limited awareness, and public perception as major obstacles. The study suggests policy incentives, such as subsidies and tax rebates, to drive adoption.

With respect to research trends and thematic evolution, Omrany et al. [68] conduct a bibliometric analysis involving three decades of research on NZEBs, identifying key themes, influential researchers, and emerging topics in the field. The analysis highlights the evolution of NZEB research, with a particular focus on energy conservation, energy production, storage, and methodologies. The study suggests new research directions, such as the integration of electric vehicles, zero-emission neighborhoods, and smart buildings, providing a comprehensive overview of the trends and gaps in the field.

The reviewed studies highlight the significant progress made in the development and implementation of ZEBs. Key advancements include improvements in building energy management systems, the integration of renewable energy sources, and the optimization of building envelopes to reduce energy demand. However, challenges persist in areas such as cost, regional adaptation, and technical integration. The literature highlights the importance of further research on overcoming these barriers, developing standardized frameworks, and improving the scalability of ZEB solutions across different climates and building types.

3.2. The role of urban digital twins in advancing energy efficiency and sustainable urban development

UDT technologies are playing an increasingly important role in enhancing energy efficiency and optimizing the management of urban systems. They are being applied to improve building performance, integrate renewable energy solutions, and manage resources more effectively. The studies reviewed in this section explore the applications of UDTs in various urban environments, from real-time monitoring of energy use to predictive maintenance and advanced data analytics that support sustainable urban development.

In the context of smart green buildings, Yang and Wang [62] provide a comprehensive review of the applications and integration of DTs. They emphasize their potential to enhance energy use, occupant comfort, and sustainability in green buildings. However, they also highlight challenges in embedding DTs into the core design of smart green buildings, noting the need for forward-looking approaches that integrate green structures and user-centered designs to foster long-term ecological benefits in urban areas. Regarding energy efficiency in buildings, Bortolini et al. [44] provide a detailed analysis of DT applications in optimizing building energy performance. Their study classifies research into four categories: optimization design, occupant comfort, building operation and maintenance, and energy consumption simulation. It highlights the potential of DTs to revolutionize energy efficiency in the built environment by identifying gaps and future directions.

Deng et al. [118] address the evolution of DTs from Building Information Modeling (BIM), proposing a five-level ladder framework for categorizing DT applications across the building lifecycle. These categories encompass energy performance optimization, construction management, and environmental monitoring. The study reveals a lack of integration between lifecycle stages, limiting the full realization of DTs' potential. They propose a structured framework to address these challenges and provide a baseline for advanced DT research. In the operational phase of buildings, Cespedes-Cubides and Jradi [46] review DT applications aimed at improving energy efficiency during operations and maintenance. Their findings identify five primary applications: component monitoring, anomaly detection, operational optimization, predictive maintenance, and scenario simulation. However, the reliance on BIM and the lack of robust data acquisition systems present significant hurdles to effective implementation.

In regard to smart energy management and thermal comfort, Lamagna et al. [72] review DT applications for optimizing energy flows in interconnected systems, such as power grids and thermal networks. The study identifies critical challenges, including real-time data processing, system interoperability, and storage integration. They propose a roadmap to address these barriers, underscoring DTs' pivotal role in transforming urban energy systems. Focusing on thermal comfort and energy optimization, Arowoiya et al. [23] examine how DTs leverage technologies like Artificial Neural Networks (ANNs) and AI-driven models to predict and manage building energy consumption. Their study highlights barriers such as limited interoperability, insufficient adoption of environmental sensors, and the lack of occupant-centered models. They call for the development of standardized frameworks and emphasize the need for collaboration to enhance DT adoption in improving building sustainability and performance.

Regarding broader urban applications, Liu et al. [73] explore DT implementation across buildings, landscapes, and urban environments.

They identify key research trends, including the development of DT frameworks for urban design, the use of DT-based analytical tools, and their application in underexplored areas such as landscape planning. Despite advancements, they call for more interdisciplinary research to fully exploit DTs' potential in developing cohesive and sustainable urban ecosystems. In advancing global practices. Papadonikolaki and Anumba [76] systemically review how DTs can support the Net Zero vision by tracking carbon emissions across assets' lifecycles for decarbonization efforts. Their study underscores the underutilization of DTs for Net Zero applications and discusses challenges such as overreliance on technocratic solutions and misconceptions about the role of visualization in DT systems. The findings emphasize emergent themes, including the need for systems thinking and the future design of DT systems to achieve Net Zero.

Addressing energy consumption forecasting, Boukaf et al. [45] evaluate the role of DTs in forecasting building energy consumption using IoT devices and ML algorithms. Their study highlights DT applications in HVAC system performance, indoor air quality improvement, and overall energy prediction, underscoring the potential for DTs to meet net-zero energy goals. In reducing energy consumption in buildings, Arsecularatne et al. [43] investigate DTs' ability to monitor and optimize energy usage, focusing on predictive maintenance and occupant behavior analysis. They emphasize the necessity of standardized frameworks and enhanced data privacy measures to fully integrate DTs into urban building systems.

The application of DT technology spans several critical areas in advancing sustainability and energy efficiency in urban environments. Onile et al. [75] examine how DTs enhance consumer energy behavior modeling through personalized recommendations and intelligent recommendation systems. Their review highlights DTs' role in improving energy efficiency and demand-side sustainability, despite challenges related to privacy concerns and data abstraction. Concerning sustainable material assessment and urban context. In relation to decarbonization frameworks, Ohueri et al. [74] develop the DT-DeFOB framework for achieving net-zero carbon targets in operating buildings. Their review integrates ISO guidelines for carbon assessment and highlights the need for dynamic criteria tailored for operational buildings. The study provides a pioneering blueprint for decarbonizing urban environments using DTs. Lastly, Ferdaus et al. [33] assess the integration of DTs with AI and blockchain technologies in urban environments. Their comprehensive review highlights several themes that illustrate DTs' innovative role in energy management, renewable integration, and achieving net-zero energy objectives.

In the context of building performance assessment, Rocco [77] integrates LCA with DTs to optimize building material selection and real-time evaluations. The study highlights how DTs facilitate rapid assessments of environmental impacts, enabling more sustainable construction practices and bridging gaps in traditional building methodologies. A recent review study by Bibri [60] develops a ZEB rating framework for sustainable smart cities by integrating DT technology. The study addresses a key challenge in energy-efficient building certifications, namely the "building performance gap"—the discrepancy between expected and actual building performance, often influenced by occupant behavior. The framework enables real-time, dynamic assessments of key parameters such as energy consumption patterns, occupant comfort, and system efficiency. This approach allows city planners to simulate various scenarios, optimize resource allocation, and ensure that buildings are both energy-efficient and aligned with the principles of sustainable smart cities. The integration of UDT in the ZEB rating system enhances the accuracy and applicability of performance evaluations, advancing the goals of climate-resilient, sustainable urban environments.

Overall, these studies underscore the catalytic role of DTs in advancing energy efficiency, green building innovation, building performance assessment, decarbonization, and sustainable urban development. They highlight critical challenges, including data integration, insufficient integration across lifecycle stages, system interoperability, a lack of standardized methodologies, scalability, and occupant-centered design while advocating for robust frameworks, interdisciplinary collaboration, and region-specific solutions to optimize DT applications and maximize their impact in shaping emerging sustainable smart cities. These insights suggest a promising trajectory for DTs in building and energy sectors, with significant implications for achieving global sustainability goals.

3.3. *Research gap identification*

The analysis of the 25 studies included in this survey reveals significant progress in the development and application of UDT and ZEB technologies in environmentally sustainable urban development. However, it also uncovers critical gaps that hinder the full realization of their synergistic potential. While advancements in key critical areas of both technologies are evident, the interplay between UDTs and ZEBs remains largely unexplored, particularly in terms of their combined impact on climate change mitigation strategies. Existing research often overlooks the critical need to synergize the management functionalities of UDTs and ZEBs. The absence of a structured and scalable framework to align their capabilities hampers cities' ability to address the interconnected challenges of environmental sustainability. This fragmentation underscores the strategic importance of integrated frameworks that enable cities to balance technological innovation with practical and adaptive solutions for climate mitigation and sustainability.

These gaps highlight the critical need for this study to propose a robust framework and strategic approaches for effectively integrating UDTs with ZEBs, thereby unlocking their collaborative potential to mitigate climate change effects and promote environmentally sustainable urban development. This study aims to address these limitations, contribute to the broader discourse on sustainable urban ecosystems, and pave the way for future interdisciplinary advancements by conducting a comprehensive state-of-the-art review and presenting a novel UDT-ZEB integration framework.

4. Research methodology

This study adopts a mixed-method approach, integrating both systematic review and bibliometric analysis, to analyze and synthesize existing research on the integration of UDTs and ZEBs in driving climate change mitigation strategies in sustainable smart cities. The systematic review serves as the primary methodological focus, providing a thorough and structured examination of the literature to address RQ 2 and RQ 3. It allows for an in-depth exploration of the content, methodologies, and outcomes of studies related to the integration of UDTs and ZEBs in the dynamic context of sustainable smart cities. In contrast, the bibliometric analysis, while secondary, plays a complementary role by offering quantitative insights into research trends, publication patterns, and emerging areas of interest related to UDT and ZEB integration to answer RQ 1.

The systematic review approach helps to synthesize qualitative findings, uncover knowledge gaps, and assess the implications of existing research. It allows for the identification of critical areas that require further investigation and exploration. Meanwhile, bibliometric analysis, using VOSviewer, provides a comprehensive mapping of research trends, networks, and key themes by analyzing citation patterns, co-occurrence of keywords, and collaboration networks. It visually highlights both the structural and dynamic features of the field, providing a broader understanding of the integration of UDTs and ZEBs and their collective role in achieving environmental sustainability and climate mitigation goals in urban environments. This dual-method approach ensures a holistic and well-rounded understanding of the multifaceted topic and the evolving knowledge landscape by addressing both the breadth of research trends and the depth of specific insights. It provides the necessary tools to identify critical areas of focus and key gaps that inform the convergence of UDTs and ZEBs while enabling a nuanced understanding of their future potential and the challenges and limitations they encounter in contributing to climate change mitigation goals within the framework of sustainable smart cities.

4.1. Research design

This research is designed primarily as a systematic review, involving a structured process of identifying, screening, selecting, extracting, analyzing, and synthesizing relevant studies, along with the tabulated analysis of UDT and ZEB indicators versus topics discussed in these studies, to develop a comprehensive framework (Fig. 1). This multiphase approach provides a robust foundation for identifying synergies and opportunities for integrating UDTs and ZEBs in the context of sustainable smart cities.

The methodology follows a thematic approach, which is particularly effective for interdisciplinary topics, where diverse perspectives need to be unified into a coherent narrative. This approach helps to highlight key trends, synthesize critical insights, and identify gaps in the current body of knowledge by categorizing the literature into central themes. It builds on and addresses the gaps identified in Section 3, particularly the absence of a comprehensive framework that integrate UDTs and ZEBs in emerging sustainable smart cities. It allows for the identification of synergies, disconnects, and priority areas for improvement by categorizing prior studies under thematic headings. It substantiates the key gaps in the literature and lays the foundation for developing a novel framework that aligns operational and strategic capabilities of UDTs and ZEBs to address the complexities of climate change mitigation and urban sustainability. Furthermore, it reinforces the relevance and originality of the proposed framework by synthesizing the latest research and developments in the field, ensuring it is grounded in current trends and best practices.

4.2. Preferred reporting items for systematic reviews and meta-analyses

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Fig. 2) was applied to ensure transparency and rigor throughout the review process. This standardized approach ensures all stages of the systematic review are clearly documented and methodically executed. To support this process, leading academic research databases, including Scopus, Web of Science (WoS), ScienceDirect, and SpringerLink, were utilized. These databases are recognized for their comprehensive coverage of high-quality, peer-reviewed studies from a wide array of academic disciplines Their use facilitated the retrieval of a wide range of academic journals, conference proceedings, and book chapters, offering a broad spectrum of resources that provide relevant insights into the integration of UDTs and ZEBs in sustainable smart cities.

To further refine the search and improve specificity and relevance, a set of carefully selected keywords and their corresponding combinations were employed. These keywords were designed to address both the technological and environmental aspects of UDTs and ZEBs, capturing the breadth of existing knowledge while focusing on the interdisciplinary nature of the study. The keyword combinations used to conduct the searches across the selected databases included: ("Digital Twins" OR "DTs") AND ("Zero Energy Buildings" OR "ZEBs"); ("Sustainable Smart Cities" OR "Smart Cities") AND ("Digital Twins" OR "DTs"); ("Sustainable Smart Cities" OR "Smart Cities") AND ("Zero Energy Buildings" OR "ZEBs"); ("Sustainable Urban Development" AND "Digital Twin") OR ("Energy Efficiency" AND "Zero Energy Buildings"); ("Smart Cities" AND "Energy Management") OR ("Digital Twins" AND "Climate Change Mitigation"); and ("Climate Change Mitigation" AND "Zero Energy Buildings") OR ("Sustainable Urban Development" AND "Zero Energy Buildings"). These combinations were applied across the title, abstract, and keyword fields of articles, ensuring a thorough and precise search to capture the most relevant literature for this review. The strategic use of Boolean operators, such as "AND" and "OR," helped optimize the results to include studies that address multiple intersecting themes while ensuring the inclusion of diverse perspectives on the convergence of UDTs and ZEBs in sustainable smart cities.

The study includes research published between 2019 and 2024, a period chosen to emphasize the most recent advancements and trends in the rapidly evolving fields of UDTs, ZEBs, and sustainable smart cities. This time span captures the latest innovations and the state-of-the-art in research, providing valuable insights into the future directions of UDT and ZEB integration in these cities. Accordingly, the study ensures a relevant and up-to-date analysis of emerging technologies and their applications in climate change mitigation and environmental sustainability.

The inclusion and exclusion criteria outlined in in Table 1 were carefully designed to ensure a focused and targeted selection of studies. This process emphasizes the inclusion of high-quality, impactful peer-reviewed research that is directly aligned with the study's aim and research questions. At the same time, it filters out studies that are irrelevant, lack sufficient detail, or do not meet the required academic standards, thereby ensuring that only the most relevant and rigorous studies are considered for this review.

4.3. Process of data extraction

The data extraction process involved systematically gathering relevant information from the selected studies to ensure consistency, accuracy, and thoroughness. Key details, including the study's aim, methodology, results, conclusions, and thematic insights, were recorded. A structured approach was employed to capture essential attributes such as core concepts, technologies, application domains, integrative frameworks, and identified challenges. This approach facilitated the collation of comprehensive and comparable data, enabling a detailed evaluation of each study's relevance and alignment with the objectives of this research. Moreover, a quality appraisal was incorporated into the process to assess the rigor and reliability of the studies included. This appraisal involved evaluating each study's details to ensure that only studies with definitive and credible evidence were included in the analysis.

4.4. Process of data analysis

Following the data extraction, the studies were analyzed using thematic synthesis, a qualitative approach that focuses on identifying recurring themes, patterns, and relationships across the literature. The analysis process involved grouping the studies into both pre-defined and emergent categories, with a specific focus on technological synergies, integration opportunities, and contributions to climate change mitigation efforts in the realm of sustainable smart cities. Special attention was given to examining the synergistic integration of UDTs and ZEBs, exploring their collaborative potential and role in addressing environmental challenges. The analysis also included cross-comparing studies to assess their alignment with the objectives of this research. This allowed for the identification of areas of convergence and divergence, revealing

Fig. 1. A flow diagram outlining the step-by-step process of developing the integrated framework.

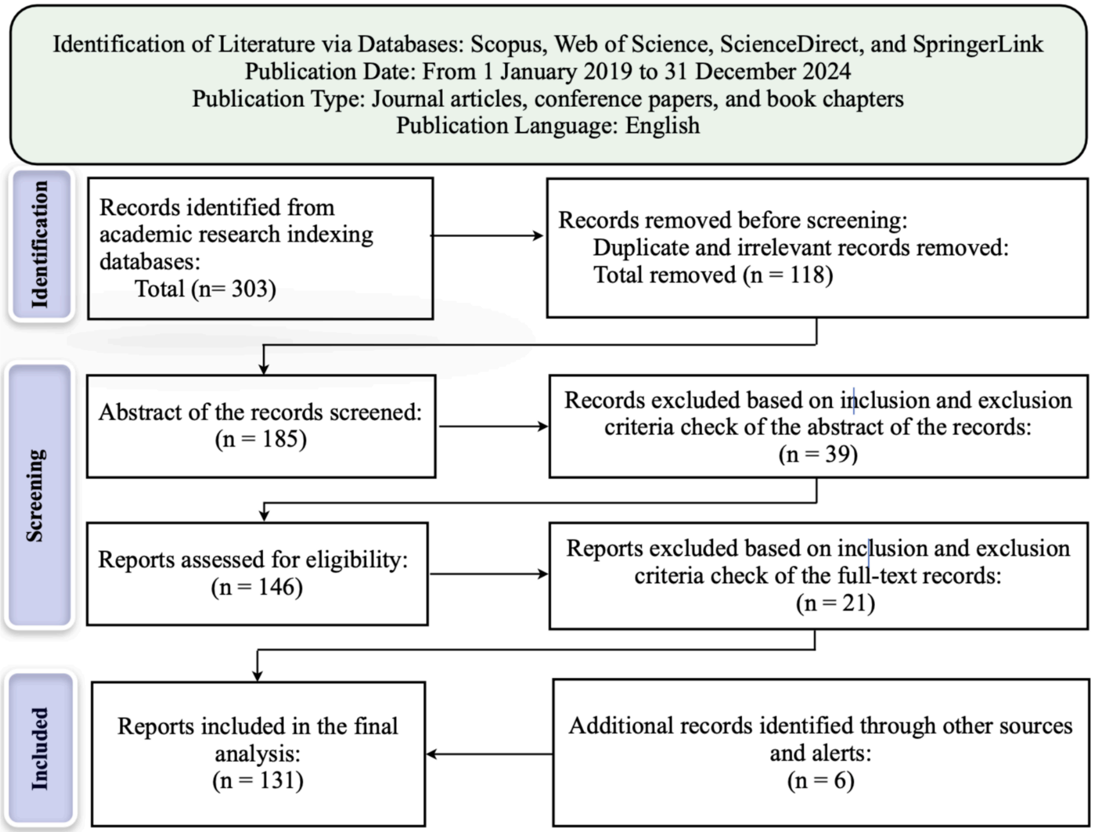

Fig. 2. The PRISMA flowchart for literature search and selection. Page et al. .
Source: Adapted from [131]

Table 1
Inclusion and Exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Studies published between 2019 and 2024.	Studies published outside the 2019–2024 timeframe.
Studies focusing on the integration of DTs and sustainable smart cities, the integration of ZEBs and sustainable smart cities, DTs and building and energy management in smart cities, or DTs for building energy efficiency.	Studies irrelevant to any of these integrative perspectives.
Studies addressing the integration of UDTs and ZEBs or ZEBs.	Studies unrelated to the integration of UDTs and ZEBs and to ZEBs
Peer-reviewed journal articles, conference papers, and book chapters.	Articles that are not peer-reviewed or published in academic outlets.
Studies published in English.	Studies written in languages other than English.

common themes and conflicting viewpoints that highlight important research areas needing further exploration.

4.5. Synthesis of findings

The synthesis process integrated the analyzed findings into a coherent narrative that informed the development of the novel framework. This approach focused on identifying the current state of knowledge regarding the integration of UDTs and ZEBs, including how UDTs can optimize the operational performance and energy management of ZEBs, and the potential pathways for their integration. Insights from thematic categories were combined to highlight synergies, address gaps, and identify opportunities for future advancements in the field. The synthesis created a unified understanding of how emerging technologies can be effectively leveraged to foster environmentally sustainable urban development by drawing connections between diverse studies. The resulting narrative reflects the state-of-the-art in the field, substantiating the novelty of the proposed framework for integrating UDTs and ZEBs in sustainable smart cities.

4.6. Limitations

While the systematic review methodology ensures rigor and comprehensive analysis, there are several limitations to acknowledge. First, the inclusion criteria focused primarily on English-language publications, which may have excluded relevant studies in other languages. In addition, the review is limited to studies published in the selected databases, potentially overlooking other valuable research published in non-indexed journals or conferences. Furthermore, the time frame of the study (2019–2024) may exclude important earlier studies that laid the groundwork for current knowledge or newer research that could contribute to emerging trends.

Another limitation is the inherent risk of selection bias, where studies that do not meet specific criteria may be excluded, leading to a potentially narrow scope. While we aimed for a structured and objective process, the categorization of studies into thematic areas can introduce a degree of subjectivity, which may affect the consistency of the analysis. The reliance on secondary data from published studies also means the findings are limited by the quality and scope of the available literature and the interpretation of these studies.

Finally, we may have excluded valuable insights from grey literature by focusing on peer-reviewed publications, including industry reports and policy documents, which could provide alternative perspectives on UDTs and ZEBs in sustainable smart cities. Despite these limitations, the methodology provides a solid foundation for addressing the research questions and offers useful insights into the integration of UDTs and ZEBs to advance environmentally sustainable development in smart cities.

5. A bibliometric analysis: term co-occurrence, cluster analysis, and publication trends

The dual approach to review allowed for a more holistic understanding of the intellectual structure and research dynamics surrounding UDTs and ZEBs. The bibliometric analysis involved the use of three key figures to better understand the distribution of research on UDTs and ZEBs in the dynamic context of sustainable smart cities. Fig. 3, which represents the results of the term co-occurrence analysis, was employed to map the relationships between key concepts and terms, revealing the main themes and areas of focus in the literature. Fig. 4, illustrating the relationship between different clusters and the weight of their occurrence, allowed for a deeper understanding of how different research topics are connected and how influential certain research clusters are in shaping the field. Finally, Fig. 5, showing the number of publications from 2019 to 2024, provided insights into the temporal trends and shifts in research activity, helping to identify emerging topics and research areas.

The primary tool utilized for bibliometric analysis was VOSviewer 1.6.17, which enabled a detailed exploration of research trends, relationships, and developments within the interdisciplinary field on focus. The datasets compiled from the relevant scholarly sources published between 2019 and 2024 included key metadata. Following the application of inclusion and exclusion criteria, the documents addressing the role of UDTs in supporting ZEBs for climate change mitigation and sustainable development in smart cities were selected for analysis.

VOSviewer was used to perform a term co-occurrence analysis, identifying the most frequently used terms and concepts related to UDTs and ZEBs and their integration in emerging sustainable smart cities. This analysis mapped the relationships between these terms and concepts, offering insights into the core themes driving the research, to reiterate. Fig. 3 presents the results of this analysis, with nodes representing frequently occurring terms. The size of each node corresponds to the frequency of the term, while links between nodes indicate their co-occurrence, visualizing the relationships between key topics in UDT, ZEB, and smart city research. Co-occurrence networks in VOSviewer are generated based on author keywords, allowing researchers to explore connections within the data. The distance-based maps illustrate the strength of relationships, where smaller distances indicate stronger associations. Items are sized according to their frequency in relevant publications, and clusters are distinguished by different colors.

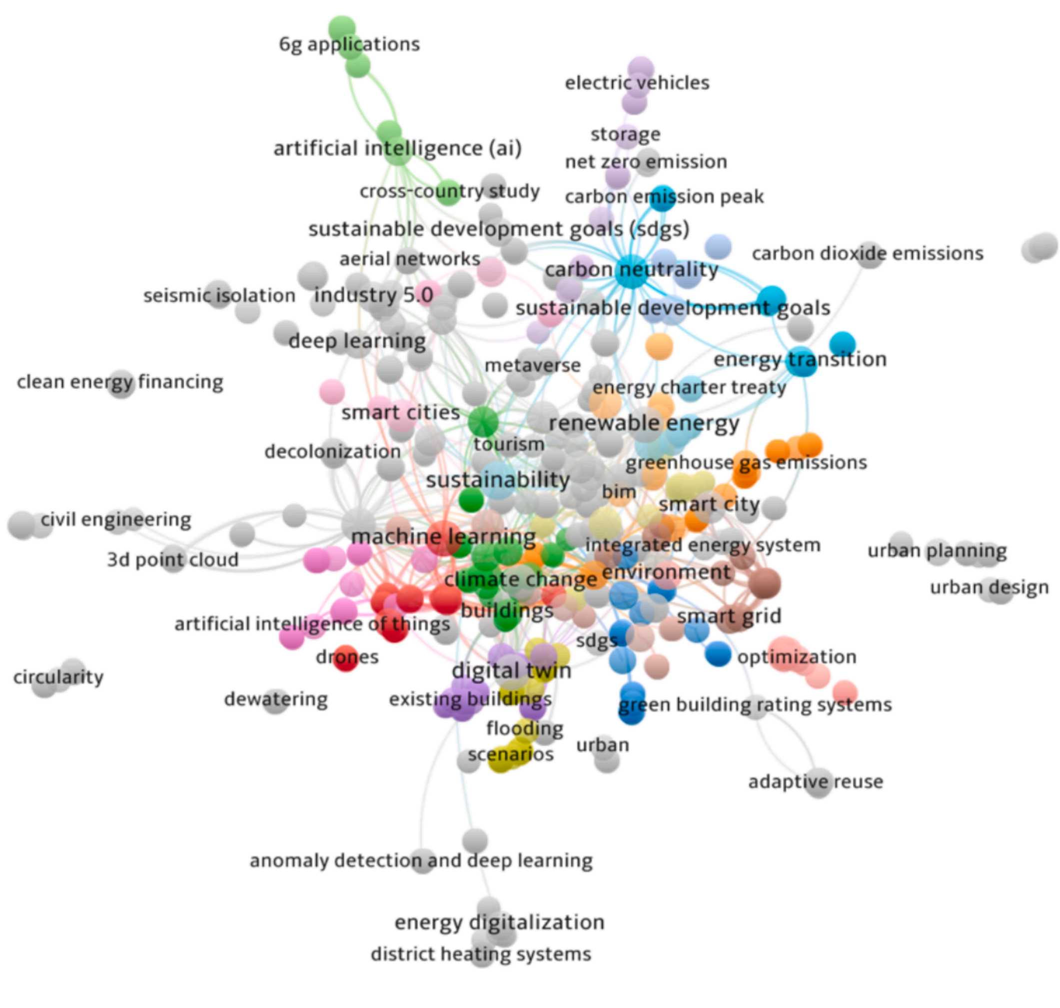

Fig. 3. Result of the term co-occurrence analysis.

The analysis identified 48 clusters with significant thematic overlap, each highlighting different aspects of UDTs, ZEBs, and related technologies. The primary focus is on five clusters due to their high relevance. The red cluster is centered around the integration of DTs, AI, ML, and Renewable Energy. It demonstrates how DTs are being combined with cutting-edge technologies to enhance renewable energy systems and their integration, offering a powerful framework for managing energy demand and supply efficiently. The green cluster emphasizes the intersection of Sustainability, Climate Change, Buildings, AI, and Digitalization. It showcases how DTs, along with advanced AI and digital technologies, are being employed to tackle the urban sustainability challenges related to climate change. This is critical for managing the environmental impact of buildings and urban systems. The blue cluster brings together terms like ZEBs, Energy Efficiency, Energy Policy, CPS, and Smart Buildings. It focuses on the application of UDTs in optimizing energy use, especially in building sectors. The integration of CPS allows for real-time monitoring and operational optimization, making it possible to enhance energy efficiency and reduce energy consumption in buildings. The light green cluster includes keywords such as Resilience, Smart Monitoring and Management, and Sustainability Transitions. It highlights the role of UDTs in improving urban resilience through advanced systems for monitoring and management. These systems support sustainable transitions by helping cities adapt to changing environmental conditions. The purple cluster prominently features keywords such as Energy, Energy Consumption, Net Zero Carbon Emissions, Existing Buildings, Building Refurbishment, and Thermal Comfort. It shows the increasing integration of energy management strategies aimed at reducing carbon footprints, with a focus on optimizing energy consumption in existing buildings and refurbishing them to meet energy performance standards.

The analysis reveals significant research trends, with a clear focus on the convergence of UDTs and ZEBs, driven by the integration of transformative technologies such as AI, IoT, and CPS. The prominence of AI and IoT in the red and green clusters underscores their increasingly instrumental role in advancing key aspects of sustainable urban development, including energy efficiency, renewable energy integration, and climate change mitigation. These technologies enable real-time monitoring, predictive analytics, and operational optimization, which are crucial for reducing energy consumption and enhancing environmental resilience in urban environments. Furthermore, the frequent occurrence of terms such as “renewable energy” and “zero energy buildings” reflects the growing emphasis on optimizing energy performance, particularly in buildings, to reduce carbon emissions and enhance sustainability. However, despite these developments, the analysis also uncovers a critical gap in the literature—the lack of comprehensive studies exploring the full integration of UDTs and ZEBs. This gap suggests that, while individual technologies show promising potential, their synergistic integration remains underexplored, limiting their ability to fully realize and optimize environmental outcomes and accelerate progress towards sustainable smart cities. This calls for further research that bridges this gap, unlocking the combined power of these technologies to meet climate change mitigation goals more effectively.

In the bibliometric analysis, Fig. 3 visualizes publication trends over time, showing the volume of research focused on specific keywords or topics. However, some keywords that appear in the VOSviewer term co-occurrence analysis do not show up in Fig. 3 due to the differing focus of each analysis. VOSviewer examines how often keywords appear together within the same literature, focusing on the relationships between terms rather than their individual frequency. For example, keywords like “renewable energy” in the red cluster, “zero energy building” in the blue cluster, and “buildings” in the green cluster do not appear in Fig. 3 as they don’t meet the threshold for publication frequency, despite being strongly connected with other dominant keywords. This highlights emerging or niche topics that may not have accumulated enough publications to be reflected in publication trends. In contrast, VOSviewer emphasizes the strength of the relationships between terms, capturing important but less frequently published keywords that are linked with more prominent topics, even though they may not yet be widely published. Thus, Fig. 3 is more focused on publication frequency, while VOSviewer identifies significant keywords based on co-occurrence, providing deeper insights into the relationships within the research landscape.

This term co-occurrence analysis uncovers significant thematic trends, emphasizing the convergence of UDTs with technologies aimed at improving energy efficiency, renewable energy integration, and climate change mitigation in sustainable urban environments. The visualization shows how different research topics are connected, providing a comprehensive view of the key drivers in this domain.

The weight of occurrence within each cluster shows the prominence of various topics and highlights the extent to which certain themes are discussed in the literature. This analysis helped identify the areas that are more heavily explored and the potential for convergence between UDTs and ZEBs. Fig. 4 illustrates the relationships between the different research clusters identified in Fig. 3, with each cluster representing a distinct research focus.

The size of the clusters in the visualization correlates with their weight of occurrence, indicating the relative importance of each theme within the research landscape. This analysis highlights the interconnectedness of various research topics related to UDTs, ZEBs, and climate change mitigation in smart cities. The prominence of each cluster indicates the degree with which specific themes dominate the literature. Fig. 4 provides insight into how UDTs and ZEBs are being studied both independently and in convergence. It also underscores the critical research areas that require further attention and development, which remains underexplored in existing literature.

In addition, a publication trend analysis was conducted to track the evolution of research interest in UDTs and ZEBs between 2019 and 2024. Fig. 5 displays the number of publications over time, indicating an increasing trend in research focus on these technologies. This time-series analysis allows for the identification of emerging areas in the interdisciplinary field and provides an understanding of the growing interest in integrating UDTs with ZEBs to support sustainable development and climate change mitigation in smart cities. The timeline reveals significant growth in the number of publications on these topics, with a noticeable increase in the frequency of articles published each year.

The trend began in 2019 with a relatively low number of publications (11), reflecting the emerging nature of research in this area. In 2020, the number of publications dropped slightly to (8), possibly due to the global disruption caused by COVID-19 , but the subsequent years saw a significant increase. In 2021, the number of publications rose to (23), and this increase accelerated in 2022 (49 publications) and 2023 (51 publications). The publication activity peaked in 2024, with (160 publications) addressing the integration of UDTs and ZEBs in sustainable urban contexts. This rising trend reflects the growing interest in these technologies and their potential role in addressing environmental sustainability challenges, particularly in climate change mitigation, in

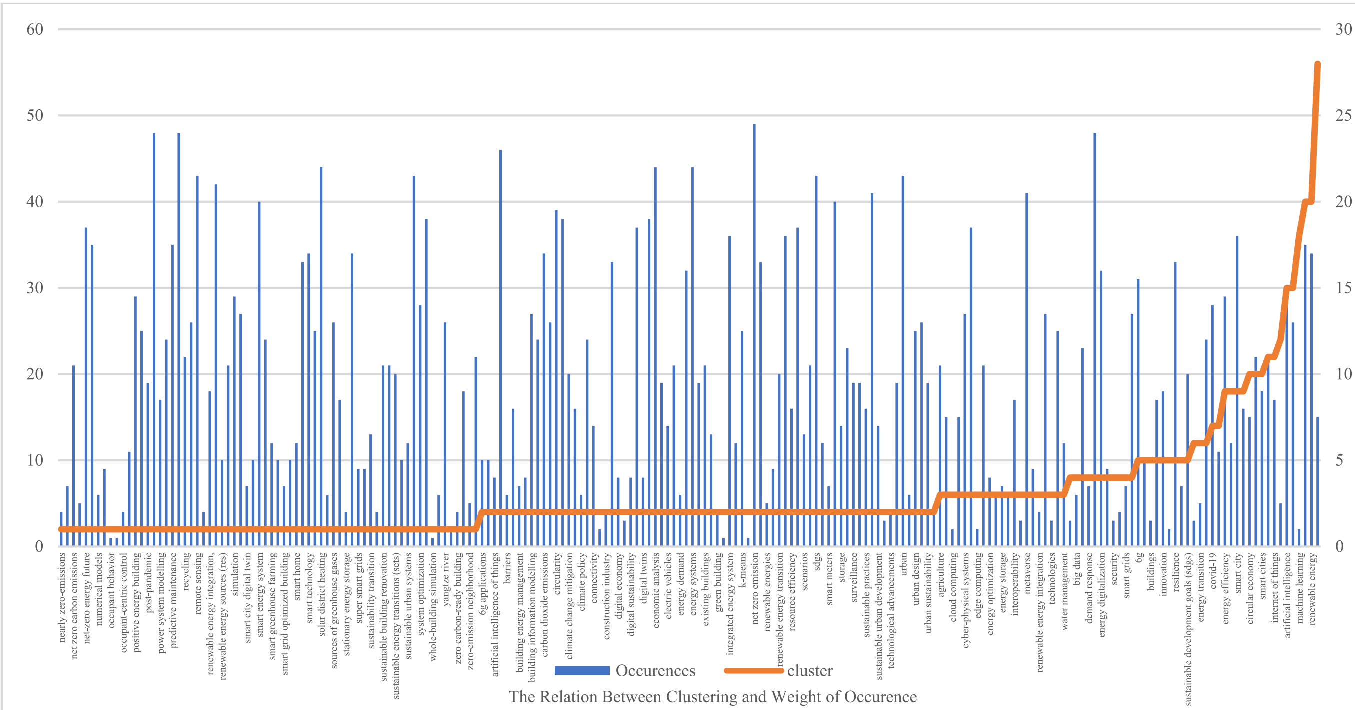

Fig. 4. The relationship between different clusters and weight of occurrence extracted from VOS viewer.

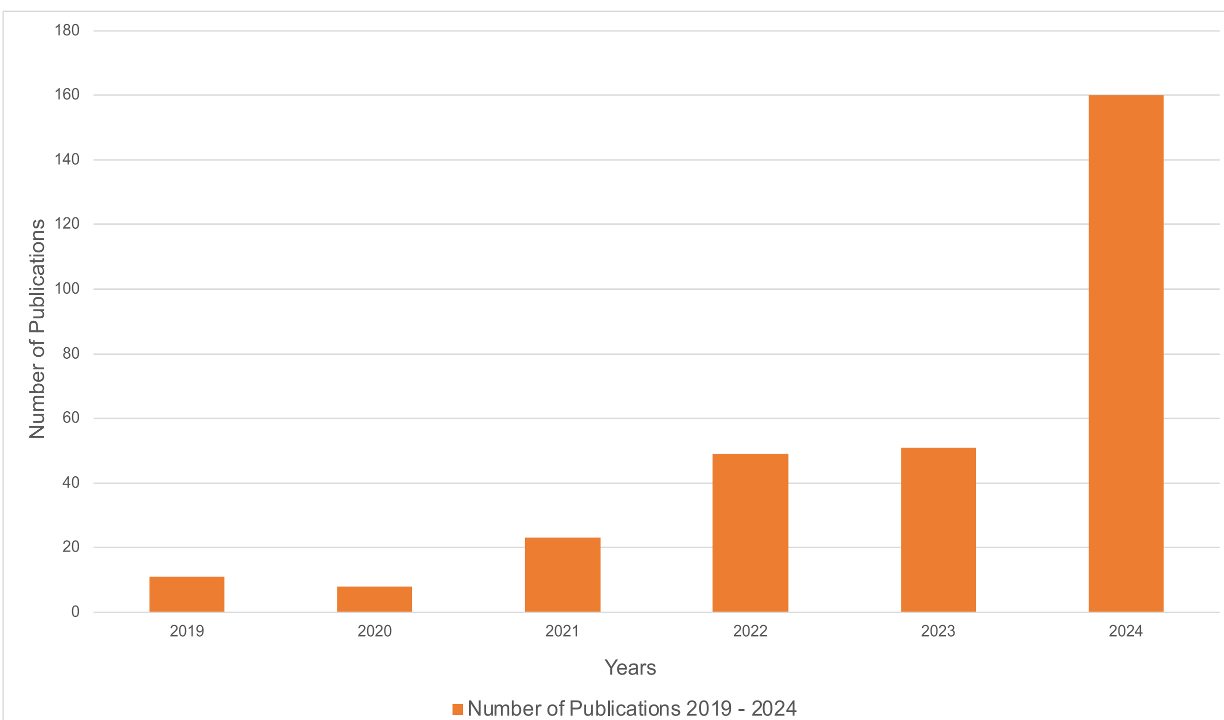

Fig. 5. Number of Publications from 2019 to 2024 extracted from VOS viewer.

urban environments. The rising number of publications over time highlights the urgent need to explore the synergistic integration of UDTs and ZEBs, which has yet to be fully realized in the research landscape. It also shows an increasing recognition of the potential of UDTs and ZEBs in sustainable urban environments . Despite this growing interest, the analysis reveals that, while these technologies are often studied independently, their full potential can be unlocked when integrated effectively. This gap in research on the synergistic integration of UDTs and ZEBs underscores the importance of further exploration into how these technologies can work together to maximize their contribution to climate change mitigation efforts in smart cities.

In summary, Figs. 3, 4, and 5 collectively provide a detailed overview of research trends, key themes, and the growing interest in the integration of UDTs and ZEBs in emerging sustainable smart cities. The bibliometric analysis uncovers significant thematic clusters, illustrating how these technologies have been studied both independently and in conjunction, with a particular emphasis on their combined potential for climate change mitigation. Concurrently, the analysis highlights a gap in research regarding their full integration, underscoring the need for further studies to harness their synergies. In particular, the growing importance of AI, IoT, and CPS, along with the significant role of renewable energy and energy-efficient buildings, points to the vast potential of UDT-ZEB integration in transforming urban environments into sustainable, resilient smart cities. However, further research is needed to optimize their combined impact based on the convergence of these advanced technologies on climate change mitigation and enhance the overall sustainability of cities. Overall, the comprehensive mapping of the research landscape sheds light on the field's evolution and identifies key areas for further investigation to advance UDT-ZEB integration in the rapidly evolving landscape of sustainable smart cities.

6. Results

In this section, we present the results of our investigation into the integration of UDTs and ZEBs as a strategy for advancing sustainable energy management and mitigating climate change effects in sustainable smart cities. The findings are structured around two central research questions: (2) How do UDTs enhance the operational performance and energy management of ZEBs in sustainable smart cities? and (3) How can a framework be developed to effectively integrate UDTs and ZEBs to advance climate change mitigation goals in sustainable smart cities, considering the synergy of their operational, technical, and performance indicators?

To address RQ 1, we focus on three core themes from the literature: (1) ZEBs, (2) DTs and ZEBs, and (3) ZEBs and Sustainable Smart Cities. Each of these themes sheds light on distinct aspects of ZEBs and UDTs and their synergistic integration and collaborative potential, collectively providing a comprehensive understanding of their role in improving energy efficiency, operational performance, and environmental sustainability in urban environments. These insights are essential to grasp how UDTs contribute to the optimization and management of ZEBs in the context of sustainable smart cities.

For RQ 2, a broader range of six themes is considered: (1) ZEBs, (2) DTs and ZEBs, (3) ZEBs and Sustainable Smart Cities, (4) DTs for Building and Energy Management in Smart Cities, (5) DTs and Building Energy Efficiency, and (6) DTs and Sustainable Smart Cities. This broader scope provides a holistic view of the integration process and the strategic framework required to optimize the collective impact of UDTs and ZEBs in advancing climate change mitigation and sustainable development in smart cities.

6.1. The role of UDTs in enhancing the operational performance and energy management of ZEBs in sustainable smart cities

6.1.1. Relevance of the three themes to answering RQ 1

ZEBs: This theme is directly relevant to RQ 1, as it focuses on the fundamental characteristics and functionalities of ZEBs, which are crucial for understanding their integration with UDTs. The studies in this theme explore energy-efficient technologies, renewable energy systems, and energy performance optimization, which are key components in achieving ZEBs. These aspects of ZEBs provide the necessary foundation for investigating how UDTs can optimize energy use, resource management, and operational efficiency in ZEB systems in the context of sustainable smart cities by examining the technological underpinnings and operational strategies of ZEBs.

UDTs and ZEBs: This theme is highly relevant to RQ 1, as it explicitly addresses the integration of UDTs and ZEBs. It explores how UDTs improve the operational performance and energy management of ZEBs through real-time data analytics, advanced modeling, and predictive maintenance capabilities. UDTs play a critical role in optimizing ZEBs, ensuring that energy consumption and production are balanced effectively. This theme offers invaluable insights into the potential of UDTs to manage and optimize ZEB energy systems, making it central to answering RQ 1 regarding the enhancement of ZEBs through UDTs.

ZEBs and Sustainable Smart Cities: This theme is equally important for RQ 1, as it explores how ZEBs contribute to energy efficiency and environmental sustainability in the context of sustainable smart cities. It examines the role of ZEBs in reducing carbon emissions, optimizing resource management, and advancing the integration of renewable energy in urban environments, which directly aligns with the operational role of UDTs in managing urban energy systems. This theme offers critical insights into how UDTs can enhance the performance and efficiency of ZEBs by investigating the integration of ZEBs within smart cities, ultimately optimizing energy usage and supporting the sustainability goals of smart cities.

Together, these three themes provide a comprehensive understanding of how UDTs enhance the operational performance and energy management of ZEBs. They address both the technological foundations and the contextual factors influencing the integration of UDTs with ZEBs, highlighting how UDTs can optimize ZEB functionalities to contribute to climate change mitigation efforts in sustainable smart cities.

6.1.2. Thematic analysis and synthesis

This subsection explores the contribution of ZEBs and UDTs in advancing climate change mitigation goals in sustainable smart cities. The synergistic integration of these technologies is crucial for maximizing the performance outcomes of ZEBs, ensuring their alignment with the objectives of sustainable urban development, and supporting the transition towards environmental sustainability.

6.1.2.1. Zero energy buildings. Senyonyi et al. [69] focuses on the role of solar energy techniques in achieving ZEBs, presenting a combination of passive and active solar techniques for energy production. The study explores the technological advancements in solar energy systems, identifies research gaps, and emphasizes the importance of experimental studies across different climates. It sets the groundwork for understanding the integral role of solar energy in ZEBs, while also highlighting key areas where further research and technological collaboration are needed. This research contributes to the broader understanding of how ZEBs can be optimized and lays the foundation for future studies on the integration of emerging technologies to further enhance energy efficiency in ZEBs.

Wang et al. [53] provide an in-depth exploration of the various technologies that are essential for achieving ZEBs, such as energy-efficient measures, renewable energy technologies, and building energy management systems. The study highlights the significant role of energy-efficient strategies, including optimized building envelopes, efficient HVAC systems, and renewable energy systems (solar, wind, biomass, and geothermal), in reducing energy consumption. Furthermore, it emphasizes the importance of integrating AI to enhance energy management, fault detection, and system optimization in ZEBs. This study provides a comprehensive overview of the technological advancements in ZEBs, setting the foundation for their integration with UDTs. Building on the role of AI in enhancing energy efficiency in ZEBs, Rocha et al. (2024) introduce the concept of the net Zero Energy cost Building (nZEcB), which aims to achieve near-zero or zero annual energy costs. Using AI techniques, including decision trees and K-means clustering, the study designs an optimal distributed generation system that integrates wind and photovoltaic energy sources, a battery bank, and an automated capacitor bank. A case study of a public building with an annual consumption of 1.748 GWh showed that the system generated 2.805 GWh per year, exceeding the building's energy demand by 160.5 %. The system also covered 99.999 % of the building's energy costs, achieving the nZEcB concept. Despite excess energy production, which compensates for losses and feed-in tariff pricing issues, the project demonstrated the economic and sustainable feasibility of using AI for energy optimization, with a payback period of 6.79 years.

Regarding the role of AI in enhancing the performance of net-zero and positive-energy buildings, Mousavi et al. [119] provide a systematic exploration of data-driven prediction and optimization techniques used in the design of these buildings. The study covers the integration of AI, machine learning, and building modeling to enhance the performance of buildings in achieving energy efficiency. It discusses the role of renewable energy supply prediction, optimizing building envelope designs, and controlling comfort levels with IoT technologies. The study aims to provide a technical framework for future researchers and engineers to implement data-driven approaches for achieving net-positive energy performance in buildings. It also identifies gaps in existing algorithms and calls for further optimization to improve prediction accuracy in the context of sustainable building design.

Furthermore, Ahmed et al. [120] focus on the renewable energy generation required to achieve net-zero energy buildings (nZEBs). The authors review various renewable energy sources, including solar, wind, and bioenergy, and examine their role in reducing energy consumption and greenhouse gas emissions in the building sector. The study discusses the technical, financial, and environmental considerations in nZEB design, emphasizing the importance of multi-criteria decision analysis for optimal decision-making. It also highlights the need for a universal decision-making framework to optimize nZEB design and operations. It provides insights into the contribution of renewable energy to nZEBs and its role in the broader decarbonization of the building sector. In line with this work, Lou and Hsieh [66] provide an in-depth analysis of net-zero-energy and net-zero-carbon buildings, discussing the importance of energy-efficient strategies and renewable energy technologies. The study emphasizes multidisciplinary approaches and the integration of LCA to evaluate both operational and embodied carbon emissions. This is particularly relevant for understanding how UDTs can contribute to reducing the carbon footprint of ZEBs by dynamically adjusting energy use, optimizing energy production, and ensuring that buildings meet both net-zero-energy and net-zero-carbon goals.

Focusing specifically on LCA**,** Kathiravel et al. [121] investigate the LCA of net-zero energy residential buildings across different climates. The authors evaluate the environmental and economic impacts of various HVAC systems (Ground Source Heat Pumps, Air Source Heat Pumps, and others) in cold, moderate, and warm climates. The results highlight the significant impact of climate on the energy demands of buildings and the global warming potential of different systems. The study finds that ground-source heat pumps perform well in colder climates despite their high initial costs, whereas air-source heat pumps are more efficient in milder climates. The research emphasizes that the combination of photovoltaic panels with HVAC systems improves the feasibility of achieving net-zero energy goals.

In addition, Jaysawal et al. [64] examine the global concept of NZEBs, focusing on renewable energy integration and energy efficiency strategies. It outlines the critical importance of achieving energy self-sufficiency in buildings through renewable energy sources and discusses the role of smart systems in facilitating energy management. The study highlights the challenges of implementing NZEBs in diverse climatic conditions, providing valuable context for how UDTs can support the management and optimization of energy systems in ZEBs by adjusting to local environmental factors and operational needs. From a different perspective**,** Mengaw et al. [67] examine the specific challenges and opportunities related to the implementation of NZEBs. It emphasizes the importance of optimizing energy utilization in regions with high cooling demands and explores how renewable energy systems can be integrated into these climates to meet the ZEB standards. The study discusses advancements in building innovation and the growing feasibility of NZEBs due to improvements in building technologies and renewable energy systems, laying the groundwork for the potential integration of UDTs in managing these systems.

Al Dakheel et al. [63] analyze the features, functions, and technologies of smart buildings, including their role in achieving nearly zero-energy performance. The study focuses on the concept of smart retrofitting and the integration of energy-efficient systems in existing buildings. The study also develops a set of key performance indicators (KPIs) for evaluating the success of smart building interventions. These indicators are essential for monitoring the operational efficiency of ZEBs and provide a useful framework for assessing their impact on sustainable urban development. Focusing on the social and technological aspects of retrofitting buildings to achieve nearly zero-energy performance, Mooses et al. [122] examine residents' perceptions of the smart retrofit intervention, revealing that acceptance varied based on individual attitudes toward technology and environmental concerns. It emphasizes the importance of incorporating social practice theories in the adoption of energy-efficient technologies, providing valuable insights into the challenges and opportunities for widespread integration of smart and sustainable technologies in achieving net-zero buildings.

Moreover, Wang et al. [123] investigate the actual energy efficiency of retrofitting residential buildings to achieve nearly zero-energy status. The study measures the impact of various energy efficiency measures, such as upgrading insulation and windows, on energy savings and cost reductions. Using a single-family home case study, the authors devise new metrics to assess the effectiveness of each retrofit measure, providing insight into the real-world performance of these measures. The findings suggest that certain retrofits, such as roof and exterior wall improvements, provide the most significant energy savings, while also offering an economic evaluation of retrofit options.

Wu and Skye [124] provide a comprehensive review of advancements in residential net-zero energy buildings (NZEBs) over the past decade. The study covers energy infrastructure, renewable energy systems, and energy efficiency measures necessary for achieving NZEBs. Key areas include the integration of renewable energy sources such as solar photovoltaics (PV), wind, and biomass, as well as the importance of energy-efficient systems such as advanced HVAC and domestic hot water systems. The study highlights the flexibility in selecting the best configuration for NZEBs, depending on local climate, building codes, and energy resources. It emphasizes the need for technology adaptation to local conditions to optimize energy savings and environmental benefits. Specifically focusing on the integration of solar PV systems.

Wu et al. [125] explore the use of genetic algorithms to design nearly-zero-energy residential buildings. The study adopts a multi-objective optimization approach to minimize heating and cooling loads, maximize PV power generation, and reduce investment costs. It evaluates nine key parameters affecting energy use and PV potential. It concludes that a careful balance of system parameters can significantly improve the energy efficiency of residential buildings. By optimizing design for various climate zones in China, the study provides a valuable approach for achieving zero-energy goals in residential buildings, offering theoretical and practical insights for future design projects.

Zhao et al. [126] investigate how correlation-based data mining techniques can enhance the operation and maintenance of zero-carbon buildings. The study focuses on analyzing the relationship between energy consumption data and environmental data in smart buildings. Applying linear and trend correlations, the study enables anomaly detection in building performance data, improving data reliability for decision-making. It presents a method for correcting anomalies based on fitting equations, which can be generalized across various scenarios in zero-carbon buildings. This data-driven approach plays a critical role in monitoring and ensuring the effective operation of energy-efficient buildings.

Wilberforce et al. [70] address the pros and cons of ZEBs, discussing the challenges impeding their widespread adoption, such as high initial costs, technological limitations, and public perception. It provides insights into policy measures, including government subsidies and public awareness campaigns, to encourage the adoption of ZEBs. The study calls for greater innovation in building technologies and emphasizes the importance of occupant behavior in the successful implementation of energy-efficient strategies. Labaran et al. [65] examine the factors influencing the adoption of energy-efficient practices in buildings, with a particular focus on barriers and facilitators in the context of achieving NZEB. It discusses the role of government policies, design standards, and incentives in promoting energy conservation in the building sector. The study highlights the importance of integrating innovative technologies, such as IoT and automation systems, to enhance energy monitoring and conservation in ZEBs.

Kalbasi and Afrand [127] assess the effectiveness of phase change materials (PCM) and thermal insulation in reducing energy demand in zero-carbon-ready buildings. Their study uses CFD-based techniques to compare the thermal behavior of walls with PCM, insulation, or a combination of both in different climates. The results indicate that PCM is more effective in warmer climates for cooling, while insulation performs better in colder climates. The study concludes that combining PCM with insulation results in a more energy-efficient building, especially in hot regions, where the cooling load can be reduced to zero. This research is important for advancing materials science in the context of energy-efficient building design and decarbonization.

The reviewed studies in this theme advance the understanding of ZEBs operate and how their performance can be optimized to meet environmental sustainability goals. They emphasize the critical role of energy-efficient measures, renewable energy technologies, and energy management systems in reducing buildings' energy consumption and achieving net-zero energy status. Furthermore, the studies underscore the importance of integrating advanced monitoring and optimization tools, such as those provided by DTs, to ensure that ZEBs continue to perform efficiently over time. This includes real-time data analytics, predictive maintenance, and operational optimization to enhance energy management and contribute to climate mitigation strategies. The studies further explore how technologies such as AI, machine learning, and BIM can enhance the integration of renewable energy systems such as solar photovoltaics, wind turbines, and heat pumps within ZEBs. Combining these elements, the studies lay the groundwork for a future where UDTs and ZEBs work in synergy to foster sustainable urban environments.

6.1.2.2. Digital twins and zero energy buildings. Arsiwala et al. [32] introduce a DT solution that integrates IoT, BIM, and AI to automate the monitoring and control of carbon dioxide emissions from operational assets, aiming to contribute to net-zero targets in buildings. A practical application is showcased through a real-life use case, which illustrates the system's capability to enhance facility management by visualizing critical spatial data for indoor air quality monitoring and employing AI to predict emissions. The results are presented via an interactive dashboard that supports stakeholders in managing emissions and making informed, data-driven retrofitting decisions. This study marks a significant step towards employing DTs in monitoring emissions and advancing towards net zero targets in existing assets in the built environment. Expanding on this, Ferdaus et al. [33] explore how advanced technologies such as AI, DTs, and blockchain play an important role in transitioning towards a net-zero energy future. The study identifies the primary challenges in implementing these technologies and offers solutions for their adoption, focusing on their impact on energy management and renewable energy integration. The study also highlights the importance of continued research to refine these technologies for better integration with traditional power systems and to overcome existing barriers to their widespread implementation.

Furthermore, Chen et al. [128] investigate the use of DT technology in modeling and simulating smart city environments to optimize energy usage, with an emphasis on renewable energy integration. The study focuses on using a combination of machine learning (GRU) and Ant Colony Optimization (ACO) to effectively manage energy distribution within smart cities. The integration of DTs in the optimization process highlights the potential for simulating energy use scenarios, offering a holistic approach to achieving net-zero energy and improving the sustainability of urban environments. Wang et al. [129] specifically focus on the role of DTs in optimizing energy management within smart buildings. They explore how DTs can be integrated into microgrids to manage renewable energy sources and reduce carbon emissions, thereby enhancing energy efficiency in urban environments. The study introduces innovative methods that combine AI, machine learning, and multi-objective optimization techniques to optimize the performance of renewable energy systems, such as solar and wind, in these microgrids. This approach underscores the potential of DTs in managing energy flows and achieving net-zero emissions goals in smart buildings.

While Wang et al. [129] narrow the focus to smart buildings, Alnaser et al. [23] expand the application of AI-driven DTs by exploring their integration with IoT to optimize energy use and foster sustainability, not just in smart buildings, but across broader urban environments, supporting zero-energy buildings and enhancing overall energy management. The study identifies the potential of AI and DTs in creating smart cities and emphasizes the role of data-driven strategies to improve energy efficiency and resilience, thus supporting the broader goals of sustainable urban development.

Shen et al. [130] present a conceptual framework for integrating BIM and DT technologies to support the development of net-zero-carbon buildings throughout their entire life cycle. The study highlights a critical gap in the current decision-making process, emphasizing the lack of a standardized data integration approach to support carbon emissions reduction and environmental sustainability. The proposed framework aims to create a comprehensive computational model that incorporates key decision variables by combining BIM for building information representation wit DTs for real-time monitoring. These variables enable more informed decision-making for the operational management of net-zero-carbon buildings. The research emphasizes the importance of integrating BIM and DT to create a standardized system for supporting decision-making processes throughout the building's life cycle, with the goal of advancing the transition to sustainable, low-carbon buildings.

Kaewunruen et al. [34] focus on applying DT technology to evaluate and enhance the energy performance of existing buildings to meet NZEB standards. Using a combination of BIM and DT simulations, the study investigates the feasibility of applying renewable energy technologies to existing buildings. The study offers a practical approach to improving energy efficiency in older buildings by providing a detailed evaluation of renewable solutions and their impact on energy savings, promoting the integration of digital twins for energy management and operation and maintenance (O&M). Emphasizing the latter, Liu et al. [35] propose a DT model for NZEB O&M by integrating BIM and IoT. The study focuses on the use of DTs to manage data across the O&M phase, enhancing the efficiency of energy management systems. It shows how digital twins can optimize energy performance and automate feedback loops for operational control, improving the overall maintenance and performance of NZEBs. This research highlights the importance of integrated data for achieving operational excellence in NZEBs. In relation nZEBs, the study by Zhao et al. [38] looks into leveraging DT technology and BIM to evaluate retrofitting schemes for existing buildings to achieve nearly nZEB. Through a 3D laser scanning approach, the study develops a Building Energy Model (BEM) to assess the feasibility of implementing renewable energy systems, particularly solar photovoltaics, in reducing energy consumption and carbon emissions. The case study demonstrates a 14.1 % reduction in energy costs, a 24.13 % increase in solar energy generation, and a substantial decrease in CO2 emissions, highlighting the potential of DT to optimize energy performance and integrate renewable energy in the retrofitting process.

Regarding the use of DT technology for energy optimization in various urban infrastructures, Agostinelli et al. [31] examine the transformation of port areas into Zero Energy Districts (ZEDs), focusing on the application of DTs for energy management in port infrastructures. The study explores how DTs can enhance the management and sustainability of port areas by integrating renewable energy sources, including solar and wind, and utilizing open-source tools for energy optimization. It provides a practical example of how DT technology can optimize energy efficiency and contribute to energy self-sufficiency, paving the way for sustainable urban infrastructure projects.

The key insights derived from this theme demonstrate the increasing role of DT technology in enhancing energy management and performance optimization of ZEBs. The integration of DTs with other technologies like AI, IoT, and BIM allows for real-time monitoring, predictive maintenance, and improved decision-making throughout the building's lifecycle. DTs are particularly effective in managing energy consumption, optimizing the integration of renewable energy sources, and reducing carbon emissions. Furthermore, they enable better management of O&M processes, leading to more efficient energy performance in both new and existing buildings. They also support the transition to net-zero-carbon buildings by offering data-driven insights that enhance the scalability of energy-saving solutions. In addition, they play a key role in retrofitting existing buildings and transforming urban areas into more sustainable, energy-efficient environments. The studies highlight the potential of DTs to bridge the gap between theoretical models and real-world energy performance, offering a comprehensive tool for achieving the environmental objectives of sustainable development.

6.1.2.3. Zero energy buildings and sustainable smart cities. Komninos [41] explores the concept of NZEDs as a key component of smart-green cities. The author discusses the potential of NZEDs to decentralize energy production and reduce carbon emissions through the integration of renewable energy technologies and smart city systems. The study outlines a model to assess the feasibility of transitioning urban districts to NZEDs, focusing on the local production of renewable energy and the integration of nature-based solutions. This research supports the development of sustainable urban systems by showing how NZEDs can contribute to carbon–neutral cities, aligning with the goals of ZEBs in reducing environmental impacts.

Mohammed et al. [36] evaluate the global adoption of ZEB techniques, focusing on residential buildings. The study presents a systematic analysis of over 40 residential buildings worldwide, assessing their technical details and performance. It highlights solar PV as the most commonly used renewable energy source for ZEBs and discusses the importance of advanced cooling technologies and heat pumps in warmer climates. It also stresses the role of building envelopes and thermal ventilation in achieving energy efficiency, particularly in cold climates. It underscores the critical technologies and strategies necessary for shaping sustainable cities by analyzing the global activities surrounding ZEBs. Expanding on this practical endeavor, Mitsopoulos et al. [40] explore the role of advanced PV technologies in achieving ZEBs across different climate conditions. It specifically investigates various cooling techniques integrated with PVs, such as radiative PV cells, externally finned PVs, and phase-change materials (PCMs). These innovations are compared with conventional PV designs for buildings in cities with varied climates, including Athens, Barcelona, Munich, and Stockholm. The results show that ZEBs can be achieved in all locations with the use of roof PVs, with BIPVs (building-integrated photovoltaics) added in colder climates. The study highlights that PV cooling techniques, particularly externally finned PVs, offer significant improvements in energy generation, especially in warmer climates. The findings also suggest that the adoption of PCM is most beneficial in hot climates. This research lays the foundation for designing ZEBs by optimizing PVs to meet energy demand and exceed it in certain climates, providing valuable insights for integrating energy-efficient technologies into sustainable urban environments.

Additionally, Alagar and Thirumal [39] discuss a hybrid energy system combining PV panels, wind energy, diesel generators, and batteries, designed for ZEBs. The study uses HOMER software to simulate energy production and consumption for a residential building in the region. The findings highlight the potential of hybrid systems in reducing carbon emissions and achieving energy self-sufficiency. The study also emphasizes the environmental benefits of integrating renewable energy sources, contributing to the overall sustainability of ZEBs in smart cities.

Zhuang et al. [30] propose a framework for making urban areas more sustainable through the development of smart cities. The study highlights the need for efficient energy consumption and the role of renewable energy systems in urban buildings. It introduces an innovative hybrid heating and cooling system powered by solar and wind energy, optimized using a deep-learning-based NARX-ANN model. The research emphasizes the importance of integrating smart control systems to optimize energy usage in buildings, contributing to the sustainability of smart cities. The findings support the feasibility of using advanced technologies such as AI and machine learning to improve energy efficiency in ZEBs.

Bibri [60] propose a novel framework for assessing ZEBs using DT technology. The authors argue that current energy efficiency certifications often overlook critical factors such as occupant comfort, leading to a "building performance gap." The study proposes integrating DTs into the ZEB rating system to enhance the accuracy of energy consumption assessments and improve building performance. DTs provide dynamic insights that help bridge the gap between theoretical models and actual building performance by incorporating real-time data on energy consumption, occupant comfort, and system efficiency. The framework offers a holistic approach to designing energy-efficient, climate-resilient buildings aligned with the principles of sustainable smart cities. This study emphasizes the role of DTs in promoting coordinated, real-time urban management solutions that enhance the performance and sustainability of ZEBs, contributing to more resilient smart cities.

From a critical perspective, Uspenskaia et al. [42] investigate the challenges and barriers to the adoption of net-zero/positive energy buildings and districts within a smart city project. The authors emphasize the difficulty of replicating successful solutions across different cities due to varying historical, geographical, political, and economic contexts. They argue that the scaling up of low-carbon solutions requires a profound understanding of replication modeling and multi-dimensional representation of these solutions. The study provides insights into how smart city projects can overcome the challenges of replication and scale-up, contributing to the broader adoption of ZEBs in sustainable urban development.

The studies in this theme highlight the role of ZEBs and NZEDs in driving sustainable urban development. Key insights include the integration of renewable energy systems, such as solar PV and wind, for achieving ZEB goals, and the use of innovative technologies such as DTs and AI for optimizing energy use. Moreover, challenges related to scaling ZEBs across diverse urban environments are highlighted, emphasizing the need for robust replication models and data-driven strategies. The research collectively demonstrates how these technologies enhance energy efficiency and reduce carbon emissions, contributing to the broader goal of climate-resilient, sustainable smart cities.

In conclusion, combining the three themes associated with RQ 1, the research related to theme 1 is the most extensive, with numerous studies addressing various facets of ZEB technologies, energy efficiency, and integration strategies in the rapidly evolving landscape of sustainable smart cities. Theme 2, while more concentrated, has a smaller number of studies compared to theme 1. In contrast, theme 3 remains notably underexplored, with fewer studies addressing the integration of UDTs and ZEBs. This limited body of research in both themes 2 and 3, particularly in review studies, underscores a critical gap in the literature. The relative scarcity of studies in theme 3 is especially significant in relation to RQ 1, highlighting the need for further in-depth research into the synergies between UDTs and ZEBs to advance climate change mitigation and sustainable urban development goals. Notably, this area remains almost entirely absent from the current scholarly landscape,

Table 2
Main technical and operational performance indicators of Urban Digital Twins.

Indicators	Description
Real-time Energy Monitoring and Management	One of the primary benefits of UDTs in relation to ZEBs is the ability to monitor and manage building energy use in real-time. UDTs enable the precise tracking of energy production, consumption, and waste. This allows for immediate adjustments in building operations to maximize energy efficiency and ensure the building maintains its zero energy status over time.
Predictive Maintenance and Operational Efficiency	UDTs can use predictive analytics to forecast future building needs and operational issues. This includes predicting HVAC system failures before they occur or identifying areas where energy inefficiency is likely to develop. Addressing these issues proactively enable buildings to maintain optimal energy performance, reduce downtime, and extend the lifespan of critical systems, all of which contribute to sustained zero energy performance.
Integration of Renewable Energy Sources	UDTs enhance the integration of renewable energy sources with building operations by optimizing when and how energy is used based on availability and demand. For example, a DT can manage the use of stored solar energy during peak demand periods or shift non-essential loads to times when solar power is most abundant, enhancing the building's overall energy balance.
Optimization of Building Design and Retrofitting	UDTs can simulate various scenarios to determine the most effective designs or retrofits for energy efficiency. This can include the optimal placement of solar panels, the best materials for insulation, or the most effective building orientation for maximum energy conservation and generation. UDTs help in making informed decisions that align with zero energy and climate mitigation goals by modeling these scenarios.
Carbon Footprint Analysis and Reduction	UDTs can calculate the carbon footprint of a building in real-time, considering factors like energy sources, building materials, and operational practices. This capability allows for ongoing assessment and strategic adjustments to minimize carbon emissions, directly contributing to climate mitigation efforts. Moreover, UDTs can integrate external data such as grid carbon intensity to make dynamic adjustments in building operations to minimize carbon output.

Table 3
Main performance indicators of Zero Energy Buildings.

Indicators	Description
Energy Efficiency	This is a primary indicator of a ZEB's performance. Energy efficiency measures how well a building uses energy to perform necessary functions such as heating, cooling, and lighting, compared to standard buildings. Effective insulation, high-performance windows, and energy-efficient HVAC systems are examples of factors that contribute to a building's energy efficiency. A building's ability to minimize energy waste is critical for reaching zero energy status.
Renewable Energy Generation	The ability of ZEBs to generate their own energy from renewable sources is a key indicator. This typically involves on-site renewable energy systems such as solar photovoltaic panels, wind turbines, or geothermal energy solutions. The proportion of energy generated versus the building's total energy consumption is crucial; ideally, the building produces enough energy on-site to meet its operational needs over a year.
Carbon Emissions	The net carbon emissions of a building, taking into account both emissions produced and emissions offset by renewable energy generation, is a key metric. ZEBs aim to have net-zero carbon emissions, making this a critical indicator of their effectiveness in mitigating climate change.
Building Envelope Performance	The performance of a building envelope (the barrier between indoor and outdoor environments, including walls, roof, and foundation) is crucial for minimizing energy loss. Effective building envelopes reduce the need for artificial heating and cooling, thus decreasing the building's energy demand and contributing to its zero energy status.
Water Efficiency and Sustainable Materials Use	While primarily aimed at energy performance, ZEBs often incorporate broader sustainability measures such as water efficiency and sustainable material usage. The first indicator measures how effectively a building uses water resources, including its capacity for water conservation, wastewater treatment, and the use of rainwater harvesting systems. The second indicator focuses on selecting building materials with low environmental impact, recycled content, and low carbon footprints to reduce the embodied carbon of a building and supports its environmental sustainability. Both practices reduce the building's overall environmental footprint, supporting broader climate mitigation goals by conserving natural resources and reducing waste.

particularly in the context of review studies, which further emphasizes the importance of addressing this gap in future research efforts. While considerable progress has been made in exploring and understanding each technology independently, the integration of UDTs and ZEBs presents an emerging area for scholarly exploration.

6.2. A novel framework for integrating urban digital twins and zero energy buildings for advancing climate change mitigation goals in sustainable smart cities

6.2.1. Main indicators of urban digital twins and zero energy buildings

This subsection provides an overview of the scholarly landscape in the interdisciplinary field of sustainable smart cities, based on the 104 reviewed studies that have been categorized into six distinct themes. The specific indicators of UDTs and ZEBs are derived from the synthesis of these studies, as described in Tables 2 and 3. These main indicators act as key benchmarks for understanding and evaluating the effectiveness of UDT and ZEB technologies in promoting environmentally sustainable development practices in smart cities. They are essential for assessing the broader impact of these technologies on urban systems and infrastructure efficiency, as well as guiding public policy to support climate change mitigation efforts.

This overview highlights the significant role that ZEBs and UDTs play in promoting sustainable development practices and climate change mitigation efforts in smart cities. ZEBs and UDTs contribute to the broader environmental goals of urban sustainability based on the interrelated indicators presented in Tables 2 and 3. These insights advocate for enhanced interdisciplinary collaboration to further optimize these integrations, ensuring that smart cities evolve into sustainable ecosystems capable of addressing contemporary and future challenges effectively.

6.2.2. Categorization of six themes based on their focus and in relation to the operational, technical, and performance indicators of urban digital twins and zero energy buildings

There are two themes related to ZEBs: (1) ZEBs and (2) ZEBs and Smart Cities. The literature under theme 1 focuses on ZEBs as a critical solution for reducing energy consumption and minimizing carbon emissions. Studies highlight advancements in energy-efficient building designs, renewable energy integration, and the use of smart technologies to optimize energy usage. The key discussions emphasize how ZEBs create buildings that balance energy needs with environmental sustainability. Moreover, theme 1 provides direct insights into the performance indicators of ZEBs. It highlights how these indicators measure the effectiveness of ZEBs in mitigating climate change and optimizing energy performance.

Regarding theme 2, smart cities integrate ZEBs into the broader urban infrastructure, with an emphasis on enhancing energy efficiency through connected building systems. This theme explores how ZEBs, as part of smart cities, improve energy performance in individual buildings and contribute to the overall sustainability of urban environments. Discussions focus on how smart grids and automated management systems help ZEBs operate more effectively within the urban energy framework, promoting sustainability at a city-wide scale. In addition, theme 2 connects ZEBs to the environmental indicators of urban sustainability, while emphasizing their contribution to climate change mitigation and sustainable development in smart cities.

Themes related to UDTs are 1) DTs for Building and Energy Management in Smart Cities, 2) DTs and Building Energy Efficiency, and 3) DTs and Sustainable Smart Cities. Concerning theme 1, UDTs play a critical role in managing building and energy systems in smart cities. This theme explores how UDTs facilitate the integration of renewable energy sources, optimize energy usage, and enable real-time monitoring across various types of buildings. It mainly pertains to UDT-specific indicators such as real-time energy monitoring and management, predictive maintenance, operational efficiency, and carbon footprint analysis.

Theme 2 examines how UDTs are employed to optimize energy efficiency across various building types. UDTs provide dynamic insights that help in making informed decisions about energy use, building design, and systems integration. The literature under this theme highlights the potential of UDTs to enhance building performance and reduce energy consumption. Theme 2 relates more or less to UDT-specific indicators.

Theme 3 emphasizes the broader impact of UDTs on urban sustainability, particularly in their role in real-time monitoring, urban system optimization, and environmental sustainability in sustainable smart cities. It highlights how UDTs can manage energy systems effectively on a city-wide scale, optimizing energy distribution and improving operational efficiency. By utilizing UDTs, sustainable smart cities can create more efficient urban systems that reduce their carbon footprints and support environmental sustainability goals. Furthermore, the integration of UDTs with urban planning enhances the adaptability of cities to climate change, fostering the development of energy-efficient urban environments. On the other hand, Theme 2 directly and indirectly addresses various UDT-specific indicators based on the applied domains, showcasing how these technologies contribute to sustainable urban development.

The only theme that directly addresses both ZEBs and UDTs is "DTs and ZEBs." This theme explicitly focuses on the integration of UDTs with ZEBs to enhance energy efficiency, renewable energy generation, carbon emissions reduction, water management, and material usage. It emphasizes how real-time data analytics, predictive maintenance, and operational optimization through UDTs can significantly improve the operational performance and energy management of ZEBs. This integration is essential for maximizing the combined impact of both technologies in the context of sustainable smart cities. Discussions focus on how UDTs monitor and adjust energy use within ZEBs, ensuring their long-term efficiency, resilience, and sustainability. Given its dual focus on both technologies, this theme relates to all relevant indicators—technical, operational, and performance—demonstrating the holistic role of UDTs in optimizing ZEBs.

6.2.3. Relevance of six themes to answering RQ 2

As regards the relevance of the themes to answering RQ 2, the first theme related to ZEBs informs RQ 2 by defining the core characteristics of ZEBs, which are essential for developing a framework that integrates ZEBs and UDTs. ZEBs' need for optimized energy management and real-time adjustments aligns directly with UDT capabilities. Understanding ZEB functional characteristics and performance indicators helps establish the requirements for UDT integration to ensure ZEBs can meet climate change mitigation goals in smart cities. The second theme related to ZEBs helps explain how emerging advanced technology solutions can be integrated with ZEBs to improve energy management and contribute to carbon reduction strategies in smart cities. This sets the stage for developing a framework that aligns ZEBs with UDTs in the context of urban sustainability.

The first theme related to UDTs provides insights into how UDTs can be utilized to optimize building and energy management in smart cities. It directly contributes to RQ2 by demonstrating how UDTs enhance operational performance and energy management within the smart city framework. The second theme highlights UDTs' capacity to optimize energy efficiency in buildings, which is crucial for integrating UDTs with advanced systems like ZEBs. This theme informs RQ2 by illustrating how UDTs can manage energy use and improve the operational efficiency of energy systems. The third theme expands on the broader role of UDTs in managing energy systems across urban environments. Its relevance to RQ2 lies in its explanation of how UDTs can be applied to urban energy systems, ensuring optimal performance in terms of energy generation, consumption, and sustainability across the larger smart city ecosystem.

The sole theme that directly relates to both ZEBs and UDTs is highly relevant to RQ2, as it emphasizes the synergy between these two technologies. It underscores how UDTs enhance ZEB performance through their computational and analytical capabilities. This integration is essential for developing a framework that combines UDTs and ZEBs to effectively achieve climate change mitigation goals and optimize sustainable energy management in smart cities.

6.2.4. Tabulated analysis and synthesis

This subsection presents a tabulated analysis of how UDTs and ZEBs are addressed across 103 articles, organized around three comprehensive tables. Table 4 outlines the topics discussed in these articles, providing a foundational overview for the following detailed syntheses. Table 5a presents a synthesis of the relevant body of work in relation to the five performance indicators of ZEBs in response to climate change mitigation, compared to the topics discussed in this work. Table 5b synthesizes the relevant body of work as related to the five technical and operational indicators of UDTs in response to climate change mitigation, compared to the topics discussed in this work. These two tables serve to contextualize the literature within the 6 distinct themes identified. This tabulated analysis and synthesis aims to highlight the integrated roles and functions of UDTs and ZEBs in enhancing the environmental sustainability of smart cities.

The analysis of themes and indicators provides valuable insights into the synergistic relationship between UDTs and ZEBs in sustainable smart cities. These findings contribute to developing a comprehensive framework that effectively integrates UDTs with ZEBs, maximizing their collective impact on climate change mitigation and the development of zero-energy, low-carbon urban ecosystems. This synthesis emphasizes the need for continued interdisciplinary collaboration and innovation to fully leverage the potential of UDTs and ZEBs, transforming urban spaces into sustainable, resilient, and energy-efficient environments.

6.2.5. Synergistic integration of ZEBs and UDTs

ZEBs and UDTs complement and enhance each other by leveraging their unique capabilities to optimize urban sustainability efforts. The integration of ZEBs with UDTs significantly amplifies their potential, as UDTs provide real-time data analytics, predictive maintenance, and system optimization, which enable dynamic adjustments in ZEB operations. This synergy allows for more efficient energy management and enhanced adaptability of ZEBs to fluctuating environmental conditions. Moreover, UDTs offer a comprehensive, city-wide perspective, ensuring that ZEBs operate in harmony with broader urban infrastructure and energy systems, enhancing their overall contribution to sustainable smart cities. On the flip side, ZEBs enhance UDT functionalities by providing them with valuable real-time operational data, which enriches their predictive accuracy. ZEBs generate vast amounts of real-

Table 4
Topics discussed in selected 103 articles.

No.	Citations	Titles	Include Zero Energy Building or Digital Twin	Topics Discussed in the Selected Articles
Theme 1: Zero Energy Buildings				
1	[53]	A Comprehensive Review on Technologies for Achieving Zero- Energy Buildings	✓	1- Key Technologies for Achieving Zero Energy Buildings
2	[67]	Recent progress in Net-Zero-Energy buildings in Tropical Climates: A review of the challenges and opportunities.	✓	2- Net Zero Energy Buildings in Tropical Climates
3	[69]	Systematic review of solar techniques in zero energy buildings.	✓	3- Solar Techniques to achieve Zero Energy Buildings
4	[66]	Towards Zero: A Review on Strategies in Achieving Net-Zero-Energy and Net-Zero-Carbon Buildings.	✓	4- Strategies of Net Zero Energy and Net Zero Carbon Buildings
5	[65]	Towards net zero energy buildings: A review of barriers and facilitators to the adoption of building energy efficiency practices	✓	5- Implementing Energy Efficiency Practices Toward Net Zero Energy Buildings
6	[64]	Concept of net zero energy buildings (NZEB)-A literature review	✓	6- Concept of Net Zero Energy Buildings
7	[122]	Residents' Perceptions of a Smart Technology Retrofit Towards Nearly Zero-Energy Performance	✓	7- Smart technologies to achieve Nearly Zero-Energy Performance.
8	[68]	A bibliometric review of net zero energy building research 1995–2022	✓	8- Net Zero Energy Building
9	[124]	Residential net-zero energy buildings: Review and perspective	✓	
10	[70]	A review on zero energy buildings – Pros and cons	✓	9- Zero Energy Building
11	[63]	Smart buildings features and key performance indicators: A review	✓	10- Smart Buildings Features and Key Performance Indicators
12	[132]	Enhancing the performance of zero energy buildings with boosted coyote optimization and Elman neural networks	✓	11- Zero Energy Building using a combination of Coyote Optimization and Elman Neural Networks
13	[120]	Assessment of the renewable energy generation towards net-zero energy buildings: A review	✓	12- Net Zero Energy Buildings and Renewable Energy Generation
14	[123]	Measured performance of energy efficiency measures for zero-energy retrofitting in residential buildings	✓	13- Zero Energy Buildings and Energy Efficiency Measures.
15	[127]	Which one is more effective to add to building envelope: Phase change material, thermal insulation, or their combination to meet zero-carbon-ready buildings?	X	14- Building Envelope and Zero Carbon –ready Buildings
16	[121]	LCA of net-zero energy residential buildings with different HVAC systems across Canadian climates: A BIM-based fuzzy approach	✓	15- Net Zero Energy Buildings and Building Life Cycle across Canadian Climates conditions
17	[51]	Net Zero Energy Cost Building system design based on Artificial Intelligence	✓	16- Net Zero Energy Cost Building and Artificial Intelligence.
18	[119]	Data-driven prediction and optimization toward net-zero and positive-energy buildings: A systematic review	✓	17- Net Zero and Positive Energy Buildings
19	[125]	Research on parametric design method of solar photovoltaic utilization potential of nearly zero-energy high-rise residential building based on genetic algorithm	✓	18-Nearly Zero Energy Building and Solar Photovoltaic based on Genetic Algorithm.
20	[126]	Enhancing Zero-Carbon Building Operation and Maintenance: A Correlation-Based Data Mining Approach for Database Analysis	X	19- Operation and Maintenance of Zero Carbon Building
Theme 2: Zero Energy Buildings and Digital Twins				
21	[31]	Renewable energy system controlled by open-source tools and Digital Twin model: Zero energy port area in Italy.	✓	20- Zero Energy Port Area and Digital Twin Model
22	[32]	Digital twin with machine learning for predictive monitoring of CO2 equivalent from existing buildings	✓	21- Digital Twin with machine learning for Predicative Monitoring and control of CO2.
23	[133]	Microgrids energy management considering net-zero energy concept: The role of renewable energy landscaping design and IoT modeling in digital twin realistic simulator	✓	22– Digital Twin Simulation for Energy Management in Net Zero Energy
24	[33]	Digital technologies for a net-zero energy future: A comprehensive review	✓	23– Digital Technologies for A Net-Zero Energy

(continued on next page)

Table 4 (*continued*)

No.	Citations	Titles	Include Zero Energy Building or Digital Twin	Topics Discussed in the Selected Articles
25	[34]	A digital-twin evaluation of net zero energy building for existing buildings.	✓	24- A Digital-Twin Evaluation of Net Zero Energy Buildings
26	[35]	Development and application of a digital twin model for Net Zero Energy Building operation and maintenance utilizing BIM-IoT integration	✓	25- Digital Twin Model for Net Zero Energy Building Operation and Maintenance
27	[134]	Hybrid approach for digital twins in the built environment	✓	26- Digital Twin in Built Environment
28	[38]	Digital-twin-based evaluation of nearly zero-energy building for existing buildings based on scan-to-BIM	✓	27- Digital-Twin-Based Evaluation of Nearly Zero-Energy Building
29	[23]	AI-Powered Digital Twins and Internet of Things for Smart Cities and Sustainable Building Environment	✓	28- Digital Twin Powered by AI & IoT for Smart Cities and Sustainable Building Environment
30	[128]	Carbon peak control for achieving net-zero renewable-based smart cities: Digital twin modeling and simulation	✓	29- Digital Twin modeling and simulating for Net Zero renewable-based in Smart Cities
31	[130]	Development of a Framework to Support Whole-Life-Cycle Net-Zero-Carbon Buildings through Integration of Building Information Modelling and Digital Twins	✓	30- Digital Twins Technologies for The Whole Life Cycle of Net Zero Carbon Buildings
Theme 3: Zero Energy Buildings and Sustainable Smart Cities				
32	[42]	Challenges and barriers for net- zero/positive energy buildings and districts—empirical evidence from the smart city project SPARCS.	✓	31- Net Zero/ Positive Energy Buildings and districts in smart cities in Smart cities
33	[39]	Stand alone PV-wind-DG-battery hybrid energy system for zero energy buildings in smart city Coimbatore, India	✓	32– Hybrid Energy Resources for Zero Energy Buildings in Smart Cities
34	[28]	Net Zero Energy Districts: Connected Intelligence for Carbon-Neutral Cities	✓	33– Net-Zero Energy Districts to achieve Carbon-Neutral Cities
35	[36]	Towards Sustainable Cities: A Review of Zero Energy Buildings Techniques and Global Activities in Residential Buildings.	✓	34- Zero Energy Buildings Techniques in Achieving and Promoting Sustainable Cities.
36	[30]	Sustainable smart city building construction methods	X	35- Sustainable smart city in Building Construction Methods
37	[40]	Innovative photovoltaic technologies aiming to design Zero-Energy buildings in different climate conditions	✓	36- Zero Energy Buildings and Photovoltaic technologies in different climate conditions
38	[12]	Leveraging Digital Twins for Zero-Energy Building Ratings in Sustainable Smart Cities: A Comprehensive Review and Novel Framework	✓	37- Zero Energy Building Rating and Digital Twins in Sustainable Smart Cities
Theme 4: Digital Twins for Building and Energy Management in Smart Cities				
39	[61]	Empowering smart cities with digital twins of buildings: Applications and implementation considerations of data-driven energy modelling in building management	✓	38- Digital Twins for Building Management in Smart Cities
40	[135]	Integrated blockchain and Digital Twin framework for sustainable building energy management.	✓	39- Digital Twin Framework for Sustainable Building Energy Management
41	[136]	Development and application of digital twin technology for integrated regional energy systems in smart cities	✓	40- Digital Twin technology in integrated regional energy systems for smart cities
42	[137]	Smart landscaping design for sustainable net-zero energy smart cities: Modeling energy hub in digital twin	✓	41- Digital Twin Technology to Optimize Energy Hubs in Net-Zero Energy Smart Cities.
43	[62]	Digital twins for intelligent green buildings	✓	42- Integration of Digital Twin technology into Intelligent Green Buildings
44	[138]	Smart Cities Net Zero Planning considering renewable energy landscape design in Digital Twin	✓	43- Utilizing Digital Twin Technology in Smart Cities & Net Zero Planning
45	[139]	Integrated management of urban resources toward Net-Zero smart cities considering renewable energies uncertainty and modeling in Digital Twin	✓	44- Integration of Digital Twin in Energy Management Towards Net Zero Smart Cities
46	[140]	Digital twins for sustainable design and management of smart city buildings and municipal infrastructure	✓	45- Digital Twins for Sustainable Design, management, and optimization in Smart City
47	[141]	Integration of an energy management tool and digital twin for coordination and	✓	46- Digital Twin and Energy Management

(*continued on next page*)

Table 4 (*continued*)

No.	Citations	Titles	Include Zero Energy Building or Digital Twin	Topics Discussed in the Selected Articles
		control of multi-vector smart energy systems.		
48	Francisco and Taylor [142]	Smart city digital twin–enabled energy management: Toward real-time urban building energy benchmarking	✓	47- Digital Twin, Smart Cities and Real –Time Energy Management
Theme 5: Digital Twins and Building Energy Efficiency				
49	[143]	Building performance simulation in the brave new world of artificial intelligence and digital twins: A systematic review.	✓	48- Digital Twin and AI in Building Performance.
50	[55]	Cyber-physical systems improving building energy management: Digital twin and artificial intelligence	✓	49- Digital Twin, Cyber-Physical Systems and AI in Building Energy Management
51	[47]	Digital twin technology for thermal comfort and energy efficiency in buildings: A state-of-the-art and future directions	✓	50- Digital Twin and Energy Efficiency
52	[44]	Digital Twins' Applications for Building Energy Efficiency: A Review.	✓	
53	[46]	A review of building digital twins to improve energy efficiency in the building operational stage	✓	
54	[144]	A digital twin framework for improving energy efficiency and occupant comfort in public and commercial buildings	✓	
55	[145]	Digital twin-driven approach to improving energy efficiency of indoor lighting based on computer vision and dynamic BIM	✓	
56	[52]	Deep learning for assessment of environmental satisfaction using BIM big data in energy-efficient building digital twins	✓	
57	[146]	Recent trends of digital twin technologies in the energy sector: A comprehensive review	✓	
58	[147]	DanRETwin: A digital twin solution for optimal energy retrofit decision-making and decarbonization of the Danish building stock	✓	
59	[148]	The Efficiency of building Maintenance Using Digital Twins: A Literature review.	✓	
60	[77]	Bibliometric Review of building Material Assessment for Energy Efficiency in urban Digital Twins.	✓	
61	[149]	Major opportunities of digital twins for smart buildings: a scientmetric and content analysis,	✓	
62	[43]	Digital Twins for Reducing Energy Consumption in Buildings: A Review	✓	51- Digital Twin and Energy Consumption
63	[150]	Exploring the Benefits and Limitations of Digital Twin Technology in Building Energy	✓	
64	[48]	A Digital Twin for Energy Consumption Prediction and Thermal Comfort Monitoring in Residential Buildings	✓	
65	[50]	Digital Twin-Driven Decision Making and Planning for Energy Consumption	✓	
66	[151]	Energy Consumption Forecasting for the Digital-Twin Model of the Building	✓	
67	[152]	Continuous model calibration framework for smart-building digital twin: A generative model-based approach.	✓	
68	[153]	BIM integration: How BIM can be leveraged to create digital twins of buildings.	✓	
69	[45]	A comprehensive review of digital twin technology in building energy consumption Forecasting	✓	
70	[154]	Comparative assessment of simple and detailed energy performance models for urban energy modelling based on digital twin and statistical typology database for the renovation of existing building stock	✓	52- Energy Performance and Digital Twin
71	[155]	Improving building energy footprint and asset performance using digital twin technology	✓	
72	[156]	Quality and accuracy of digital twin models for the neighborhood-level building energy performance calculations	✓	

(*continued on next page*)

Table 4 (*continued*)

No.	Citations	Titles	Include Zero Energy Building or Digital Twin	Topics Discussed in the Selected Articles
73	[157]	Classifying the operational energy performance of buildings with the use of digital twins	✓	
74	[158]	Digital twin technology for integrated energy system and its application	✓	
75	[159]	Digital twins: Creating digital twins of buildings can enable the simulation and optimization of building systems and operations.	✓	
76	[160]	Digital Twin in the Design and Dynamic Assessment of Energy Performance of Multi-Family Buildings	✓	
77	[75]	Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review	✓	53- Digital Twin and Energy Services
78	[161]	Digital twin-based assessment framework for energy savings in university classroom lighting	✓	54- Digital Twin and Energy Management
79	[162]	Digital Twin as energy management tool through IoT and BIM data integration	✓	
80	[163]	Energy digital twin technology for industrial energy management: Classification, challenges and future	✓	
81	[72]	A comprehensive review on digital twins for smart energy management system	✓	
82	[164]	Creating Digital Twins of Smart Buildings on The Azure Digital Twins Platform.	✓	
83	[165]	Reviewing applications of digital twins in building management in response to the Covid-19 pandemic.	✓	
84	[71]	From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry	✓	55- Digital Twin and Intelligent Buildings
85	[166]	Towards occupant-driven district energy system operation: A digital twin platform for energy resilience and occupant well-being	✓	56- Digital Twin and Energy System Operation
86	[167]	Digital twin: vision, benefits, boundaries, and creation for buildings	✓	57- Digital Twin for Predictive Maintenance
87	[168]	Digital Twins & Sustainability: A Pathway to Building Positive-Energy District	✓	58- Digital Twin and Sustainability for Positive Energy Districts
88	[169]	Digital Twin for Accelerating Sustainability in Positive Energy District: A Review of Simulation Tools and Applications	✓	
89	[73]	A Systematic Review of the Digital Twin Technology in Buildings, Landscape and Urban Environment from 2018 to 2024	✓	59-Digital Twins in Architecture, Engineering, and Construction (AEC) industry
90	[74]	Digital twin for decarbonizing operating buildings: A systematic review and implementation framework development.	✓	60- Digital Twins for Decarbonizing Operation Buildings
Theme 6: Digital Twins and Smart Sustainable Cities				
91	[170]	Digital twins for cities: Analyzing the gap between concepts and current implementations with a specific focus on data integration	✓	61-Digital Twin and Smart Cities
92	[118]	A systematic review of a digital twin city: A new pattern of urban governance toward smart cities	✓	
93	[171]	Smart city based on digital twins	✓	
94	[112]	Architecting smart city digital twins: Combined semantic model and machine learning approach.	✓	
95	[92]	Smart City Digital Twins, 3D Modeling and Visualization Tools, and Spatial Cognition Algorithms in Artificial Intelligence-based Urban Design and Planning	✓	
96	[172]	Navigating urban complexity: The transformative role of digital twins in smart city development	✓	
97	[173]	Urban “Digital Twins” for smart cities and citizens	✓	62-Urban Digital Twin and Smart Cities
98	[110]	Urban digital twins for smart cities and citizens: The case study	✓	

(continued on next page)

Table 4 (*continued*)

No.	Citations	Titles	Include Zero Energy Building or Digital Twin	Topics Discussed in the Selected Articles
		of Herrenberg, Germany		
99	[25]	The synergistic interplay of artificial intelligence and digital twin in environmentally planning sustainable smart cities: A comprehensive systematic review	✓	63- Digital Twin and Sustainable Smart Cities
100	[26]	Artificial internet of things, sensor-based digital twin urban computing vision algorithms, and blockchain cloud networks in sustainable smart city administration	✓	
101	[27]	Urban Digital Twin Challenges: A systemic review of urban digital twin challenges and perspectives for sustainable smart cities	✓	
102	[107]	Generative spatial artificial intelligence for sustainable smart cities: A pioneering large flow model for urban digital twin	✓	
103	[24]	Artificial Intelligence of Sustainable Smart City Brain and Digital Twin Systems: A Pioneering Framework for Advancing Environmental Sustainability.	✓	

time data on energy usage, carbon emissions, and resource efficiency, which feed directly into UDTs. These data exchange enhances the ability of UDTs to simulate energy flows, optimize decision-making, and improve long-term operational strategies. Furthermore, ZEBs offer practical, real-world insights into the functioning of energy systems, improving the relevance and precision of simulations used by UDTs in designing energy-efficient urban environments. Thus, the integration of ZEBs supports the operational optimization of UDTs and enhances their capacity to predict, model, and plan. This interconnected approach fosters a more robust and holistic framework for advancing the climate change mitigation goals of sustainable smart cities.

6.2.6. A novel framework for integrating urban digital twins and zero energy buildings in sustainable smart cities

6.2.6.1. Description of essential components and their relationships and Interactions. Essential The novel framework introduced in this study integrates UDTs with ZEBs to optimize their performance, enhance energy efficiency, boost renewable energy integration, and reduce carbon footprints, thereby supporting climate change mitigation efforts in the context of sustainable smart cities. This framework is designed to bridge the gap between building-level energy management and larger urban energy systems, addressing key sustainability challenges at both the individual building and city-wide levels. While a single ZEB can be energy-efficient, it contributes only a fraction of the city's overall environmental sustainability efforts. Connecting ZEBs to broader urban systems, this framework maximizes their impact, improves energy resilience across the city, and enables cities to make smarter, data-driven decisions about their energy and resource management. Ultimately, the framework ensures that ZEBs contribute to the overall smart city infrastructure, promoting energy management, water conservation, material efficiency, and carbon emissions reduction. The essential components of this framework are outlined in Table 6.

In summary, ZEBs play a crucial role in reducing reliance on non-renewable energy sources and minimizing greenhouse gas emissions. UDTs further enhance their effectiveness and amplify their impact by optimizing performance and driving climate change mitigation efforts. This integrated approach is essential for achieving the ambitious goals of environmentally sustainable urban development. Moving forward, further research should focus on developing robust tools and methodologies that can facilitate the practical implementation of this framework across diverse urban environments.

6.2.6.2. Visual representation of essential components and practical case examples. The essential components of the integrated framework are depicted in Fig. 6 based on Table 6. To better illustrate the practical application of the integrated framework, the following case examples demonstrate how the synergy between UDTs and ZEBs can optimize energy management and contribute to climate change mitigation efforts in sustainable smart cities. These examples highlight the real-world integration of UDTs and ZEBs in different urban settings, showcasing their combined potential to enhance energy efficiency, boost renewable energy integration, reduce carbon emissions, and support the transition to more sustainable, resilient urban environments.

Smart City with integrated UDTs and ZEBs for energy management: In a sustainable smart city, UDTs are used to collect real-time data on energy consumption, building performance, and renewable energy generation from ZEBs. For instance, ZEBs equipped with solar photovoltaics and energy storage systems can generate and store renewable energy. The UDTs continuously monitor the building's energy production and consumption patterns, while also assessing the environmental impact of different energy sources. The UDTs can, by analyzing these data, predict fluctuations in energy demand throughout the day and automatically optimize energy usage. For example, during peak hours, when energy demand is high, the UDT can redirect stored energy from the ZEB's batteries to power building operations, minimizing reliance on the grid and reducing carbon emissions. The integration of these technologies ensures that the building operates efficiently, contributing to the city's overall climate change mitigation strategies, such as reducing greenhouse gas emissions and enhancing energy resilience.

Integration for urban energy efficiency in mixed-use development: In a mixed-use urban development with multiple buildings, UDTs integrate with ZEBs to optimize city-wide energy usage. Each ZEB in the development utilizes renewable energy solutions, such as wind turbines and geothermal systems, to meet its energy needs. UDTs collect real-time data across all buildings, measuring factors like energy consumption, weather patterns, and the performance of renewable energy systems. When one of the buildings faces increased energy demand due to external conditions like a heatwave, the UDTs can dynamically redistribute energy from other buildings with excess capacity or stored energy, ensuring optimal energy efficiency across the development. In addition, the UDTs provide predictive maintenance data, alerting maintenance teams to potential issues with renewable energy systems or energy storage units before they disrupt the building's operations. UDTs and ZEBs collectively contribute to the development's sustainable energy practices, reducing operational costs, enhancing resilience, and supporting the city's overall climate action goals by enabling this proactive approach to energy management and system optimization.

Table 5a
Zero Energy Buildings Indicators in response to climate change mitigating versus topics discusses in selected articles.

No.	Topics discussed in selected articles	Zero Energy Buildings Indicators in Response to Climate Change Mitigation					Citation. No. from Table 4.
		Energy Efficiency	Renewable Energy Generation	Carbon Emissions	Building Envelope Performance	Water Efficiency and Sustainable Materials Use	
1	Key Technologies for Achieving Zero Energy Buildings	✓	✓	✓	✓	x	1
2	Net Zero Energy Buildings in Tropical Climates	✓	✓	✓	✓	x	2
3	Solar Techniques to achieve Zero Energy Buildings	✓	✓	✓	✓	✓	3
4	Strategies of Net Zero Energy and Net Zero Carbon Buildings	✓	✓	✓	✓	✓	4
5	Implementing Energy Efficiency Practices Toward Net Zero Energy Buildings	✓	✓	✓	✓	✓	5
6	Concept of Net Zero Energy Buildings	✓	✓	✓	✓	✓	6
7	Smart technologies to achieve Nearly Zero-Energy Performance.	✓	✓	✓	✓	✓	7
8	Net Zero Energy Building	✓	✓	✓	✓	✓	8
		✓	✓	✓	✓	✓	9
9	Zero Energy Building	✓	✓	✓	✓	x	10
10	Smart Buildings Features and Key Performance Indicators	✓	✓	✓	✓	x	11
11	Zero Energy Building using a combination of Coyote Optimization and Elman Neural Networks	✓	✓	✓	✓	✓	12
12	Net Zero Energy Buildings and Renewable Energy Generation	✓	✓	✓	✓	✓	13
13	Zero Energy Buildings and Energy Efficiency Measures.	✓	✓	✓	✓	✓	14
14	Building Envelope and Zero Carbon –ready Buildings	✓	✓	✓	✓	✓	15
15	Net Zero Energy Buildings and Building Life Cycle across Canadian Climates conditions	✓	✓	✓	✓	✓	16
16	Net Zero Energy Cost Building and Artificial Intelligence.	✓	✓	✓	x	x	17
17	Net Zero and Positive Energy Buildings	✓	✓	✓	✓	x	18
18	Nearly Zero Energy Building and Solar Photovoltaic based on Genetic Algorithm.	✓	✓	✓	✓	x	19
19	Operation and Maintenance of Zero Carbon Building	✓	✓	✓	✓	x	20
20	Zero Energy Port Area and Digital Twin Model	✓	✓	✓	x	x	21
21	Digital Twin with machine learning for Predicative Monitoring and control of CO2.	✓	✓	✓	✓	x	22
22	Digital Twin Simulation for Energy Management in Net Zero Energy	✓	✓	✓	x	x	23
23	Digital Technologies for A Net-Zero Energy	✓	✓	✓	x	x	24
24	A Digital-Twin Evaluation of Net Zero Energy Buildings	✓	✓	✓	✓	x	25
25	Digital Twin Model for Net Zero Energy Building Operation and Maintenance	✓	✓	✓	✓	x	26
26	Digital Twin in Built Environment	✓	✓	✓	✓	x	27
27	Digital-Twin-Based Evaluation of Nearly Zero-Energy Building	✓	✓	✓	✓	x	28
28	Digital Twin Powered by AI & IoT for Smart Cities and Sustainable Building Environment	✓	✓	✓	✓	✓	29
29	Digital Twin modeling and simulating for Net Zero renewable-based in Smart Cities	✓	✓	✓	x	x	30
30	Digital Twins Technologies for The Whole Life Cycle of Net Zero Carbon Buildings	✓	✓	✓	✓	x	31
31	Net Zero / Positive Energy Buildings and districts in smart cities in Smart cities	✓	✓	✓	✓	x	32
32	Hybrid Energy Resources for Zero Energy Buildings in Smart Cities	✓	✓	✓	✓	x	33
33	Net – Zero Energy Districts to achieve Carbon-Neutral Cities	✓	✓	✓	✓	✓	34
34	Zero Energy Buildings Techniques in Achieving and Promoting Sustainable Cities	✓	✓	✓	✓	✓	35
35	Sustainable smart city in Building Construction Methods	✓	✓	✓	✓	x	36
36	Zero Energy Buildings and Photovoltaic technologies in different climate conditions	✓	✓	✓	✓	x	37
37	37- Zero Energy Building Rating and Digital Twins in Sustainable Smart Cities	✓	✓	✓	x	✓	38

Table 5b
Urban Digital Twins Indicators in response to climate change mitigating versus topics discusses in selected articles.

No.	Topics discussed in selected articles	Urban Digital Twins (UDTs) Indicators in response to climate change mitigation					Citation. No. from Table 4.
		Real-time Energy Monitoring and Management	Predictive Maintenance and Operational Efficiency	Integration of Renewable Energy Sources	Optimization of Building Design and Retrofitting	Carbon Footprint Analysis and Reduction	
20	Zero Energy Port Area and Digital Twin Model	✓	✓	✓	✓	✓	21
21	Digital Twin with machine learning for Predicative Monitoring and control of CO2.	✓	✓	✓	✓	✓	22
22	Digital Twin Simulation for Energy Management in Net Zero Energy	✓	✓	✓	✓	✓	23
23	Digital Technologies for A Net-Zero Energy	✓	✓	✓	✓	✓	24
24	A Digital – Twin Evaluation of Net Zero Energy Buildings	✓	✓	✓	x	✓	25
25	Digital Twin Model for Net Zero Energy Building Operation and Maintenance	✓	✓	✓	✓	✓	26
26	Digital Twin in Built Environment	✓	✓	✓	x	✓	27
27	Digital-Twin-Based Evaluation of Nearly Zero-Energy Building	✓	✓	✓	✓	✓	28
28	Digital Twin Powered by AI & IoT for Smart Cities and Sustainable Building Environment	✓	✓	✓	✓	✓	29
29	Digital Twin modeling and simulating for Net Zero renewable-based in Smart Cities	✓	✓	✓	✓	✓	30
30	Digital Twins Technologies for The Whole Life Cycle of Net Zero Carbon Buildings	✓	✓	✓	✓	✓	31
38	Digital Twins for Building Management in Smart Cities	✓	✓	✓	x	✓	39
39	Digital Twin Framework for Sustainable Building Energy Management	✓	✓	✓	✓	✓	40
40	Digital Twin technology in integrated regional energy systems for smart cities	✓	✓	x	✓	x	41
41	Digital Twin Technology to Optimize Energy Hubs in Net-Zero Energy Smart Cities.	✓	✓	✓	✓	✓	42
42	Integration of Digital Twin technology into Intelligent Green Buildings	✓	✓	✓	✓	✓	43
43	Utilizing Digital Twin Technology in Smart Cities & Net Zero Planning	✓	✓	✓	✓	✓	44
44	Integration of Digital Twin in Energy Management Towards Net Zero Smart Cities	✓	✓	✓	✓	✓	45
45	Digital Twins for Sustainable Design, management, and optimization in Smart City	✓	✓	✓	✓	x	46
46	Digital Twin and Energy Management	✓	✓	✓	x	✓	47
47	Digital Twin, Smart Cities and Real –Time Energy Management	✓	✓	✓	✓	✓	48
48	Digital Twin and AI in Building Performance.	x	✓	x	✓	x	49
49	Digital Twin, Cyber-Physical Systems and AI in Building Energy Management	✓	✓	✓	✓	✓	50
50	50- Digital Twin and Energy Efficiency	✓	✓	✓	✓	✓	51
		✓	✓	✓	✓	✓	52
		✓	✓	✓	✓	✓	53
		✓	✓	✓	✓	x	54
		✓	✓	x	✓	x	55
		✓	✓	x	✓	x	56
		✓	✓	✓	✓	✓	57
		✓	✓	✓	✓	✓	58
		✓	✓	✓	✓	✓	59
		✓	✓	✓	x	✓	60

(continued on next page)

Table 5b (*continued*)

No.	Topics discussed in selected articles	Urban Digital Twins (UDTs) Indicators in response to climate change mitigation					Citation. No. from Table 4.
		Real-time Energy Monitoring and Management	Predictive Maintenance and Operational Efficiency	Integration of Renewable Energy Sources	Optimization of Building Design and Retrofitting	Carbon Footprint Analysis and Reduction	
		✓	✓	x	✓	x	61
51	51- Digital Twin and Energy Consumption	✓	✓	✓	x	✓	62
		✓	✓	✓	✓	✓	63
		✓	✓	x	✓	✓	64
		✓	✓	✓	✓	✓	65
		✓	✓	✓	✓	x	66
		✓	✓	x	✓	✓	67
		✓	✓	x	✓	x	68
		✓	✓	✓	✓	✓	69
52	52-Energy Performance and Digital Twin	✓	✓	✓	x	✓	70
		✓	✓	x	✓	x	71
		✓	✓	x	✓	x	72
		✓	✓	x	✓	✓	73
		✓	✓	x	x	x	74
		✓	✓	✓	✓	x	75
		✓	✓	✓	✓	✓	76
53	53- Digital Twin and Energy Services	✓	✓	✓	✓	✓	77
54	54- Digital Twin and Energy Management	✓	✓	✓	✓	✓	78
		✓	✓	x	✓	x	79
		✓	✓	✓	✓	✓	80
		✓	✓	✓	✓	✓	81
		✓	✓	x	✓	x	82
		✓	✓	x	✓	✓	83
55	55- Digital Twin and Intelligent Buildings	✓	✓	✓	✓	✓	84
56	56- Digital Twin and Energy System Operation	✓	✓	x	✓	x	85
57	57- Digital Twin for Predictive Maintenance	✓	✓	x	✓	x	86
58	58- Digital Twin and Sustainability for Positive Energy Districts	✓	✓	✓	✓	✓	87
		✓	✓	✓	✓	✓	88
59	59- Digital Twins in Architecture, Engineering, and Construction (AEC) industry	✓	✓	x	✓	✓	89
60	60- Digital Twins for Decarbonizing Operation Buildings	✓	✓	✓	✓	✓	90
61	61-Digital Twin and Smart Cities	✓	✓	✓	x	✓	91
		✓	✓	x	✓	x	92
		✓	✓	x	✓	x	93
		✓	✓	x	✓	x	94
		✓	✓	x	✓	x	95
		✓	✓	✓	✓	✓	96
62	62- Urban Digital Twin and Smart Cities	✓	✓	✓	✓	x	97
		✓	✓	✓	✓	✓	98
63	63- Digital Twin and Sustainable Smart Cities	✓	✓	✓	x	✓	99
		✓	✓	✓	✓	✓	100
		✓	x	x	x	x	101
		✓	✓	x	x	x	102
		✓	x	x	x	x	103

These case examples demonstrate how the integration of UDTs and ZEBs can optimize energy performance, ensure operational efficiency, and contribute to climate change mitigation in real-world urban environments. In this context, the integration of UDT technical and operational indicators with ZEB performance indicators, as illustrated in Fig. 6, creates a synergistic relationship. This integration, as demonstrated in the case examples, allows for dynamic adjustments that optimize energy management and resource utilization, ultimately achieving significant environmental outcomes. The integrated framework enhances the ability of smart cities to meet their environmental sustainability and climate change mitigation goals effectively by aligning both indicators.

7. Discussion

This study aimed to explore how the integration of UDT and ZEB technologies could contribute to advancing climate change mitigation and promoting sustainable development in smart cities. The findings provide valuable insights into how UDTs can optimize ZEB performance and energy management, laying the foundation for a comprehensive framework to guide their integration in sustainable urban environments. This section provides a comprehensive discussion that summarizes the findings in relation to the research questions, compares them with existing literature, explores their implications for research, practice, and policymaking, and addresses the key challenges while highlighting directions for future research.

7.1. *Summary of the findings*

The results of this study address three research questions. Regarding RQ 1, the bibliometric analysis revealed emerging trends in the convergence of UDTs and ZEBs, with a strong focus on optimizing

Table 6
Key components of the integrated framework for UDTs and ZEBs in sustainable smart cities.

Essential Components	Detailed Description
ZEB Technologies: At the core of the framework, ZEBs focus on energy-efficient building technologies and renewable energy integration. The goal is to reduce the dependency on external energy sources, optimize energy consumption, and utilize on-site renewable energy generation to achieve zero-energy status.	• Energy-efficient building design (e.g., optimized building envelopes, insulation, and HVAC systems). • Renewable energy systems (e.g., solar photovoltaics, wind turbines, hybrid energy systems, energy storage solutions). • Building energy management systems (e.g., smart meters, sensors for monitoring energy use). • Water management (e.g., smart water systems for efficient use and reduction of waste). • Sustainable material usage (e.g., integration of sustainable construction materials to lower environmental impact). • CPS-based integration (connecting buildings and energy systems with digital systems to enable real-time monitoring, optimization, and enhanced decision-making through AI and IoT technologies).
UDT Technologies: UDTs are utilized to create a dynamic digital representation of physical urban assets (buildings, energy systems, etc.). They enable real-time monitoring, predictive analytics, and decision-making to optimize energy consumption and ensure the continuous performance of ZEBs. UDTs serve as an intelligent layer for managing and analyzing data generated by the built environment.	• Real-time monitoring and data analytics (e.g., continuous energy use tracking, environmental data gathering). • Predictive maintenance (e.g., predicting when building systems require maintenance or upgrades). • Operational optimization (e.g., adjusting energy systems based on real-time conditions to enhance efficiency). • Water and resource management (e.g., monitoring and optimizing water and material usage throughout the urban ecosystem). • Carbon footprint analysis and reduction (e.g., monitoring, analyzing, and assessing carbon emissions across urban infrastructures and building operations, optimizing energy flows, and making real-time adjustments to building systems to reduce CO2 emissions and improve overall environmental performance across the city). • CPS-based integration: (e.g., managing interconnected physical systems such as energy grids, water networks, and building energy systems, leveraging AI and IoT for real-time data processing, system responsiveness, and enhanced decision-making).
Integration Mechanisms: The integration of UDTs with ZEBs is at the heart of the framework, creating a synergistic relationship between smart buildings and urban systems. This involves the seamless connection of building-level data (from ZEBs) to broader city-wide systems managed by UDTs. The framework aims to reduce urban carbon footprints, improve energy resilience, and contribute to the overall sustainability of smart cities.	• Data-driven decision-making: UDTs leverage real-time data from ZEBs to inform operational adjustments, ensuring the optimal performance of both ZEBs and the broader urban systems they are part of. • Smart energy management: UDTs optimize energy distribution across buildings (ZEBs) and other urban infrastructure, balancing supply and demand on a city-wide scale for improved energy efficiency. • Real-time adaptive systems: These systems continuously adjust energy systems and building operations based on data collected by UDTs, enabling dynamic responses to fluctuations in energy demand and environmental conditions. • Water and Wastewater Management Systems: These systems optimize water and wastewater management within buildings (ZEBs) and across city-wide systems through the integration of UDTs, ensuring efficient use, conservation, and environmental sustainability.
Climate Change Mitigation and Environmental Sustainability Goals: The integration of UDTs and ZEBs ultimately serves the broader objectives of climate change mitigation and environmental sustainability. The framework aims to reduce urban carbon footprints, improve energy resilience, and contribute to sustainable smart cities.	• Energy efficiency (improving overall energy use efficiency in buildings and urban systems). • Carbon emissions reduction (achieving net-zero emissions through the integration of renewable energy and advanced technologies). • Resource optimization (e.g., optimizing water and energy usage through smart systems and data insights). • Sustainable development (e.g., promoting green infrastructure and reducing urban environmental impacts).
Sustainable Smart Cities: These cities represent the overarching vision that drives the integration of UDTs and ZEBs, where energy efficiency, climate resilience, and carbon reduction are at the core of urban development. Powered by AI, IoT, and CPS, these technologies work in synergy to create urban environments that maximize energy efficiency and enable cities to effectively adapt to changing climate conditions.	• Optimizing energy usage: At both the building (ZEB) and city-wide (UDT) scales, the integration ensures energy efficiency across all systems. • Enhancing resilience: The synergy between UDTs and ZEBs enables cities to respond effectively to environmental changes and energy supply fluctuations. • Reducing carbon footprints: The integration of renewable energy systems and advanced data-driven management techniques reduces urban carbon footprints. • Improving urban sustainability: Combining resource management, energy efficiency, and sustainable infrastructure, the integration of UDTs and ZEBs facilitates the development of cities that align with environmental goals, ensuring that urban areas become energy-efficient, resilient, and sustainable.

energy efficiency, enhancing renewable energy integration, reducing carbon emissions, and improving building performance. It also highlighted key research patterns, including the growing interest in using AI, machine learning, and CPS in UDT systems for real-time monitoring, predictive maintenance, and control of ZEBs, indicating a shift towards data-driven solutions in sustainable urban development. Concerning RQ 2, the study underscores that UDTs enhance ZEBs by providing real-time monitoring, advanced data analytics, and predictive maintenance. These capabilities enable the optimization of energy consumption and production, ensuring ZEBs maintain their net-zero energy status. The study emphasizes the integration of renewable energy sources, where UDTs facilitate efficient energy distribution and help manage fluctuations in energy demand, a critical aspect of achieving sustainable urban energy systems. As regards RQ 3, the study highlights the critical need for a comprehensive framework that considers the technical and operational aspects of integrating UDTs with the performance indicators of ZEBs. This study proposes a strategic approach that merges data-driven insights from UDTs with the sustainability objectives of ZEBs, aiming to optimize their collective impact on climate change mitigation and enhance sustainable development in smart cities.

7.2. Interpretation of the findings

The findings of this study contribute to the growing body of

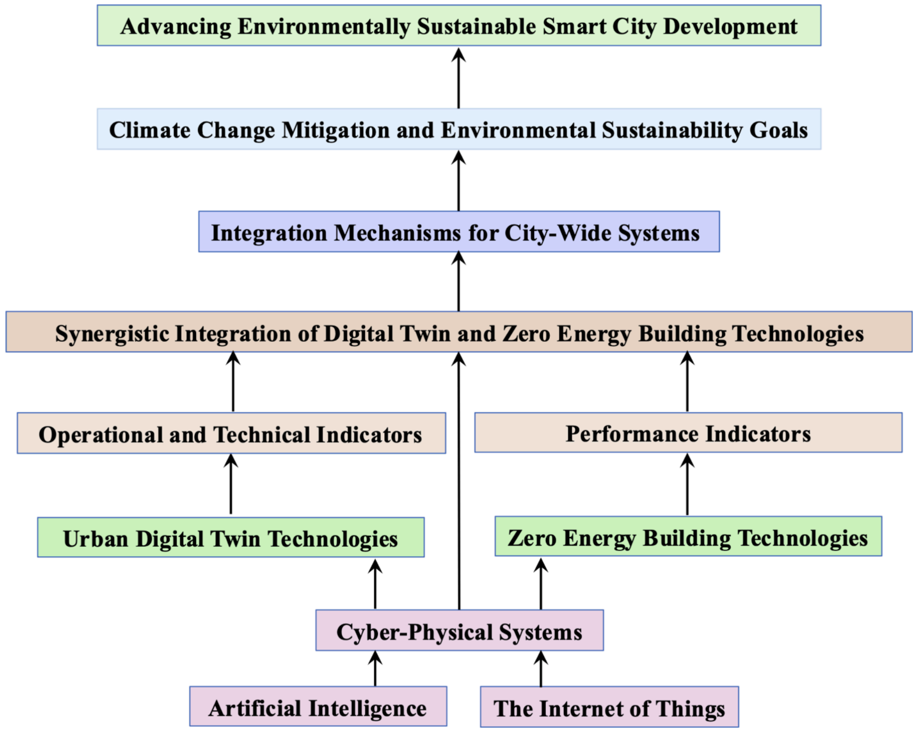

Fig. 6. A novel framework for integrating Urban Digital Twins and Zero Energy Buildings to advance environmentally sustainable smart city development.

knowledge on the integration of UDTs and ZEBs by aligning with the identified trends and addressing the research questions posed in the introduction. The integration of UDTs and ZEBs provides a promising pathway for enhancing energy management and optimizing building performance in emerging sustainable smart cities. In terms of emerging trends (RQ1), the integration of UDTs with ZEBs is evolving to focus on advanced data-driven solutions, such as IoT, AI, machine learning, and CPS, as well as their integration. Their computational, analytical, and operational capabilities help ZEBs maintain their energy balance while reducing their environmental impact. The bibliometric analysis revealed a strong trend towards interdisciplinary research, particularly the convergence of emerging technologies with renewable energy systems.

As regards RQ2, the study illustrates that UDTs enhance the operational performance and energy management of ZEBs by providing real-time insights into energy consumption, predicting system failures, and optimizing energy flows between buildings, the grid, and storage systems. This dynamic approach is particularly critical in the context of smart cities, where the complexity of urban systems requires advanced, data-driven solutions to optimize resource utilization and minimize environmental impact. Sustainable smart cities can achieve more efficient energy use, enhance sustainability, and reduce operational costs by integrating UDTs into ZEBs. Furthermore, the ability of UDTs to dynamically adjust energy systems based on external factors, such as weather conditions and diverse climates, further strengthens the integration of ZEBs within sustainable smart city frameworks.

Regarding RQ3, the proposed framework for integrating UDTs and ZEBs outlines the critical role of data-driven technologies in optimizing sustainable energy management, improving building performance, and enhancing environmental sustainability. The integration of the performance indicators of ZEBs and the technical and operational indicators of UDTs within a unified framework enables city planners and developers to create more sustainable, resilient, and energy-efficient buildings. The framework also emphasizes the need for an interdisciplinary approach, combining technological innovations with policy support and industry collaboration to address the challenges and accelerate the adoption of UDTs and ZEBs in urban settings.

In addition, the framework recognizes that ZEBs operate not just as isolated entities but are part of the broader energy and infrastructure networks in a sustainable smart city. Integrating ZEBs with UDTs enables the transfer of building-level data (like energy use, renewable energy generation, and performance metrics) into city-wide systems managed by UDTs**.** This allows for more dynamic, real-time optimization**,** not just at the building level but also at the city scale, impacting energy distribution, resource management, and carbon reduction efforts**.**

The findings indicate that UDTs, when integrated with ZEBs, can significantly improve the energy performance of buildings, promote the efficient use of renewable resources, and reduce the environmental impact of urban infrastructures. Specifically, UDTs offer dynamic, real-time monitoring and predictive capabilities that enhance the operational management of ZEBs, providing actionable insights to further optimize energy efficiency and maintain zero-energy status. This research highlights the synergies between UDTs and ZEBs, emphasizing their potential to contribute to the realization of smart, environmentally sustainable, and climate-resilient cities. It provides a solid foundation for developing a comprehensive framework to guide the future integration of these technologies, with an emphasis on achieving the broader environmental objectives of sustainable smart cities.

7.3. A comparative analysis with previous studies

This study makes a significant contribution to the broader discourse on environmentally sustainable urban development by addressing a critical gap in the integration of UDTs and ZEBs—an area that has been largely overlooked in prior review research. While existing literature has made notable progress in advancing our understanding of these technologies and their practical applications, often in isolation, it has scarcely addressed the importance of the systematic exploration of their collaborative potential and combined impact on advancing climate change mitigation in the dynamic context of sustainable smart cities. The current study critically evaluates this body of research, identifying the limitations of fragmented studies, and proposes a unified approach that bridges the gap between UDTs and ZEBs in this context. This subsection compares the findings of the current study with existing literature on ZEBs and UDTs, highlighting key similarities, differences, and contributions to the body of knowledge. It offers valuable insights into how these technologies have been explored separately and underscores their potential for integration to enhance climate change mitigation efforts and sustainable development practices in smart cities.

Several review studies provide comprehensive insights into the technological advancements and challenges in ZEBs. A large part of this research highlights the significant progress made in the development and implementation of ZEBs, including improvements in energy management systems, renewable energy integration, carbon emission reduction, and building envelope optimization (e.g., [36,53,64,69]). However, other studies (e.g., [63,66,67,70]) reveal ongoing challenges, including cost, regional adaptation, and technical integration.

Similarly, several review studies underscore the critical role of UDTs in advancing energy efficiency and supporting sustainable urban development. Key studies (e.g., [44,62]) emphasize the potential of UDTs in optimizing building energy performance, improving occupant comfort, and enabling real-time monitoring. Deng et al. [118] propose frameworks integrating UDTs with BIM for better lifecycle management, aligning with the operational goals of ZEBs. Cespedes-Cubides and Jradi [46] review UDT applications in the operational phase, specifically highlighting predictive maintenance and anomaly detection, which are critical to ensuring the sustained energy performance of ZEBs. Arowoiya et al. [47] examine how UDTs, combined with AI, can optimize building energy consumption, focusing on predictive modeling and occupant behavior analysis. Bibri [60] extend the relevance of UDTs by developing a ZEB rating framework that integrates real-time data to optimize energy consumption patterns, ensuring alignment with sustainable smart city principles.

The current study complements the findings from the two sets of review studies by further focusing on the integration of UDTs with ZEBs. While previous research has primarily examined ZEB technologies independently, this study emphasizes the synergistic potential of combining ZEBs and UDTs. It proposes a novel framework for their integration, which has not been explored in earlier reviews. In contrast to prior research that explores ZEB technologies and their challenges in isolation, this study broadens the scope by focusing on how UDTs can improve the operational efficiency and energy management of ZEBs, making them more adaptive and efficient in real-time conditions. This integration makes a significant step forward in advancing climate change mitigation efforts in sustainable smart cities.

In addition, the current study stands out by proposing a conceptual framework that integrates UDTs with ZEBs to optimize their joint performance. Unlike previous review studies, this research not only explores how UDTs can optimize energy flows but also bridges the gap by focusing on their integration with ZEBs, a combination that has not been systematically explored. The contribution of this study lies in its novelty, as it is the first to propose a framework specifically designed to integrate UDTs with ZEBs to enhance climate change mitigation efforts.

In summary, this study makes an original contribution by pioneering the convergence of emerging technological, environmental, and urban domains. It provides new insights into the role of UDTs and ZEBs in shaping the complex dynamics of their integration. Accordingly, the study complements and expands on existing work and lays the foundation for future research, particularly in exploring the practical implementation and scalability of UDT and ZEB integrations in diverse urban settings, thus contributing to sustainable urban futures.

7.4. Implications for research, practice, and policy

The findings of this study have significant implications for the development of sustainable smart cities, offering practical, theoretical, and policy recommendations for advancing the integration of UDTs and ZEBs.

The integration of UDTs with ZEBs provides a compelling practical solution for improving energy efficiency, integrating renewable energy, reducing carbon emissions, and fostering environmental sustainability in urban settings. Urban planners and developers can optimize the performance of ZEBs by leveraging the computational and analytical functionalities of UDTs, making them more adaptive to changing energy demands, climate conditions, and occupant behaviors. UDTs enable continuous monitoring of energy consumption patterns and environmental variables, facilitating predictive maintenance and energy management to ensure that ZEBs operate at peak efficiency throughout their lifecycle. This integration enhances operational performance and leads to significant cost savings by reducing resource waste and optimizing building operations. Furthermore, UDTs provide a flexible platform for scaling ZEB technologies across different urban environments, ensuring that energy systems are tailored to the unique needs of each city or district.

The development of a novel framework for integrating UDTs and ZEBs contributes significantly to theoretical knowledge in the field of sustainable smart cities. This study advances our understanding of how digital and physical infrastructures can be combined to achieve climate change mitigation goals by combining the technological capabilities of UDTs and the sustainability objectives of ZEBs. It broadens the theoretical landscape by highlighting the potential of UDTs to optimize energy efficiency and the broader operational performance of ZEBs in real-time. This approach challenges existing paradigms of building performance and resource management by incorporating dynamic, data-driven models that reflect the complex, evolving nature of urban systems. Moreover, the research offers an interdisciplinary framework that enhances urban design and energy management, contributing to the broader academic discourse on integrating advanced digital technologies with sustainable building practices. This theoretical framework provides a comprehensive model for designing future urban ecosystems that advance global environmental sustainability goals.

The findings underscore the urgent need for supportive policies to facilitate the widespread adoption of UDTs and ZEBs in urban development. Governments and policymakers have a critical role in promoting the integration of these technologies by establishing regulations and incentives that encourage the adoption of energy-efficient, net-zero, or carbon–neutral building standards. Policies should prioritize the development of regulatory frameworks that incentivize renewable energy integration, support advanced data analytics, and provide financial backing for the implementation of smart technologies in building design. Furthermore, the study highlights the need for policies that enable collaboration between the public and private sectors to address the financial, technical, and regulatory barriers that hinder large-scale implementation of UDTs and ZEBs. Financial incentives, such as subsidies for renewable energy systems or tax breaks for implementing smart building technologies, can significantly reduce upfront costs and increase the adoption of these technologies in diverse urban environments. In addition, how specific policies could mitigate data privacy concerns involves strengthening data protection regulations to secure the sensitive information collected by UDTs and ZEBs, which ensures that data handling complies with privacy laws and building trust among users. Moreover, governments can invest in creating public–private partnerships to develop the necessary infrastructure and training programs that facilitate the integration of UDTs and ZEBs.

7.5. Challenges and barriers

While the integration of UDTs and ZEBs holds significant promise for advancing climate change mitigation goals and enhancing sustainable development practices in smart cities, key challenges remain in translating theoretical frameworks into real-world applications. These challenges encompass technical, social, environmental, regulatory, and financial aspects that must be addressed to ensure the successful integration of these technologies within sustainable smart cities.

One of the major challenges in integrating UDTs with ZEBs is the complexity of managing real-time data, ensuring interoperability between different systems, and addressing the technical limitations of current DT models. The integration of renewable energy systems (such as solar panels, wind turbines, and battery storage) with UDTs and ZEBs requires sophisticated monitoring and control systems that can handle the dynamic nature of energy production and consumption. Moreover, the scalability of these systems in larger urban settings remains a significant technical hurdle. For example, integrating real-time data monitoring and control systems across various building technologies may present challenges, potentially delaying the deployment of UDT-driven energy management systems. In addition, the implementation of solar-powered ZEBs can encounter technical hurdles in synchronizing renewable energy systems with building energy management platforms. These practical challenges highlight the critical need to enhance system interoperability and improve real-time data handling in the integration of UDTs and ZEBs.

Moreover, data privacy concerns related to the deployment of UDTs also need to be addressed. UDTs rely on continuous data collection and real-time monitoring of building systems, raising concerns about data privacy and security. Protecting sensitive information related to energy consumption, occupancy behavior, and system performance is crucial to ensure the widespread acceptance and use of these technologies. Securing these data from cyber threats is an ongoing challenge, as breaches could undermine the benefits of UDT integration. To safeguard data integrity and security in UDTs, it is crucial to implement robust cybersecurity frameworks. These should include end-to-end encryption for data transmission, regular security audits, and the use of secure, compliant cloud services for data storage. In addition, access control mechanisms should be enforced to limit data access based on roles and responsibilities. Implementing advanced intrusion detection systems and real-time security monitoring can also help detect and respond to potential threats swiftly, thereby minimizing risks. These measures will protect sensitive information and bolster user confidence in UDT technology, enhancing its adoption and effectiveness. A case example of data privacy concerns could involve the deployment of UDTs in smart city initiatives, where challenges emerged in integrating citizen data from various building systems, leading to the implementation of stricter data privacy regulations and data anonymization protocols.

In addition, the success of ZEBs and UDTs is also influenced by human behavior, including the adoption of energy-efficient practices and the use of smart technologies by building occupants. Residents' attitudes toward smart technology retrofits play a critical role in the widespread adoption of ZEBs. There is a need to foster greater acceptance and understanding of these technologies among urban residents to ensure their successful implementation.

Furthermore, environmental factors, including the variability of renewable energy resources across diverse climates and geographical locations, present significant challenges for the deployment of ZEBs and their integration with UDTs. In regions with less favorable climates for renewable energy generation, such as areas with low sunlight or inconsistent wind patterns, energy production may not be sufficient to meet the energy demand of buildings. This requires additional strategies such as energy storage or hybrid energy systems to ensure a reliable and sustainable energy supply. Focusing on specific geographies involves tailoring sustainable technologies to the unique characteristics of different urban environments. This approach recognizes that cities vary widely in climate, infrastructure, regulatory landscapes, and socioeconomic factors, which all influence the effectiveness and implementation strategies of UDTs and ZEBs. As another example, deploying ZEBs in colder regions might emphasize thermal insulation and energy-efficient heating systems due to harsh winter conditions, while in tropical climates, the focus could be on natural ventilation and solar energy systems to reduce the cooling energy demand. Research can provide more actionable insights and develop localized solutions that are more likely to succeed by adapting these technologies to specific geographic requirements, thus enhancing the overall sustainability and resilience of urban areas around the world.

Moreover, regulatory frameworks for the integration of digital technologies and renewable energy systems in building design are still evolving, with inconsistent policies across regions and climates hindering the large-scale adoption of these technologies. For example, the lack of standardized regulations across cities can result in delays in the adoption of ZEBs, particularly regarding grid connectivity for energy storage systems. Climate-specific solutions and adaptable policies are key to overcoming these challenges and ensure the effective deployment of ZEBs and UDTs in a variety of environmental contexts.

While the integration of UDTs and ZEBs presents numerous advantages in advancing climate change mitigation goals, it is important to consider the environmental costs associated with the increasing use of advanced technologies. The widespread adoption of UDTs, powered by AI and AIoT, raises concerns about the energy consumption and environmental impact of these systems. The production, operation, and disposal of AI systems, sensors, and digital infrastructure can significantly contribute to carbon emissions and resource depletion. The high computational power required to manage real-time data from UDTs, along with the energy demands of AI models and data processing, further exacerbates the environmental footprint of these technologies. In addition, the lifecycle impacts of energy systems integrated with UDTs, such as the manufacturing and disposal of solar panels, wind turbines, and battery storage, must also be accounted for when evaluating the overall sustainability of ZEBs and UDTs. Addressing these environmental costs is essential to ensure that the benefits of these technologies outweigh their potential negative effects, and to promote a truly sustainable and circular approach to smart city development.

Lastly, the high initial costs of implementing ZEBs and UDTs are another significant barrier. Despite long-term savings in energy costs, the capital investment required to integrate renewable energy systems, advanced building technologies, and DTs is often prohibitive for many building owners and urban developers and planners. An example would be a smart city project that may face significant upfront costs due to the need for high-tech energy-efficient buildings and renewable energy systems, which can delay the implementation of a city-wide smart energy grid. Financial incentives, subsidies, and supportive policy frameworks are essential to make these technologies more accessible and financially viable for broader adoption.

7.6. Suggestions for future research

Several promising opportunities emerge for future research to further advance the interdisciplinary field of sustainable smart cities. Table 7 summarizes the key research areas identified for future exploration based on the findings of this study, which focuses on the integration of UDTs and ZEBs to mitigate climate change effects and enhance sustainable urban development practices.

These research areas, once explored, hold the potential to unlock new possibilities for effectively integrating UDTs and ZEBs, thus optimizing their contribution to achieving the goals of sustainable, efficient, and climate-conscious smart cities.

8. Conclusion

This study aimed to systematically explore the integration of UDTs and ZEBs for advancing climate change mitigation goals in sustainable smart cities. The primary objectives were to: (1) identify the key emerging trends and research patterns in this area; (2) investigate the role of UDTs in enhancing the operational performance and energy management of ZEBs; (3) and develop a novel framework for the integration of UDTs and ZEBs to optimize their collective impact on climate change mitigation in sustainable smart cities. A critical gap identified in the literature was the lack of a comprehensive framework that integrates UDTs and ZEBs to effectively address environmental challengers in

Table 7
Summarizes the key research areas identified for future exploration based on the findings.

Research Areas	Description
Exploring the scalability of UDT and ZEB integration	Future studies could focus on the scalability of integrating UDTs and ZEBs in large urban settings. This would involve evaluating the feasibility of applying these technologies in diverse climates, building typologies, and geographic locations, as well as addressing the challenges associated with integrating them into existing infrastructure.
Behavioral insights into technology adoption	Research that investigates the social aspects of adopting ZEBs and UDTs, including the perceptions, attitudes, and behaviors of building occupants and urban residents, could provide valuable insights into how to increase the acceptance and uptake of these technologies. Understanding the factors that influence consumer behavior could help design more effective engagement strategies and promote wider adoption.
Adaptation to specific geographies	Future research should emphasize the adaptation of UDTs and ZEBs and their integration to specific geographic conditions. This approach would involve tailoring technologies to local climates, urban infrastructure, and regulatory environments, which ensure that sustainable solutions are both effective and contextually relevant.
Evaluating long-term performance and empirical validation	While much of the existing literature focuses on the potential benefits of UDTs and ZEBs, there is a need for longitudinal studies that track the performance of these systems over time. Future research could investigate how the integration of UDTs and ZEBs performs in real-world conditions, assessing energy savings, operational efficiency, and the achievement of climate goals over extended periods. This should include empirical validation and testing to provide concrete evidence of their effectiveness and to identify potential areas for improvement in their deployment and management.
Integrating emerging technologies	As new technologies such as blockchain, AI, AIoT, and advanced sensors continue to evolve, future research should explore how these innovations can further enhance the integration of UDTs and ZEBs. For example, blockchain could facilitate the decentralized management of energy in smart grids, while AI could optimize the energy consumption patterns of buildings in real-time.
Enhancing data privacy and security	Further research is needed to explore the implementation of privacy and security measures in data collection, analysis, and transmission systems related to UDTs and ZEBs to ensure trust and compliance.
Addressing environmental costs of advanced technologies	Future studies should consider the environmental costs of advanced technologies, such as AI, AIoT, and blockchain, including energy consumption during production, operation, and disposal of these technologies.
Challenges in real-world implementations of UDTs and ZEBs	Future research should focus on city-specific implementations, examining local case studies to address the unique challenges encountered in the real-world deployment of UDTs and ZEBs, especially their integration. Key areas of investigation could include the high upfront costs associated with ZEB construction, the organizational and social issues preventing the wide adoption of UDTs, and the regulatory gaps that exist in smart city governance. Understanding these localized challenges are crucial for optimizing the integration and scaling of these technologies to meet the specific needs of diverse urban environments.

smart city development. This study aimed to bridge this gap by developing an integrated framework that harnesses the synergies between UDTs and ZEBs, maximizing their combined potential to enhance environmentally sustainable development practices in smart cities.

The findings of the study provide valuable insights into how UDTs and ZEBs can be integrated to advance climate change mitigation goals in sustainable smart cities. The study addressed three key research questions. Regarding RQ 1, the bibliometric analysis revealed key trends in the convergence of UDTs and ZEBs, highlighting an increasing focus on renewable energy technologies, real-time energy management, and the role of digital systems in optimizing building performance. The analysis also identified a growing body of research that emphasizes the importance of AI, IoT, and CPS technologies and related data-driven approaches in advancing environmental sustainability goals in urban settings. Transitioning to RQ 2, UDTs enhance the operational performance and energy management of ZEBs by providing real-time monitoring, advanced data analytics, and predictive maintenance. The integration of UDTs with ZEBs allows for better management of renewable energy sources, improves energy efficiency, reduces carbon emissions, and decrease operational costs. UDTs also enable more accurate performance assessments and the identification of inefficiencies, contributing to the long-term sustainability of ZEBs in smart cities. Moving to RQ 3, the study developed a novel framework that integrates UDTs and ZEBs. This framework takes into account technical, operational, and performance indicators of both technologies. This comprehensive approach ensures that UDTs and ZEBs can work synergistically to drive sustainable development and mitigate climate change in sustainable smart cities.

The findings represent a significant contribution to the body of knowledge, as it provides insights into how the collaborative integration of UDTs and ZEBs can maximize environmental impact and operational efficiency in urban settings. This research is particularly relevant in light of the growing emphasis on smart cities and sustainable development in recent years, and the potential for UDTs to play a crucial role in advancing ZEBs and other environmental solutions.

The conceptual framework developed in this study has significant implications for the integration of UDTs and ZEBs in sustainable smart cities. It provides a structured approach to harnessing the synergy between these technologies, enabling enhanced decision-making, dynamic energy optimization, and improved performance of ZEBs. It ensures that both UDTs and ZEBs are aligned with broader objectives of environmental sustainability, contributing to the creation of energy-efficient, carbon–neutral urban environments. Moreover, it serves as a practical guide for urban planners, developers, and policymakers, offering a strategic tool for designing and implementing integrated systems that promote energy efficiency, reduce carbon footprints, and support the transition toward net-zero smart cities.

Actionable future directions for advancing the integration of UDTs and ZEBs can be effectively explored through targeted pilot projects and strategic collaborations. One promising pilot project could focus on urban retrofitting, where an existing urban area is selected to implement UDTs and ZEBs to enhance energy efficiency and reduce carbon emissions. This would serve to demonstrate the practical benefits and establish a scalable model for other cities. Another pilot could involve integrating ZEBs with local smart grids through UDTs, optimizing energy distribution and consumption with a focus on real-time data analysis and response capabilities. For specific collaborations, forming partnerships between academic institutions and technology companies could drive forward innovations in AI and AIoT applications within UDTs and ZEBs. In addition, engaging in international cooperation with existing sustainable smart city initiatives could provide valuable opportunities to exchange insights, methodologies, and advanced technological solutions. These collaborations would enhance the development and application of these technologies and ensure their broader global impact and relevance.

This study makes several important contributions to the field of sustainable smart cities. It proposes a comprehensive framework for integrating UDTs and ZEBs. It provides a unified approach to optimizing these technologies in the context of sustainable smart cities. It offers practical insights into how UDTs can be used to enhance the performance of ZEBs, providing actionable guidelines for stakeholders seeking to integrate these technologies into their projects. Lastly, it identifies key emerging trends in the integration of UDTs and ZEBs and highlights critical research gaps that need to be addressed in future studies.

The limitations of our study primarily stem from its focus on recent literature, which may inadvertently overlook foundational works essential for understanding the full historical context and evolution of UDTs and ZEBs. Recognizing this gap, future research should include a comprehensive historical analysis to deepen understanding of how these technologies have developed and their trajectory within sustainable urban development. Furthermore, the study's reliance on qualitative data, while providing rich insights, limits the direct applicability of our findings to specific quantitative outcomes. To address this, future research should prioritize empirical studies that measure tangible impacts of UDT and ZEB integration. Such studies would be crucial in quantifying energy efficiency improvements, reductions in carbon emissions, and enhancements in operational efficiencies. Specifically, future empirical assessments should focus on: measuring energy consumption before and after ZEB implementation within various urban settings to assess actual energy savings; conducting quantitative tracking of carbon emission reductions directly attributable to the integration of UDTs and ZEBs, providing concrete evidence of their role in climate change mitigation; and analyzing operational metrics to evaluate the time and cost savings achieved through the use of UDTs in urban infrastructure management.

In conclusion, this study advances knowledge in the field of sustainable smart urban development, emphasizing the critical role of data-driven approaches in achieving climate change mitigation goals. Despite the challenges identified, the study illustrates that the integration of UDTs and ZEBs presents a viable and advanced solution for meeting the environmental objectives of sustainable smart cities. In addition, this work serves as a valuable resource for the future design and management of urban environments capable of meeting the challenges of tomorrow. Future research should focus on exploring the scalability, social acceptance, long-term performance, and environmental costs of these technologies, while also investigating the integration of emerging technological innovations to further amplify their impact. It should also address quantitative aspects to provide robust data that validate the theoretical models and qualitative findings discussed and serve as a strong foundation for informed policymaking and further technological enhancements in sustainable urban development. This approach would strengthen the evidence base for the effectiveness of UDTs and ZEBs to ensure that their potential benefits are both realized and clearly demonstrated.

CRediT authorship contribution statement

Simon Elias Bibri: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jeffrey Huang:** Writing – review & editing, Investigation, Conceptualization. **Osama Omar:** Visualization, Investigation, Data curation. **Inji Kenawy:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors acknowledge the financial support provided by Innosuisse for the Blue City Flagship Project (Flagship ID #PFFS-21- 03).

Data availability

No data was used for the research described in the article.

References

[1] A. Abu-Rayash, I. Dincer, Development of an integrated model for environmentally and economically sustainable and smart cities, Sustainable Energy Technol. Assess. 73 (2024) 104096, https://doi.org/10.1016/j.seta.2024.104096.

[2] R.H. Al-Dabbagh, Dubai, the sustainable, smart city, Renewable Energy Environ. Sustainability 7 (3) (2022) 12.

[3] F.A. Almalki, S.H. Alsamhi, R. Sahal, J. Hassan, A. Hawbani, N.S. Rajput, A. Saif, J. Morgan, J. Breslin, Green IoT for eco-friendly and sustainable smart cities: future directions and opportunities, Mobile Networks Appl. (2021), https://doi.org/10.1007/s11036-021-01790-w.

[4] S.E. Bibri, The underlying components of data-driven smart sustainable cities of the future: a case study approach to an applied theoretical framework, European Journal of Futures Research 9 (13) (2021), https://doi.org/10.1186/s40309-021-00182-3.

[5] S.E. Bibri, J. Krogstie, Data-driven smart sustainable cities of the future: a novel model of urbanism and its core dimensions, strategies, and solutions, Journal of Futures Studies 25 (2) (2020) 77–94, https://doi.org/10.6531/JFS.202012_25(2).0009.

[6] X.H. Chu, D. Ge, S. Alamri, D. Toghraie, Greening smart cities: an investigation of the integration of urban natural resources and smart city technologies for promoting environmental sustainability, Sustain. Cities Soc. 99 (2023) 104985, https://doi.org/10.1016/j.scs.2023.104985.

[7] D. Peteleaza, A. Matei, R. Sorostinean, A. Gellert, U. Fiore, B.C. Zamfirescu, F. Palmieri, Electricity consumption forecasting for sustainable smart cities using machine learning methods, Internet Things 27 (2024) 101322, https://doi.org/10.1016/j.iot.2024.101322.

[8] S.L. Tripathi, S. Ganguli, A. Kumar, T. Magradze, Intelligent green technologies for sustainable smart cities, John Wiley & Sons, 2022.

[9] M.E.E. Alahi, A. Sukkuea, F.W. Tina, A. Nag, W. Kurdthongmee, K. Suwannarat, S.C. Mukhopadhyay, Integration of IoT-enabled technologies and artificial intelligence (AI) for smart city scenario: recent advancements and future trends, Sensors 23 (11) (2023) 5206.

[10] T. Alam, R. Gupta, S. Qamar, A. Ullah, Recent Applications of Artificial Intelligence for Sustainable Development in Smart Cities, in: M. Al-Emran, K. Shaalan (Eds.), Recent Innovations in Artificial Intelligence and Smart Applications. Studies in Computational Intelligence, vol 1061, Springer, Cham, 2022, https://doi.org/10.1007/978-3-031-14748-78.

[11] S. Bibri, J. Krogstie, A. Kaboli, A. Alahi, Smarter eco-cities and their leading-edge artificial intelligence of things solutions for environmental sustainability: a comprehensive systemic review, Environmental Science and Ecotechnlogy 19 (2023), https://doi.org/10.1016/j.ese.2023.100330.

[12] S.E. Bibri, A. Alexandre, A. Sharifi, J. Krogstie, Environmentally sustainable smart cities and their converging AI, IoT, and big data technologies and solutions: an integrated approach to an extensive literature review, Energy Informatics 6 (2023) 9.

[13] S. El Himer, M. Ouaissa, Z. Boulouard, Artificial Intelligence of Things (AIoT) for Renewable Energies Systems. In S. El Himer, M. Ouaissa, A. A. A. Emhemed, M. Ouaissa, & Z. Boulouard (Eds.), Artificial Intelligence of Things for Smart Green Energy Management (Studies in Systems, Decision and Control (2022), Vol. 446, pp. 1–19). Springer.https://doi.org/10.1007/978-3-031-04851-71.

[14] S. El Himer, M. Ouaissa, A.A.A. Emhemed, M. Ouaissa, Z. Boulouard, (Eds.). Artificial Intelligence of Things for Smart Green Energy Management (2022). Springer. .

[15] M.K. Gourisaria, G. Jee, G. Harshvardhan, D. Konar, P.K. Singh, in: Artificially Intelligent and Sustainable Smart Cities, Springer, 2022, pp. 237–268.

[16] T.T. Hoang, T.N. Nguyen, D. Nawara, R. Kashef, Connecting the indispensable roles of IoT and artificial intelligence in smart cities: a survey, Journal of Information and Intelligence 2 (3) (2024) 261–285, https://doi.org/10.1016/j.jiixd.2024.01.003.

[17] A. Kataria, S. Rani, S. Kautish, Artificial intelligence of things for sustainable development of smart city infrastructures, in: W. Leal Filho, S. Kautish, T. Wall, S. Rewhorn, S.K. Paul (Eds.), Digital Technologies to Implement the UN Sustainable Development Goals (world Sustainability Series), Springer, Cham, 2024, https://doi.org/10.1007/978-3-031-68427-210.

[18] P. Mishra, G. Singh, Artificial Intelligence for Sustainable Smart Cities, in: Sustainable Smart Cities, Springer, Cham, 2023, https://doi.org/10.1007/978-3-031-33354-5_6.
[19] H. Nguyen, D. Nawara, R. Kashef, Connecting the indispensable roles of IoT and artificial intelligence in smart cities: a survey, Journal of Information and Intelligence 2 (3) (2024) 261–285, https://doi.org/10.1016/j.jiixd.2024.01.003.
[20] P.K. Singh, M. Paprzycki, M. Essaaidi, S. Rahimi, (eds). Sustainable Smart Cities. Studies in Computational Intelligence (2023a), vol 942. Springer, Cham. https://doi.org/10.1007/978-3-031-08815-5_14.
[21] A. Zaidi, S.-S.-M. Ajibade, M. Musa, F.V. Bekun, New insights into the research landscape on the application of artificial intelligence in sustainable smart cities: a bibliometric mapping and network analysis approach, Int. J. Energy Econ. Policy 4 (2023) 287.
[22] S.E. Bibri, Artificial Intelligence and Artificial Intelligence of Things Solutions for Smarter Eco-Cities: Advancing Environmental Sustainability and Climate Change Strategies. In Artificial Intelligence of Things for Smarter Eco-Cities: Pioneering the Environmental Synergies of Urban Brain, Digital Twin, Metabolic Circularity, and Platform (2025a), CRC/Taylor & Francis Group, https://doi.org/10.1201/9781003536420.
[23] A.A. Alnaser, M. Maxi, H. Elmousalami, AI-powered digital twins and internet of things for smart cities and sustainable building environment, Appl. Sci. 14 (24) (2024) 12056, https://doi.org/10.3390/app142412056.
[24] S.E. Bibri, J. Huang, Artificial Intelligence for Sustainable Smart City Brain and Digital Twin Systems: Environmental Synergies of Real-Time Management and Predictive Planning, Environmental Science and Ecotechnology (in press), 2025.
[25] S.E. Bibri, J. Huang, S.K. Jagatheesaperumal, J. Krogstie, The synergistic interplay of artificial intelligence and digital twin in environmentally planning sustainable smart cities: a comprehensive systematic review, Environ. Sci. Ecotechnol. 20 (2024) 100433, https://doi.org/10.1016/j.ese.2024.100433.
[26] A. Matei, M. Cocoşatu, Artificial internet of things, sensor-based digital twin urban computing vision algorithms, and blockchain cloud networks in sustainable smart city administration, Sustainability 16 (16) (2024) 6749, https://doi.org/10.3390/su16166749.
[27] C. Weil, S.E. Bibri, R. Longchamp, F. Golay, A. Alahi, Urban digital twin challenges: a systematic review and perspectives for sustainable smart cities, Sustain. Cities Soc. 99 (2023) 104862, https://doi.org/10.1016/j.scs.2023.104862.
[28] N. Komninos, Net zero energy districts: connected intelligence for carbon-neutral cities, Land 11 (2022) 210, https://doi.org/10.3390/land11020210.
[29] K.S. Mohamed, Deep Learning for IoT "Artificial Intelligence of Things (AIoT)", in: Deep Learning-Powered Technologies. Synthesis Lectures on Engineering, Science, and Technology. Springer, Cham, 2023 https://doi.org/10.1007/978-3-031-35737-4_3.
[30] H. Zhuang, J. Zhang, B.A. Muthu, Sustainable smart city building construction methods, Sustainability 12 (12) (2020) 4947, https://doi.org/10.3390/su12124947.
[31] S. Agostinelli, F. Cumo, M.M. Nezhad, G. Orsini, G. Piras, Renewable energy system controlled by open-source tools and Digital Twin model: zero energy port area in Italy, Energies 15 (5) (2022) 1817, https://doi.org/10.3390/en15051817.
[32] A. Arsiwala, F. Etemadi, M. Zoher, Digital twin with machine learning for predictive monitoring of CO2 equivalent from existing buildings, Energy and Buildings 284 (2023) 112851–112874, https://doi.org/10.1016/j.enbuild.2023.112851.
[33] M.M. Ferdaus, T. Dam, S. Anavatti, S. Das, Digital technologies for a net-zero energy future: a comprehensive review, Renew. Sustain. Energy Rev. 202 (2024) 114681, https://doi.org/10.1016/j.rser.2024.114681.
[34] S. Kaewunruen, P. Rungskunroch, J. Welsh, A digital-twin evaluation of net zero energy building for existing buildings, Sustainability 11 (1) (2019) 159, https://doi.org/10.3390/su11010159.
[35] Z. Liu, M. Li, W. Ji, Development and application of a digital twin model for net zero energy building operation and maintenance utilizing BIM-IoT integration, Energ. Buildings 328 (2025) 115170, https://doi.org/10.1016/j.enbuild.2024.115170.
[36] G.A. Mohammed, M. Mabrouk, G. He, K.I. Abdrabo, Towards sustainable cities: a review of zero energy buildings techniques and global activities in residential buildings, Energies 16 (9) (2023) 3775, https://doi.org/10.3390/en16093775.
[37] O. Omar, Near zero-energy buildings in Lebanon: the use of emerging technologies and passive architecture, Sustainability 12 (6) (2020) 2267, https://doi.org/10.3390/su12062267.
[38] L. Zhao, H. Zhang, Q. Wang, H. Wang, Digital-twin-based evaluation of nearly zero-energy building for existing buildings based on scan-to-BIM, Adv. Civ. Eng. (2021), https://doi.org/10.1155/2021/6638897.
[39] K. Alagar, S. Thirumal, Standalone PV-wind-DG-battery hybrid energy system for zero energy buildings in smart city Coimbatore, India. Advanced Controllers for Smart Cities: An Industry 4.0 Perspective (2021), 55-63. https://doi.org/10.1007/978-3-030-48539-9_5.
[40] G. Mitsopoulos, V. Kapsalis, A. Tolis, D. Karamanis, Innovative photovoltaic technologies aiming to design zero-energy buildings in different climate conditions, Appl. Sci. 14 (19) (2024) 8950, https://doi.org/10.3390/app14198950.
[41] N. Komninos, Transformation of industry ecosystems in cities and regions: a generic pathway for smart and green transition, Sustainability 14 (15) (2022) 9694, https://doi.org/10.3390/su14159694.
[42] D. Uspenskaia, K. Specht, H. Kondziella, T. Bruckner, Challenges and barriers for net-zero/positive energy buildings and districts—empirical evidence from the smart city project SPARCS, Buildings 11 (2) (2021) 78, https://doi.org/10.3390/buildings11020078.
[43] B. Arsecularatne, N. Rodrigo, R. Chang, Digital twins for reducing energy consumption in buildings: a review, Sustainability 16 (2024) 9275, https://doi.org/10.3390/su16219275.
[44] R. Bortolini, R. Rodrigues, H. Alavi, L.F.D. Vecchia, N. Forcada, Digital twins' applications for building energy efficiency: a review, Energies 15 (19) (2022) 1–18, https://doi.org/10.3390/en15197002.
[45] M. Boukaf, F. Fadli, N. Meskin, A comprehensive review of digital twin technology in building energy consumption Forecasting, IEEE Access 1 (2024), https://doi.org/10.1109/access.2024.3498107.
[46] A.S. Cespedes-Cubides, M. Jradi, A review of building digital twins to improve energy efficiency in the building operational stage, Energy Informatics 7 (1) (2024), https://doi.org/10.1186/s42162-024-00313-7.
[47] V.A. Arowoiya, R.C. Moehler, Y. Fang, Digital twin technology for thermal comfort and energy efficiency in buildings: a state-of-the-art and future directions, Energy Built Environ. 5 (5) (2024) 641–656, https://doi.org/10.1016/j.enbenv.2023.05.004.
[48] F. Dinmohammadi, M. Shafiee, A digital twin for energy consumption prediction and thermal comfort monitoring in residential buildings, EGU General Assembly (2024), https://doi.org/10.5194/egusphere-egu24-22348.
[49] S. El Sayary, O. Omar, Designing a BIM energy-consumption template to calculate and achieve a net-zero-energy house, Sol. Energy 216 (2021) 315–320.
[50] Y. Fathy, M. Jaber, Z. Nadeem, Digital twin-driven decision making and planning for energy consumption, J. Sens. Actuator Netw. 10 (2) (2021) 37, https://doi.org/10.3390/jsan10020037.
[51] H.R. Rocha, R. Fiorotti, D.M. Louzada, L.J. Silvestre, W.C. Celeste, J.A. Silva, Net zero energy cost building system design based on artificial intelligence, Appl. Energy 355 (2024) 122348, https://doi.org/10.1016/j.apenergy.2023.122348.
[52] W. Wang, H. Guo, X. Li, S. Tang, J. Xia, Z. Lv, Deep learning for assessment of environmental satisfaction using BIM big data in energy-efficient building digital twins, Sustainable Energy Technol. Assess. 50 (2021) 101897, https://doi.org/10.1016/j.seta.2021.101897.
[53] Y. Wang, B. Hu, X. Meng, R. Xiao, A comprehensive review on technologies for achieving zero- energy buildings, Sustainability 16 (2024) 10941, https://doi.org/10.3390/su162410941.
[54] S. Acharya, A.A. Khan, T. Päivärinta, Interoperability levels and challenges of digital twins in cyber–physical systems, J. Ind. Inf. Integr. 42 (2024) 100714, https://doi.org/10.1016/j.jii.2024.100714.
[55] S. Agostinelli, F. Cumo, G. Guidi, C. Tomazzoli, Cyber-physical systems improving building energy management: digital twin and artificial intelligence, Energies 14 (8) (2021) 2338, https://doi.org/10.3390/en14082338.
[56] S.E. Bibri, Transformative Integration of Artificial Intelligence of Things and Cyber-Physical Systems of Systems Advancing Smarter Eco-Cities and Sustainable Smart Cities. In Artificial Intelligence of Things for Smarter Eco-Cities: Pioneering the Environmental Synergies of Urban Brain, Digital Twin, Metabolic Circularity, and Platform (2025c), CRC/Taylor & Francis Group. https://doi.org/10.1201/9781003536420.
[57] S.E. Bibri, J. Huang, O. Omar, Leveraging Digital Twins for Zero-Energy Building Ratings in Sustainable Smart Cities: A Comprehensive Review and Novel Framework. In Digital Twins for Smart Metabolic Circular Cities: Innovations in Planning and Climate Resilience. Smart Cities Book Series (2025), Elsevier, UK. ISBN: 9780443333330. (in press).
[58] O. Herzog, M. Jarke, S.Z. Wu, Cooperating and competing digital twins for Industrie 4.0 in urban planning contexts, Science 5 (4) (2023) 44, https://doi.org/10.3390/sci5040044.
[59] G. Mylonas, A. Kalogeras, G. Kalogeras, C. Anagnostopoulos, C. Alexakos, L. Muñoz, Digital twins from smart manufacturing to smart cities: a survey, IEEE Access 9 (2021) 143222–143249.
[60] S.E. Bibri, Transforming Smarter Eco–Cities with Artificial Intelligence: Harnessing the Synergies of Circular Economy, Metabolic Circularity, and Tripartite Sustainability. In Artificial Intelligence of Things for Smarter Eco-Cities: Pioneering the Environmental Synergies of Urban Brain, Digital Twin, Metabolic Circularity, and Platform (2025b), CRC/Taylor & Francis Group. https://doi.org/10.1201/9781003536420.
[61] M. Elnour, A.M. Ahmad, S. Abdelkarim, F. Fadli, K. Naji, Empowering smart cities with digital twins of buildings: applications and implementation considerations of data-driven energy modelling in building management, Build. Serv. Eng. Res. Technol. 45 (4) (2024) 475–498, https://doi.org/10.1177/01436244241239290.
[62] B. Yang, F. Wang, Digital twins for intelligent green buildings, Buildings 12 (865) (2022) 1–21, https://doi.org/10.3390/buildings12060856.
[63] J. Al Dakheel, C. Del Pero, N. Aste, F. Leonforte, Smart buildings features and key performance indicators: a review, Sustain. Cities Soc. 61 (2020) 102328, https://doi.org/10.1016/j.scs.2020.102328.
[64] R.K. Jaysawal, S. Chakraborty, D. Elangovan, S. Padmanaban, Concept of net zero energy buildings (NZEB)-a literature review, Cleaner Eng. Technol. 11 (2022) 100582, https://doi.org/10.1016/j.clet.2022.100582.
[65] Y.H. Labaran, H. Mato, G. Saini, A.A. Musa, Towards net zero energy buildings: a review of barriers and facilitators to the adoption of building energy efficiency practices, Environmental Research and Technology 7 (1) (2023) 118–130, https://doi.org/10.35208/ert.1320207.
[66] H.-L. Lou, S.-H. Hsieh, Towards zero: a review on strategies in achieving net-zero-energy and net-zero-carbon buildings, Sustainability 16 (2024) 4735, https://doi.org/10.3390/su16114735.
[67] M.A. Mengaw, W.J. Mengesha, H.B. Madessa, Recent progress in net-zero-energy buildings in tropical climates: a review of the challenges and opportunities,

Lecture Notes in Civil Engineering 1003–1013 (2025), https://doi.org/10.1007/978-3-031-69626-884.
[68] H. Omrany, R. Chang, V. Soebarto, Y. Zhang, A. Ghaffarianhoseini, J. Zuo, A bibliometric review of net zero energy building research 1995–2022, Energ. Buildings 262 (2022) 111996, https://doi.org/10.1016/j.enbuild.2022.111996.
[69] B. Senyonyi, H. Mahmoud, H. Hassan, Systematic review of solar techniques in zero energy buildings, Clean Techn. Environ. Policy (2024), https://doi.org/10.1007/s10098-024-03004-9.
[70] T. Wilberforce, A. Olabi, E.T. Sayed, K. Elsaid, H.M. Maghrabie, M. A. Abdelkareem, A review on zero energy buildings – pros and cons, Energy Built Environ. 4 (1) (2021) 25–38, https://doi.org/10.1016/j.enbenv.2021.06.002.
[71] M. Deng, C.C. Menassa, V.R. Kamat, From BIM to digital twins: a systematic review of the evolution of intelligent building representations in the AEC-FM industry, Itcon 26 (2021) 58–83, https://doi.org/10.36680/j.itcon.2021.005.
[72] M. Lamagna, D. Groppi, M.M. Nezhad, G. Piras, A comprehensive review on digital twins for smart energy management system, International Journal of Energy and Environmental Quality 6 (2021) 323–334, https://doi.org/10.2495/EQ-V6-N4-323-334.
[73] W. Liu, Y. Lv, Q. Wang, B. Sun, D. Han, A systematic review of the digital twin technology in buildings, landscape and urban environment from 2018 to 2024, Buildings 14 (11) (2024) 3475, https://doi.org/10.3390/buildings14113475.
[74] C.C. Ohueri, M. Masrom, T.E. Seghier, Digital twin for decarbonizing operating buildings: a systematic review and implementation framework development, Energ. Buildings 320 (2024) 114567, https://doi.org/10.1016/j.enbuild.2024.114567.
[75] A.E. Onile, R. Machlev, E. Petlenkov, Y. Levron, J. Belikov, Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: a review, Energy Rep. 7 (2021) 997–1015, https://doi.org/10.1016/j.egyr.2021.01.090.
[76] E. Papadonikolaki, C. Anumba, How can Digital Twins support the Net Zero Vision? In Lecture notes in civil engineering (2023), (pp. 81–97). https://doi.org/10.1007/978-3-031-32515-17.
[77] A. Rocco, Bibliometric review of building material assessment for energy efficiency in urban digital twins, International Journal of Applied and Structural Mechanics 35 (2023) 22–32, https://doi.org/10.55529/ijasm.35.22.32.
[78] F. Khan, R.L. Kumar, S. Kadry, Y. Nam, M.N. Meqdad, Cyber physical systems: a smart city perspective, International Journal of Electrical and Computer Engineering (IJECE) 11 (4) (2021) 3609–3616, https://doi.org/10.11591/ijece.v11i4.pp3609-3616.
[79] R.K. Mishra, C.L. Kumari, S. Chachra, P.S.J. Krishna, A. Dubey, R.B. Singh, (Eds.), Smart Cities for Sustainable Development. Advances in Geographical and Environmental Sciences. Springer (2022).
[80] A. Sharifi, Z. Allam, S.E. Bibri, A.R. Khavarian-Garmsir, Smart cities and sustainable development goals (SDGs): a systematic literature review of co-benefits and trade-offs, Cities 146 (2024) 104659, https://doi.org/10.1016/j.cities.2023.104659.
[81] S.E. Shmelev, I.A. Shmeleva, Smart and sustainable benchmarking of cities and regions in Europe: the application of multicriteria assessment, Cities 156 (2025) 105533, https://doi.org/10.1016/j.cities.2024.105533.
[82] N. Tura, V. Ojanen, Sustainability-oriented innovations in smart cities: a systematic review and emerging themes, Cities 126 (2022) 103716, https://doi.org/10.1016/j.cities.2022.103716.
[83] N. Rane, S. Choudhary, J. Rane, Artificial Intelligence and machine learning in renewable and sustainable energy strategies: a critical review and future perspectives, Partners Universal International Innovation Journal 2 (3) (2024) 80–102, https://doi.org/10.5281/zenodo.12155847.
[84] A. Mishra, A.V. Jha, B. Appasani, A.K. Ray, D.K. Gupta, A.N. Ghazali, Emerging technologies and design aspects of next generation cyber physical system with a smart city application perspective, International Journal of System Assurance Engineering and Management 14 (Suppl 3) (2023) 699–721, https://doi.org/10.1007/s13198-021-01523-y.
[85] B.K. Mishra, (Ed.), Handbook of Research on Applications of AI, Digital Twin, and Internet of Things for Sustainable Development, (2023). Hershey, PA: IGI Global. .
[86] K.D. Singh, P. Singh, R. Chhabra, G. Kaur, A. Bansal, V. Tripathi, Cyber-Physical Systems for Smart City Applications: A Comparative Study. In 2023 International Conference on Advancement in Computation & Computer Technologies (InCACCT), (2023b) (pp. 871-876). Gharuan, India.https://doi.org/10.1109/InCACCT57535.2023.10141719.
[87] H. Thamik, J.D.F. Cabrera, J. Wu, The Digital Paradigm: Unraveling the Impact of Artificial Intelligence and Internet of Things on Achieving Sustainable Development Goals, in: S. Misra, K. Siakas, G. Lampropoulos (Eds.), Artificial Intelligence of Things for Achieving Sustainable Development Goals (lecture Notes on Data Engineering and Communications Technologies, Vol. 192, Springer, Cham, 2024, https://doi.org/10.1007/978-3-031-53433-1_2.
[88] A.F. Gkontzis, S. Kotsiantis, G. Feretzakis, V.S. Verykios, Enhancing urban resilience: smart city data analyses, forecasts, and digital twin techniques at the neighborhood level, Future Internet 16 (2) (2024) 47, https://doi.org/10.3390/fi16020047.
[89] A.A. Salunke, Reinforcement learning empowered digital twins: pioneering smart cities towards optimal urban dynamics, EPRA International Journal of Research & Development (IJRD) (2023), https://doi.org/10.36713/epra13959.
[90] X. Ye, J. Du, Y. Han, G. Newman, D. Retchless, L. Zou, Y. Ham, Z. Cai, Developing human-centered urban digital twins for community infrastructure resilience : a research agenda, J. Plan. Lit. 38 (2) (2023) 187–199, https://doi.org/10.1177/08854122221137861.
[91] F.N. Abdeen, S. Shirowzhan, S.M.E. Sepasgozar, Citizen-centric digital twin development with machine learning and interfaces for maintaining urban infrastructure, Telematics Inform. 84 (2024) 102032, https://doi.org/10.1016/j.tele.2023.102032.
[92] S. Beckett, Smart city digital twins, 3D modeling and visualization tools, and spatial cognition algorithms in artificial intelligence-based urban design and planning, Geopolitics, History, and International Relations 14 (1) (2022) 123–138. https://www.jstor.org/stable/48679657.
[93] K. Zvarikova, J. Horak, S. Downs, Digital twin algorithms, smart city technologies, and 3D spatio-temporal simulations in virtual urban environments, Geopolitics, History and International Relations 14 (1) (2022) 139–154, https://doi.org/10.48550/arXiv.2302.09419.
[94] R. Sharma, N. Sharma, Applications of artificial intelligence in cyber-physical systems, Cyber Physical Systems 1–14 (2022), https://doi.org/10.1201/9781003202752-1.
[95] M. Bundas, C. Nadeau, T. Nguyen, J. Shantz, M. Balduccini, T.C. Son, Towards a framework for characterizing the behavior of AI-enabled cyber-physical and IoT systems. In: 2021 IEEE 7th world forum on internet of things (WF-IoT), (2021), New Orleans, LA, USA, 2021, pp 551–556. https://doi.org/10.1109/WF-IoT51360.2021.9595077.
[96] A. Haldorai, A review on artificial intelligence in internet of things and cyber-physical systems, Journal of Computational Natural Sciences 3 (1) (2023) 12–23.
[97] P. Radanliev, D.C.D. Roure, M. Van Kleek, O. Santos, U.D. Ani, Artificial Intelligence in Cyber Physical Systems. (2020), https://doi.org/10.2139/ssrn.3692592.
[98] M. Batty, Digital twins, Environ. Plann. B: Urban Anal. City Sci. 45 (5) (2018) 817–820, https://doi.org/10.1177/2399808318796416.
[99] B. Lei, P. Janssen, J. Stoter, F. Biljecki, Challenges of urban digital twins: a systematic review and a Delphi expert survey, Autom. Constr. 147 (2023) 104716, https://doi.org/10.1016/j.autcon.2022.104716.
[100] U.A. Lenfers, N. Ahmady-Moghaddam, D. Glake, F. Ocker, D. Osterholz, J. Ströbele, T. Clemen, Improving model predictions—integration of real-time sensor data into a running simulation of an agent-based model, Sustainability 13 (2021) 7000, https://doi.org/10.3390/su13137000.
[101] G. Papyshev, M. Yarime, Exploring city digital twins as policy tools: a task-based approach to generating synthetic data on urban mobility, Data Policy 3 (2021) e16.
[102] D. Topping, T.J. Bannan, H. Coe, J. Evans, C. Jay, E. Murabito, N. Robinson, Digital twins of urban air quality: opportunities and challenges, Front. Sustainable Cities 3 (2021) 786563.
[103] Z. Ballouch, R. Hajji, F. Poux, A. Kharroubi, R. Billen, A prior level fusion approach for the semantic segmentation of 3D point clouds using deep learning, Remote Sens. (Basel) 14 (2022) 3415, https://doi.org/10.3390/rs14143415.
[104] J. Ferré-Bigorra, M. Casals, M. Gangolells, The adoption of urban digital twins, Cities 131 (2022) 103390, https://doi.org/10.1016/j.cities.2022.103390.
[105] B. Wang, Q. Wang, J.C.P. Cheng, C. Yin, Object verification based on deep learning point feature comparison for scan-to-BIM, Autom. Constr. 142 (2022) 104515, https://doi.org/10.1016/j.autcon.2022.104515.
[106] G. White, A. Zink, L. Codecá, S. Clarke, A digital twin smart city for citizen feedback, Cities 110 (2021) 103064, https://doi.org/10.1016/j.cities.2020.103064.
[107] J. Huang, S.E. Bibri, P. Keel, Generative spatial artificial intelligence for sustainable smart cities: A pioneering large flow model for urban digital twin, Environmental Science and Ecotechnology (in press), 2025.
[108] E. Marcucci, V. Gatta, M. Le Pira, L. Hansson, S. Bråthen, Digital twins: a critical discussion on their potential for supporting policy-making and planning in urban logistics, Sustainability 12 (2020) 10623, https://doi.org/10.3390/su122410623.
[109] Y. Wu, K. Zhang, Y. Zhang, Digital twin networks: a survey, IEEE Internet Things J. 8 (18) (2021) 13789–13804, https://doi.org/10.1109/JIOT.2021.3079510.
[110] F. Dembski, M. Letzgus, M. Ruddat, C. Yamu, Urban digital twins for smart cities and citizens: the case study of Herrenberg, Germany, Sustainability 12 (6) (2020), https://doi.org/10.3390/su12062307.
[111] J. Luo, P. Liu, L. Cao, Coupling a physical replica with a digital twin: a comparison of participatory decision-making methods in an urban park environment, ISPRS Int. J. Geo Inf. 11 (2022) 452, https://doi.org/10.3390/ijgi11080452.
[112] M. Austin, P. Delgoshaei, M. Coelho, M. Heidarinejad, Architecting smart city digital twins: combined semantic model and machine learning approach, J. Manag. Eng. 36 (4) (2020) 04020026, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000825.
[113] S.M. Zayed, G.M. Attiya, A. El-Sayed, E.-E.-D. Hemdan, A review study on digital twins with artificial intelligence and internet of things: concepts, opportunities, challenges, tools and future scope, Multimed. Tools Appl. 1–27 (2023), https://doi.org/10.1007/s11042-023-15611-7.
[114] E. O'Connell, W. O'Brien, M. Bhattacharya, D. Moore, M. Penica, Digital twins: enabling interoperability in smart manufacturing networks, Telecom 4 (2) (2023) 265–278, https://doi.org/10.3390/telecom4020016.
[115] P. De Wilde, Building performance simulation in the brave new world of artificial intelligence and digital twins: a systematic review, Energ. Buildings (2023), https://doi.org/10.1016/j.enbuild.2023.113171.
[116] U. Cali, et al., Digital twins: Shaping the future of energy systems and smart cities through cybersecurity, efficiency, and sustainability. In 2023 International Conference on Future Energy Solutions (FES), (2023). (pp. 1-6). Vaasa, Finland. https://doi.org/10.1109/FES57669.2023.10182868.
[117] M. El-Gohary, R. El-Abed, O. Omar, Prediction of an efficient energy-consumption model for existing residential buildings in lebanon using an artificial neural

network as a digital twin in the era of climate change, Buildings 13 (12) (2023) 3074.
[118] T. Deng, K. Zhang, Z.M. Shen, A systematic review of a digital twin city: a new pattern of urban governance toward smart cities, Journal of Management Science 6 (2021) 125–134, https://doi.org/10.1016/j.jmse.2021.03.003.
[119] S. Mousavi, M.G. Villarreal-Marroquín, M. Hajiaghaei-Keshteli, N.R. Smith, Data-driven prediction and optimization toward net-zero and positive-energy buildings: a systematic review, Build. Environ. 242 (2023) 110578, https://doi.org/10.1016/j.buildenv.2023.110578.
[120] A. Ahmed, T. Ge, J. Peng, W. Yan, B.T. Tee, S. You, Assessment of the renewable energy generation towards net-zero energy buildings: a review, Energ. Buildings 256 (2021) 111755, https://doi.org/10.1016/j.enbuild.2021.111755.
[121] R. Kathiravel, S. Zhu, H. Feng, LCA of net-zero energy residential buildings with different HVAC systems across Canadian climates: a BIM-based fuzzy approach, Energ. Buildings 306 (2024) 113905, https://doi.org/10.1016/j.enbuild.2024.113905.
[122] V. Mooses, I. Pastak, P. Kamenjuk, A. Poom, Residents' perceptions of a smart technology retrofit towards nearly zero-energy performance, Urban Plan. 7 (2) (2022) 20–32, https://doi.org/10.17645/up.v7i2.5020.
[123] Q. Wang, Y. Yin, Y. Chen, Y. Liu, Carbon peak management strategies for achieving net-zero emissions in smart buildings: advances and modeling in digital twin, Sustainable Energy Technol. Assess. 64 (2024) 103661, https://doi.org/10.1016/j.seta.2024.103661.
[124] W. Wu, H.M. Skye, Residential net-zero energy buildings: review and perspective, Renew. Sustain. Energy Rev. 142 (2021) 110859, https://doi.org/10.1016/j.rser.2021.110859.
[125] H. Wu, F. Deng, H. Tan, Research on parametric design method of solar photovoltaic utilization potential of nearly zero-energy high-rise residential building based on genetic algorithm, J. Clean. Prod. 368 (2022) 133169, https://doi.org/10.1016/j.jclepro.2022.133169.
[126] Y. Zhao, R. Liu, Z. Liu, Y. Lu, L. Liu, J. Wang, W. Liu, Enhancing zero-carbon building operation and maintenance: a correlation-based data mining approach for database analysis, Sustainability 15 (18) (2023) 13671, https://doi.org/10.3390/su151813671.
[127] R. Kalbasi, M. Afrand, Which one is more effective to add to building envelope: phase change material, thermal insulation, or their combination to meet zero-carbon-ready buildings? J. Clean. Prod. 367 (2022) 133032 https://doi.org/10.1016/j.jclepro.2022.133032.
[128] L. Chen, X. Li, J. Zhu, Carbon peak control for achieving net-zero renewable-based smart cities: digital twin modeling and simulation, Sustainable Energy Technol. Assess. 65 (2024) 103792, https://doi.org/10.1016/j.seta.2024.103792.
[129] Z. Wang, H. Shen, G. Deng, X. Liu, D. Wang, Measured performance of energy efficiency measures for zero-energy retrofitting in residential buildings, Journal of Building Engineering 91 (2024) 109545, https://doi.org/10.1016/j.jobe.2024.109545.
[130] K. Shen, L. Ding, C. Wang, Development of a framework to support whole-life-cycle net-zero-carbon buildings through integration of building information modelling and digital twins, Buildings 12 (10) (2022) 1747, https://doi.org/10.3390/buildings12101747.
[131] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, E.A. Akl, S.E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M.M. Lalu, T. Li, E.W. Loder, E. Mayo-Wilson, S. McDonald, L.A. McGuinness, L.A. Stewart, J. Thomas, A.C. Tricco, V.A. Welch, P. Whiting, D. Moher, The prisma 2020 statement: an updated guideline for reporting systematic reviews, Int. J. Surg. 88 (2021) 105906, https://doi.org/10.1016/j.ijsu.2021.105906.
[132] S.A. Lan, N. Razmjooy, Enhancing the performance of zero energy buildings with boosted coyote optimization and Elman neural networks, Energy Rep. 11 (2024) 5214–5226, https://doi.org/10.1016/j.egyr.2024.05.001.
[133] P. Wu, X. Mei, Microgrids energy management considering net-zero energy concept: the role of renewable energy landscaping design and IoT modeling in digital twin realistic simulator, Sustainable Energy Technol. Assess. 63 (2024) 103621, https://doi.org/10.1016/j.seta.2024.103621.
[134] Y.W. Lin, T.L.E. Tang, C.J. Spanos, Hybrid approach for digital twins in the built environment, in: In Proceedings of the Twelfth ACM International Conference on Future Energy Systems, 2021, pp. 450–457, https://doi.org/10.1145/3447555.3466585.
[135] F. Khalifa, M. Marzouk, Integrated blockchain and digital twin framework for sustainable building energy management, J. Ind. Inf. Integr. 43 (2025) 100747, https://doi.org/10.1016/j.jii.2024.100747.
[136] W. Huang, Y. Zeng, W. Zeng, Development and application of digital twin technology for integrated regional energy systems in smart cities, Sustainable Comput. Inf. Syst. 36 (100781) (2022) 1–10, https://doi.org/10.1016/j.suscom.2022.100781.
[137] H. Liu, K. Zoh, Smart landscaping design for sustainable net-zero energy smart cities: Modeling energy hub in digital twin, Sustainable Energy Technol. Assess. 65 (103769) (2024) 1–10, https://doi.org/10.1016/j.seta.2024.103769.
[138] H. Wang, Y. Wang, Smart cities net zero planning considering renewable energy landscape design in digital twin, Sustainable Energy Technol. Assess. 63 (2024) 103629, https://doi.org/10.1016/j.seta.2024.103629.
[139] X. Zhao, Y. Zhang, Integrated management of urban resources toward Net-Zero smart cities considering renewable energies uncertainty and modeling in Digital Twin, Sustainable Energy Technol. Assess. 64 (2024) 103656, https://doi.org/10.1016/j.seta.2024.103656.
[140] Z. Tan, Z. Li, Digital twins for sustainable design and management of smart city buildings and municipal infrastructure, Sustainable Energy Technol. Assess. 64 (103682) (2024) 1–10, https://doi.org/10.1016/j.seta.2024.103682.
[141] E. O'Dwyer, I. Peng, R. Charlesworth, S. Butler, N. Shah, Integration of an energy management tool and digital twin for coordination and control of multi-vector smart energy systems, Sustain. Cities Soc. 62 (102412) (2020) 1–14, https://doi.org/10.1016/j.scs.2020.102412.
[142] A.N.M. Francisco, J.E. Taylor, Smart city digital twin–enabled energy management: toward real-time urban building energy benchmarking, J. Manag. Eng. 36 (2) (2019) 1–11, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000741.
[143] P. Wilde, Building performance simulation in the brave new world of artificial intelligence and digital twins: a systematic review, Energ. Buildings (2023), https://doi.org/10.1016/j.enbuild.2023.113171.
[144] A. Clausen, K. Arendt, A. Johansen, F.C. Sangogboye, M.B. Kjærgaard, C.T. Veje, B.N. Jørgensen, A digital twin framework for improving energy efficiency and occupant comfort in public and commercial buildings, Energy Informatics 4 (S2) (2021), https://doi.org/10.1186/s42162-021-00153-9.
[145] Y. Tan, P. Chen, W. Shou, A.-M. Sadick, Digital twin-driven approach to improving energy efficiency of indoor lighting based on computer vision and dynamic BIM, Energ. Buildings 270 (2022) 112271, https://doi.org/10.1016/j.enbuild.2022.112271.
[146] C. Ghenai, L. Alhaj Husein, M. Al Nahlawi, A.K. Hamid, M. Bettayeb, Recent trends of digital twin technologies in the energy sector: a comprehensive review, Sustainable Energy Technol. Assess. 54 (2022) 102837, https://doi.org/10.1016/j.seta.2022.102837.
[147] M. Jradi, B.E. Madsen, J.H. Kaiser, DanRETwin: a digital twin solution for optimal energy retrofit decision-making and decarbonization of the Danish building stock, Appl. Sci. 13 (2023), https://doi.org/10.3390/app13179778.
[148] I. Puiu, T. Fortiş, The efficiency of building maintenance using digital twins: a literature review, Lecture Notes on Data Engineering and Communications Technologies 201–211 (2024), https://doi.org/10.1007/978-3-031-57931-8_20.
[149] F.A. Ghansah, W. Lu, Major opportunities of digital twins for smart buildings: a scientometric and content analysis, Smart Sustainable Built Environ. 13 (1) (2024) 63–84, https://doi.org/10.1108/SASBE-09-2022-0192.
[150] F. Tahmasebinia, L. Lin, S. Wu, Y. Kang, S. Sepasgozar, Exploring the benefits and limitations of digital twin technology in building energy, Appl. Sci. 13 (2023) 8814, https://doi.org/10.3390/app13158814.
[151] J. Henzel, Ł. Wróbel, M. Fice, M. Sikora, Energy consumption forecasting for the digital-twin model of the building, Energies 15 (12) (2022) 4318, https://doi.org/10.3390/en15124318.
[152] D.D. Eneyew, M.A. Capretz, G.T. Bitsuamlak, Continuous model calibration framework for smart-building digital twin: a generative model-based approach, Appl. Energy 375 (2024) 124080, https://doi.org/10.1016/j.apenergy.2024.124080.
[153] N. Mwanga, J. Svensson, B. Hassan, BIM integration: How BIM can be leveraged to create digital twins of buildings. Researchgate, (2024, September 1). Retrieved January 11, 2025, fromhttps://www.researchgate.net/publication/384327332_BIM_Integration_How_BIM_can_beleveraged_to_create_digital_twins_of_buildings.
[154] J. Hallik, E. Arumägi, E. Pikas, T. Kalamees, Comparative assessment of simple and detailed energy performance models for urban energy modelling based on digital twin and statistical typology database for the renovation of existing building stock, Energ. Buildings 323 (2024) 114775, https://doi.org/10.1016/j.enbuild.2024.114775.
[155] M.A. Jafari, E. Zaidan, A. Ghofrani, K. Mahani, F. Farzan, Improving building energy footprint and asset performance using digital twin technology, IFAC-PapersOnLine 53 (3) (2020) 386–391, https://doi.org/10.1016/j.ifacol.2020.11.062.
[156] E.-R. Parts, E. Pikas, T.M. Parts, E. Arumägi, I. Liiv, T. Kalamees, Quality and accuracy of digital twin models for the neighbourhood-level building energy performance calculations, E3S Web of Conferences 396 (2023) 04021, https://doi.org/10.1051/e3sconf/202339604021.
[157] P. Spudys, N. Afxentiou, P. Georgali, E. Klumbyte, A. Jurelionis, P. Fokaides, Classifying the operational energy performance of buildings with the use of digital twins, Energ. Buildings 290 (2023) 113106, https://doi.org/10.1016/j.enbuild.2023.113106.
[158] H. Li, T. Zhang, Y. Huang, in: Digital Twin Technology for Integrated Energy System and Its Application, IEEE, 2021, pp. 422–425, https://doi.org/10.1109/DTPI52967.2021.9540160.
[159] J. Kimberly, Digital twins: Creating digital twins of buildings can enable the simulation and optimization of building systems and operations, (2024). Researchgate. Retrieved January 11, 2025, from https://www.researchgate.net/publication/383360242_Digital_Twins_Creating_digital_twins_of_buildings_can_enable_the_simulation_and_optimization_of_building_systems_and_operations?tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6InNlYXJjaCIsInBhZ2UiOiJzZWFyY2giLCJwb3NpdGlvbiI6InBhZ2VIZWFkZXIifX0.
[160] R. Rutkowski, M. RaczyÅL nski, R. IwaÅL nkowicz, R. Nowak, Digital twin in the design and dynamic assessment of energy performance of multi-family buildings, Energies 17 (2024) 6150, https://doi.org/10.3390/en17236150.
[161] H. Seo, W.S. Yun, Digital twin-based assessment framework for energy savings in university classroom lighting, Buildings 12 (5) (2022) 544, https://doi.org/10.3390/buildings12050544.
[162] A. Schweigkofler, O. Braholli, S. Akro, D. Siegele, P. Penna, C. Marcher, L. Tagliabue, D. Matt, Digital Twin as energy management tool through IoT and BIM data integration. CLIMA 2022 Conference, 2022.

[163] W. Yu, B. Young, E. Klinac, T.G. Walmsley, Energy digital twin technology for industrial energy management: classification, challenges and future, Renewable and Sustainable Energy Reviews 161 (112407) (2022) 1–14, https://doi.org/10.1016/j.rser.2022.112407.

[164] A. Kalaida, M. Pan, Creating Digital twins of smart buildings on the azure digital twins platform, Municipal Economy of Cities 6 (187) (2024) 2–7, https://doi.org/10.33042/2522-1809-2024-6-187-2-7.

[165] H.A. Hassony, A.L. Ahmed, Reviewing applications of digital twins in building management in response to the Covid-19 pandemic, AIP Conference Proceedings 3092 (2024) 040005, https://doi.org/10.1063/5.0199662.

[166] M. Mosteiro-Romero, P. Alva, R. Stouffs, C. Miller, Towards occupant-driven district energy system operation: a digital twin platform for energy resilience and occupant well-being. In PLEA 2022: Will Cities Survive? Passive and Low Energy Architecture (PLEA), (2022). November 23–25, 2022, Santiago, Chile (pp. 834–839). https://scholarbank.nus.edu.sg/handle/10635/243262.

[167] S.H. Khajavi, N.H. Motlagh, A. Jaribion, L.C. Werner, J. Holmström, Digital twin: vision, benefits, boundaries, and creation for buildings, IEEE Access 7 (2019) 147406–147419, https://doi.org/10.1109/ACCESS.2019.2946515.

[168] A. Greco, A. Kerstens, Digital Twins & Sustainability: A Pathway to Building Positive-Energy Districts | Cutter Consortium, (2024). Retrieved January 11, 2025, from https://www.cutter.com/article/digital-twins-sustainability-pathway-building-positive-energy districts#:~:text=Digital%20innovations%20like%20digital%20twins,usage%20of%20excess%20solar%20energy.

[169] X. Zhang, J. Shen, P.K. Saini, M. Lovati, M. Han, P. Huang, Z. Huang, Digital twin for accelerating sustainability in positive energy district: a review of simulation tools and applications, Front. Sustain. Cities 3 (2021) 663269, https://doi.org/10.3389/frsc.2021.663269.

[170] I. Jeddoub, A. Njock Guenang, R. Hajji, R. Billen, Digital twins for cities: analyzing the gap between concepts and current implementations with a specific focus on data integration, International Journal of Applied Earth Observation and Geoinformation 122 (103440) (2023), https://doi.org/10.1016/j.jag.2023.103440.

[171] L. Deren, Y. Wenbo, S. Zhenfeng, Smart city based on digital twins, Comput. Urban Sci. 1 (4) (2021) 1–11, https://doi.org/10.1007/s43762-021-00005-y.

[172] D. Peldon, S. Banihashem, K. LeNguyen, S. Derrible, Navigating urban complexity: the transformative role of digital twins in smart city development, Sustain. Cities Soc. 111 (105583) (2024) 1–18, https://doi.org/10.1016/j.scs.2024.105583.

[173] C. Saranya, K. Haripriya, S. Bhargava, C. Tejashree, J.T. Thomas, Urban "Digital Twins" for smart cities and citizens. In International Conference on Recent Trends in Computing & Communication Technologies (ICRCCT'2K24), 2024.

[174] H. Xu, F. Omitaomu, S. Sabri, S. Zlatanova, X. Li, Y. Song, Leveraging generative AI for urban digital twins: A scoping review on the autonomous generation of urban data, scenarios, designs, and 3D city models for smart city advancement, Urban Informatics 3 (1) (2024) Article 29, https://doi.org/10.1007/s44212-024-00060-w.