J Multidisciplinary Scientific Journal

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Review

A Systemic Digital Transformation for Smart Net-Zero Cities: A State-of-the-Art Review

Farzaneh Mohammadi Jouzdani *, Vahid Javidroozi, Hanifa Shah and Monica Mateo Garcia

Faculty of Computing, Engineering and the Built Environment (CEBE), Birmingham City University, Belmont Row, Birmingham B4 7RQ, UK; vahid.javidroozi@bcu.ac.uk (V.J.); hanifa.shah@bcu.ac.uk (H.S.); monica.mateogarcia@bcu.ac.uk (M.M.G.)

* Correspondence: farzaneh.mohammadi.2904@gmail.com

Abstract: This paper presents a state-of-the-art review of digital transformation for developing smart net-zero cities, highlighting the significance of systems thinking and the key components of digital transformation including people, data, technology and process. Urban areas are experiencing increasing challenges from rapid growth and climate issues, making digital transformation a crucial strategy for enhancing sustainability and efficiency. In this context, systems thinking is essential, as it provides a holistic perspective that acknowledges the interdependence of urban sectors which can facilitate a more comprehensive, adaptable, and strategically integrated approach. This review examines findings from 22 sources and proposes a framework to investigate and represent the necessity of a digital transformation approach that effectively balances these elements and promotes a systems thinking approach. Also, by examining the findings from a systems thinking perspective, this research analyses the potential of effective digital transformation to support the complex needs of smart net-zero city developments. The findings indicate a widespread recognition of the digital transformation potential as a practical implementation strategy. It is imperative to formulate digital transformation strategies that are practical and comprehensively incorporate all elements: people, technology, processes, and data. Additionally, the review highlights the critical role of systems thinking in the development of these digital transformations as it facilitates the integration of interdependent urban sectors, including energy, transformation, and building, to achieve a holistic and integrated transformation.

Keywords: digital transformation; smart net-zero city; systems thinking; smart cities; net-zero cities

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Academic Editor: Cinzia Buratti

Received: 16 December 2024
Revised: 27 February 2025
Accepted: 28 February 2025
Published: 6 March 2025

Citation: Jouzdani, F.M.; Javidroozi, V.; Shah, H.; Mateo Garcia, M. A Systemic Digital Transformation for Smart Net-Zero Cities: A State-of-the-Art Review. *J* **2025**, *8*, 11. https://doi.org/10.3390/j8010011

1. Introduction

Urbanisation is a worldwide phenomenon that has resulted in more than half of the world's population being categorised as urban citizens. This rapid growth of urbanisation resulted in a variety of advantages and obstacles. Although cities serve as economic hubs, supporting employment opportunities and driving innovation and prosperity, they also contribute to environmental issues such as air and noise pollution and global warming [1]. Urban development and greenhouse gas emissions are positively correlated at the national, regional, and city levels [2]. Urban growth can contribute to a huge positive impact on energy demand and energy consumption, which is identified as one of the key determinants of city greenhouse gas emissions [3]. The global climate change issue, caused by the emission of greenhouse gases like CO_2, poses a threat to both humanity and the natural environment and is the main concern for governments and cities around the world [4].

An increase in public awareness of global warming in urban areas has contributed to global efforts and collaborations to reduce greenhouse gas emissions [5]. As an example of the global effort towards this aim, in the Paris Agreement, all participating nations have committed to restricting the rise in global temperatures to below 2 °C and striving to limit it even more, to below 1.5 °C [6]. Following the Paris Agreement, many global strategies have been established to reach a zero balance in greenhouse gas emissions by 2050 or earlier [7]. In parallel, the necessity of achieving zero emissions in cities has been extensively recognised and analysed in academic literature.

As a result of the wide practical and academic attempts in this area, different categories for reducing GHG emissions to zero such as 'zero carbon city', 'zero emission city', 'carbon natural city', 'green city', and 'net-zero city' have been determined and utilised by academia and governments. Although these categories may vary slightly, they share a common feature of attaining a balance in production and absorption of emissions (carbon or GHG) in urban areas.

Furthermore, the integration of innovative digital technologies into city infrastructures has been recognised as a crucial element in achieving reductions in greenhouse gas (GHG) emissions [8–13]. Smart cities will facilitate the incorporation of digital technology into the physical infrastructure and society of the city through the utilisation of ICT allowing for efficient management of the urban system [14]. This integration would enhance the effective management of energy consumption in several sectors of smart cities [15].

Transportation and building are the primary urban sectors that are responsible for the highest levels of energy consumption and emissions of greenhouse gases [11]. As an example of a smart city transportation solution, a smart traffic control system can effectively minimise fuel and time wastage by regulating congestion, which leads to a reduction in energy consumption and GHG emissions [16]. In the building sector, smart meters are a digital intervention that can accurately monitor energy usage, boost energy security, and optimise energy distribution in smart networks, hence facilitating efficient energy management [17]. Various smart solutions are being presented and utilised for diverse sectors of smart cities, comprising smart people, smart economy, smart government, smart mobility, smart environment, and smart living [18].

However, employing smart solutions in urban areas to transition towards smart cities is a major transformation that requires a complicated transition from conventional approaches to a digitally focused approach [19]. Digital transformation facilitates the incorporation of digital technologies and innovative solutions, leading to a streamlined and effective path towards the development of smart cities [20]. It allows for interaction between humans and digital technologies through the use of information technology (IT) supported by big data, cloud computing, mobile, and social technologies [21].

Research Motivation

While it is often recognised that a smart city should strive for the complete elimination of greenhouse gas (GHG) emissions [22], the literature indicates that the environmental aspect of smart cities has not been adequately addressed [23]. Furthermore, the integration and intersection of smart cities and some categories such as 'green', 'net-zero', and 'zero carbon' have been overlooked. Therefore, it is crucial to recognise this relationship to accurately understand and distinguish these categories.

Furthermore, according to [24] the concept of digital transformation encompasses four essential elements: people, technology, processes, and data. They identified the key components of the technology aspect including the application of digital tools and technologies, cybersecurity, and the approach to adopting emerging technologies. Advanced technologies as the main driver of digital transformation can enable effective management of data, improve collaboration and communication, and provide services and products [25].

Digital leadership is a critical component of the "people" element in digital transformation that can make a vital impact on providing digital strategies, improving time efficiency and productivity [26]. This component can be enabled by the governments and the other institutions in the city [27]. Also, continuous learning by people (city residents) to develop essential digital skills is another important factor that is required to support adaptability and collaboration in digital transformation [28]. However, people's resistance to change is a significant challenge that is required to be addressed in the development of digital transformation [28].

Digitalisation, optimisation, and automation have been recognised as crucial measures in the "Process" element of digital transformation [24]. This involves identifying, evaluating, documenting, and establishing new processes that are compatible with the new technologies that are being implemented [29]. However, continuous monitoring and management of the process is essential for digital transformation [30].

"Data", as a key component of digital transformation, play a pivotal role in facilitating efficient decision-making [31]. Utilising the city's data will allow for the identification, development, and implementation of ideas, methods, and strategies that are crucial for effectively managing a digital transformation in the city system [32]). Multiple studies have highlighted the crucial role of data analysis in finding essential solutions that facilitate progress towards smart cities and have emphasised the need for more research on data in the development of smart cities [33,34]. Therefore, reviewing data in the digital transformation for smart cities will improve our knowledge and provide direction for future studies and practical smart net-zero city developments.

However, it is crucial to take into account that cities operate as complex systems comprising interrelated components, and any modification to one component will have an impact on the functioning of other components within the overall network of the city [35]. Moreover, the rapid incorporation of technology has led to the significant interconnectedness of many components inside smart cities, creating a complex system that cannot be understood independently and requires a systematic approach to enable efficient transformation [36]. As a result, many scholars have highlighted the significance of adopting a system thinking approach to effectively manage the digital transformation of cities [33,37,38]. However, limited studies investigate the significance of integrating systems thinking when transforming cities into smart cities. Hence, it is crucial to understand how previous research employs a systemic approach to examine the digital transformation of cities, to uncover both the opportunities and obstacles involved.

The all-mentioned points are a strong motivation to conduct this review research. The following represents the structure of this study. The research background, motivation, and research questions are provided in Section 1 of the study. It is followed by Section 2 that outlines the resource identification and selection to answer the research questions. At the analysis stage, tables and figures are utilised to facilitate a discussion on current research about the digital transformation for smart net-zero cities. The analysis stage starts with the allocation of a distinct code to each publication, facilitating efficient grouping and referencing during the review process. The analysis is organised into five primary theme sections: net-zero city, smart city, smart net-zero city, digital transformation for smart cities and net zerocities, and cities as a system. Every publication is examined and discussed within a section that is most relevant to its focus. This thematic structure ensures a consistent narrative and enables an efficient and comprehensive understanding of the literature by connecting each paper's content with its relative concept. The last section of analysis is dedicated to a thematic analysis in which all the examined papers are analysed collectively through the lenses of the mentioned themes. Then, Section 4 provides the research implications and proposes a framework to fill the analysed gap. Additionally, in conclusion, the study explains the key findings, opportunities, and constraints it encountered and outlines the contributions and future opportunities.

2. Research Methodology

This research utilises a state-of-the-art (SoTA) methodology to examine current research on digital transformation for smart net-zero cities, focusing on the integration of systems thinking and the key components of digital transformation: people, technology, process, and data. The following research questions will be addressed in this study:

What significant progress and accomplishments have been achieved concerning a "Digital Transformation" towards developing a smart net-zero city?

1. What are the existing roadmaps, frameworks, or methods for digital transformation towards smart net zero cities?
2. Have those frameworks or methods been developed based on a system thinking approach?
3. What are the challenges, limitations, and opportunities concerning digital transformation towards smart net-zero cities?

Figure 1 illustrates the publication patterns by year. As has been demonstrated in the figure, the first big jump in literature occurred in 2018. Therefore, the focus of this review will be on the publications between 2018 and 2023.

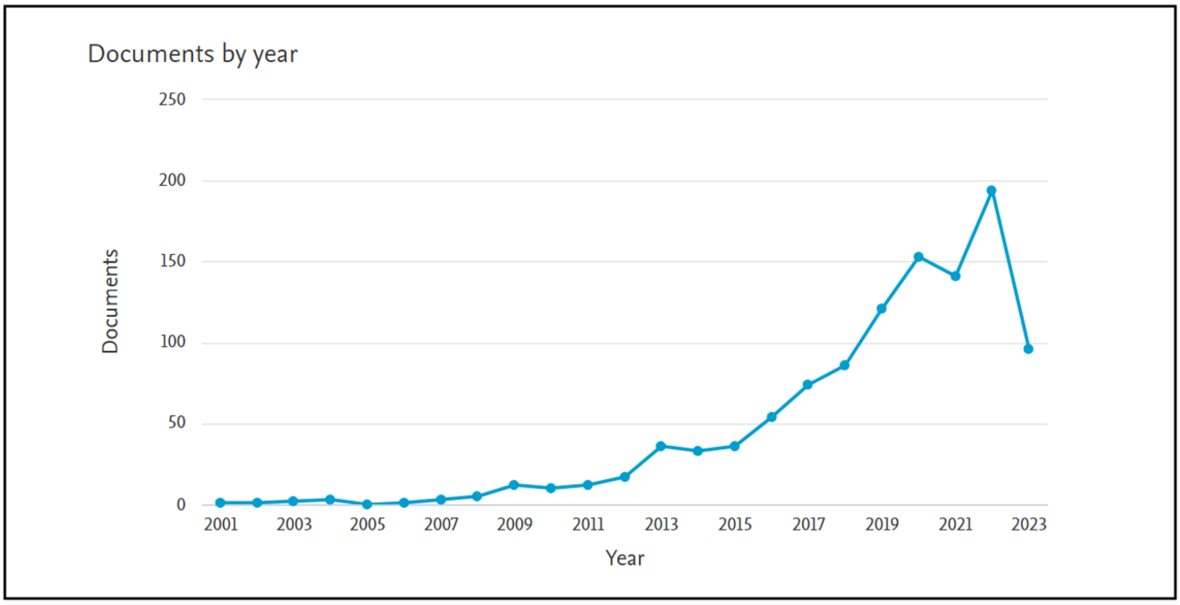

Figure 1. Publications patterns per year.

Figure 2 represents the search strategy that has been employed in this review to find the most relevant resources.

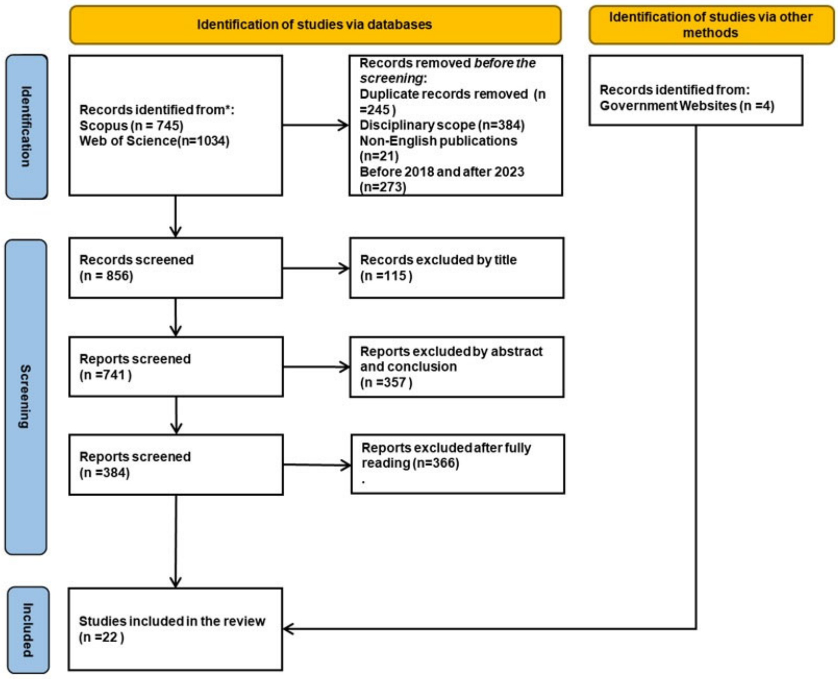

Figure 2. State-of-the-art search strategy stages.

2.1. Identification Stage

At the identification stage, several keywords were employed to identify the optimal keyword match that produces the most relevant publications. As a result, four main categories have been identified:

A. Smart: Through analysing several reviews of smart cities (e.g., [39–42], the following keywords have been recognised for this category: 'smart', 'intelligent', and 'data-driven'.

B. Net-zero: The term "net-zero" can be considered relatively recent as just a few studies have utilised this term and most of it has been used interchangeably with other words in this area. Therefore, the following keywords have been selected for this category to facilitate a thorough review: 'net-zero', 'zero emission', 'zero carbon', 'emission-free', 'green', 'carbon neutral', 'neutral', carbon-free, and 'free emission'.

C. City: To discover relevant publications in the city context, the following collection of words has been identified: 'city', 'cities', 'urban', and 'metropolises'.

D. Digital transformation: Various investigations and reviews have been conducted on the digital transformation and a variety of keywords and search terms have been used. Following are the commonly used keywords: 'digital transformation', 'digitalisation', and Transition'.

After identifying four sets of keywords, the Boolean operators have been used to determine the most relevant research terms: ("Digitalisation" OR "Digital transformation" OR "Transition" OR "Transformation") AND ("Smart" OR "Intelligent" OR "data-driven") AND ("net-zero" OR "zero emission" OR "zero carbon" OR "emission-free" OR "green" OR "Carbon neutral" OR "neutral" OR "carbon-free" OR "free emission") AND ("city" OR "cities" OR "urban" OR "metropolis").

The Web of Science and Scopus are widely regarded as databases encompassing several scientific disciplines and are commonly employed for literature research [42]. Therefore, in this review, the relevant resources have been identified by utilising the Scopus and Web of Science databases in accordance with the established search terms. The initial research of the identified search terms revealed 745 results in Scopus and 1034 results in Web of Science.

At the identification stage, after comparing the records from Scopus and Web of Science, we found 245 duplicated records that have been removed from the database. We utilised the knowledge obtained from the previous stages to establish inclusion and exclusion criteria and enhance our search. Only publications that have been written in English languages are included in the records; therefore, we have removed 21 non-English publications. Furthermore, considering the time frame that has been confirmed in Figure 1, the publications must fall between 2018 and 2023. As a result, 273 records that are not in the determined time frame have been eliminated.

2.2. Screening and Included Stages

At the screening stage, from the remaining records, 115 publications, which were identified to be irrelevant to the research topic, were excluded after skimming. Furthermore, a total of 357 records were eliminated from the database following a thorough examination of their abstracts and conclusions. At the last stage of screening, 384 records were fully read, and we decided to select 18 of them as the most relevant papers to be included in the review. In addition, 4 documents from the government website, which were matched to the subject area, have been identified and added to the final review records. Ultimately, a total of 22 records were selected for final analysis.

3. The Results of the State-of-the-Art Analysis

Table 1 represents the codes and scope dedication for the identified publications and government documents for the final review.

Table 1. Identified academic resources for the final review.

Code	Scope	References
P1	Identifying the core areas of net-zero-carbon city transformation	[43]
P2	Investigating the net-zero carbon city key elements, as well as present initiatives, implementation strategies, and opportunities to propose a roadmap towards net-zero-carbon cities in three stages	[44]
P3	Enhancing traditional planning approaches by empowering society and establishing a new strategy for net-zero cities by designing six-step cycle principles	[45]
P4	Developing a framework for integrating climate mitigation strategies throughout urban systems in three levels of systems integration	[46]
P5	Assessing the impact of digitalisation on emission reduction	[34]
P6	Exploring artificial intelligence (AI)-driven solutions for net-zero transition in smart cities	[37]
P7	The application of machine learning, deep learning, and remote sensing technologies for zero emission city transformation	[47]
P8	Investigating city indicators to transform to NZED through renewable energy, smart city, and nature-based solutions	[48]
P9	Exploring the impact of data analysis and intelligent technologies in moving towards carbon-neutral cities	[33]
P10	Investigating a variety of aspects of smart city developments and suggesting the implementation of new practical indicators for the design of smart cities that are associated with green buildings (GBs) and electric vehicles (EVs), as well as investigating the challenges to the advancement of smart cities and proposing solutions to overcome them	[49]
P11	Investigating the impact of smart cities on the green development of cities	[50]
P12	Analysing the potential impact of smart city solutions in the city sectors on climate change adoption	[51]
P13	Utilising an analytical framework to explore the relationship between smart cities and green cities	[52]
P14	Assessing the current urban development approaches and proposing a structure for an inclusive model that incorporates principles of sustainable development	[53]
P15	Proposing a framework for a smart and zero carbon city, focusing on the community	[54]
P16	Proposing a framework for a smart zero carbon city	[55]
P17	Investigating the green smart city concept to propose a framework	[56]
P18	Developing a plan for city transformation to a smart zero carbon city	[38]
P19	Outlining the EU strategy to achieive climate neutrality through sustainable growth, emission reduction, and innovative solutions	[10]
P20	Presenting the United States' strategy to reach net-zero emissions through adopting clean energy, reducing emissions, and adopting innovations and world-wide leadership in climate	[13]
P21	Outlining the United Kingdom's net-zero strategy, focusing on city sector decarbonisation, technological advancement, green investment, and creating new jobs and sustainable growth of economy while maintaining social equity	[13]
P22	Presenting China's roadmap to carbon neutrality, emphasising emission reduction, utilising renewable and clean energy, and integrating the technological advancements and policies	[57]

3.1. Net-Zero Cities

3.1.1. Overview of Net Zero Cities

GHG refers to carbon dioxide, methane, nitroxide, and fluorinated gases, which contribute to trapping heat in the atmosphere [58]. The literature and government publications utilise several terms to describe the goal of lowering or eliminating GHG, including "zero emission", "zero carbon", "green", "net-zero", and some other terms. However, in some publications, they have been utilised interchangeably [22]. The goal of zero emission (emission-free, free emission, zero emission) is to eliminate both direct and indirect GHG [59], while the concept of a "zero carbon city" (carbon-free, carbon neutral, zero carbon, neutral) requires a deep decarbonisation of all sectors of the city [44]. Therefore, zero emission refers to the complete elimination of all GHG, whereas zero carbon specifically aims at removing carbon dioxide in the city. Since carbon dioxide accounts for more than 70% of GHG [58]), sometimes, these terms have been utilised interchangeably.

A green city, on the other hand, aims to maximise the social and economic benefits while maintaining a high environmental performance and efficient utilisation of resources [60]. Therefore, green cities have not only accomplished a state of zero emissions but also maintained a harmonious relationship between society and nature. Finally, a net-zero city is a city where the emissions released into the atmosphere are equal to the amount of emissions eliminated from it [61]. As a result, the emission in a net-zero city is not zero; however, the amount of emissions produced and removed from the atmosphere is equivalent.

3.1.2. Net-Zero City Development

Various efforts have been made by academia and governments to achieve net-zero cities [44]. The Paris Climate Agreement, approved by 197 countries in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC), guides international efforts to maintain GHG to a level that reduces the risks caused by the effects of global warming [62]. According to the Paris Agreement, all participating nations have committed to restricting the rise in global temperatures to below 2 °C and to striving to limit it even more, to below 1.5 °C [6]. As of February 2021, a total of 124 countries across the globe have officially announced their commitment to attaining carbon neutrality and reaching a state of zero emissions of carbon dioxide by either the year 2050 or 2060 [63].

Analysis of the Net-Zero Papers

P1 conducted a literature review study to assess the latest progress in the research of net-zero cities. Following the investigation's findings, they proposed the theoretical framework for net-zero cities, which is integrated with the principles of sustainable development goals. In this framework, the main sectors required to attain net-zero targets have been identified as city paradigm, heating energy, waste management, building, urban growth, and industry. They emphasised the need to establish evaluation indicators that are based on unique achievements, as well as the adaptability and flexibility of policies to encourage communities to work towards achieving net-zero goals.

P2 undertook a literature study to examine the objectives and key elements, present initiatives, and success of net-zero cities. The proposed framework for a net-zero city consists of three primary stages: demand reduction, supply change, and carbon capture enhancement. In addition to discussing implementation strategies, roadmaps, opportunities, and obstacles for net-zero cities, they also emphasised the importance of adopting a systemic approach and cross-sectoral solutions because of the complex relationships between city sectors.

P3 utilised participatory action studies and an investigation of a case study in Taiwan to enhance traditional planning approaches and establish a six-step cycle principle for achieving net-zero cities through the implementation of smart technologies. The process involves the following steps: (1) establishing commitment, (2) identifying available and required value and resources, (3) measuring and assessing carbon impact, (4) creating an integrated plan for environmental, economic, and energy aspects, (5) developing flexible energy system plan, and (6) monitoring digital performance. The results aim to enable policymakers and planners, as well as to encourage participation from the public, to accomplish net-zero objectives.

P4 proposed a framework that supports the transformation to net-zero cities in three levels of systems integration. Three tiers of integration have been provided in the framework and the solutions for each level have been discussed. For the first level of integration (Tier 1), some solutions, such as smart building, utilising renewable energy, and minimizing waste, have been discussed as sector-specific solutions that have the lowest level of system integration. The suggested solutions for Tier 2 involve further improvements in the integration among different sectors of the city, such as the implementation of shared mobility alternatives and the adoption of a holistic waste management system. Finally, in the advanced system integration level (Tier 3), circular economy and compact urban form are examples of solutions that have been provided. Therefore, they demonstrated that the strategies and actions-based system integration and cross-sectoral solutions have the potential of shifting to reaching net-zero targets in the cities.

After examining the literature and government documents on net-zero cities, it was noted that the main emphasis was on two key themes: decarbonisation and digitalisation. Table 2 illustrates the intervention proposed by the literature and practical investigations based on the category mentioned. Generally, all the measures and policies that contribute to the reduction of carbon emissions can be included in decarbonisation. For example, in the energy sector, renewable energy, hydrogen integration, and energy storage measures are some steps that will reduce fossil fuel consumption and lead to decarbonisation [13]. In transportation, encouraging the use of public transportation and other healthy forms of mobility, such as biking and walking, can contribute to the decarbonisation process [1].

Electrification is another important measure that refers to the process of converting existing fossil fuel-based operations into electricity aiming to create a clean and reliable source of energy [64]. Electrification solutions, such as replacing fossil fuels with electricity, have been proposed in publications for several sectors, including the energy sector [10], transportation [65], industry [66], and heating and building [67]. However, it is crucial to note that this electricity must be generated from renewable sources of energy [68].

Digitalisation in cities refers to using digital technology to improve efficiency, reliability, and sustainability in utilising the city resources [69]. Many publications highlighted the importance of digitalisation to achieve net-zero city objectives. For example, utilising AI algorithms as a digitalisation approach in the energy sector can facilitate energy consumption monitoring and contribute to energy-saving [47]. Integrating digital technologies for traffic monitoring in transportation will enhance the effectiveness of traffic management, resulting in improved energy, cost, and time efficiency [16]. Implementing building information modelling (BIM) in the construction industry would enable the effective interchange of information across stakeholders, resulting in improved sustainability and efficiency [70].

Table 2. The results of categorising cities' interventions in digitalisation and decarbonisation.

Decarbonisation	Digitalisation
-Renewable energy and hydrogen integration and energy storage measures [13] -District heating and cooling, waste of energy, biomass [38] -Promoting alternative and healthy modes of transportation, like walking and biking, and public transportation [1] -Clean hydrogen and biofuels in heavy-duty transport [13] -Improving the efficiency of heating appliances and investment in public building [13] -Waste management [71] -Circular economy, bioeconomy, carbon sink [10] -Carbon capture usage and storage (CCUS), green jobs and skills, carbon pricing [13] -Demand and material efficiency in industry [72] -Urban forestry and greening initiatives [73] -Nature-based infrastructure solutions [74] -Promoting community awareness of carbon emissions [75] -Green choice empowerment [13] -Changing lifestyles [76] -Generating electricity from renewable energy [10] -Electric vehicle infrastructure and electrifying vehicles [13,57] -Heating and building electrification [67] -Industry electrification -Renewable energy integration and electric charging infrastructure [55]	-Smart energy system [54] -Integrating smart grid, AI, and blockchain [77] -Predictive analysis techniques [78] -Digital twin for real-time monitoring [79] -Smart building [49] -Energy management system [80] -Augmented reality (AR) and virtual reality (VR) in the building lifecycle [81] -Building information modelling (BIM) and digital twin [70] -AI integration for optimisation, monitoring, and automation [82] -Integrating intelligent transportation [83] -Smart parking system [84] -Mobility as a service [85] -Connected and autonomous vehicles [86] -Shared mobility system [87] -Digital traffic monitoring system [16] -Digital twin for enhancing transportation systems and energy efficiency [88] -AI for predictive maintenance, demand forecasting, and traffic management [89]

3.2. Smart City

Smart cities leverage information and communication technologies to maximise the use of digital technologies and enhance efficient information sharing across all sectors of the city, leading to increased sustainability [90]. Smart cities have the potential to enhance urban resource management, leading to improved energy efficiency, the preservation of a sustainable environment, and the advancement in both economy and quality of life [14]. Literature has thoroughly investigated the dimensions of smart cities. However, the most recognised smart city dimensions include smart government, smart living, smart economy, smart people, and smart transportation [91].

Smart government involves allocating resources towards digital and emerging technologies while also devising innovative approaches to establishing more adaptable and sustainable government systems and infrastructures [92]. Effective governance is crucial in smart cities to facilitate the implementation and improvement of digital infrastructure and services [93]. E-governance can facilitate effective communication and interaction among all stakeholders in smart cities by leveraging advanced technologies such as artificial intelligence, cloud computing, and the Internet of Things [40].

Smart living refers to a broader concept that includes components encompassing smart building, smart healthcare, and smart education [90]. Smart building incorporates advanced digital technology such as sensors, control systems, and data analysis tools to improve building operation and energy efficiency while also increasing the quality of life [94]. Smart healthcare employs advanced digital technology to fundamentally revolutionise the conventional medical system, enhancing healthcare efficiency, convenience, and personalisation [95]. Smart education empowers learners to engage in intelligent thinking, perform tasks with efficiency, and effectively resolve problems by utilising a smart learning environment that is individual-centric, with adoptable learning and collaborative tools [96].

The smart economy utilises information technology solutions to enhance efficiency and uncover issues by utilising the collected data from the city sectors to make informed decisions, allocate resources effectively, and foster collaboration across different sectors [97]. A smart economy fosters technical advancements to enhance the efficient utilisation of urban resources, promote sustainability, and enhance the overall well-being of its residents [93]. Smart people are an essential resource for smart cities, who can effectively utilise the intelligent services provided to them and actively engage in the administration and operation of the city, thus contributing to the success of smart cities [98]. Smart transportation employs and integrates innovative sensors, computers, communication technology, and management practices to enhance the safety and efficiency of the transport sector [16]. Analysing 70 case studies in China proved that implementing smart transportation systems can effectively reduce carbon dioxide emissions not just in the transportation sector but also in other city sectors [99].

3.3. Smart Net-Zero City

Although to consider a city as a smart city, it must prioritise achieving sustainability, current smart city approaches do not incorporate a progressive and authentic focus on sustainability [100]. Therefore, very limited definitions for smart net-zero cities have been provided in the literature. For example, [55] define a smart net-zero city as an innovative urban area that leverages emerging control technologies, clean and renewable energy sources, and active collaborations among city stakeholders to optimise resource efficiency, eradicate carbon emissions, and minimise energy consumption. This research defines smart net-zero cities as "a system that utilises data to analyse the complex interactions between technology, individuals, and the environment to facilitate informed decision-making for improving city services efficiency, and resource management, minimising energy consumption, and maintaining a balance between emissions released into the atmosphere and those removed from it".

Analysis of the Smart Net-Zero City Papers

The concepts of smart cities and net-zero cities have mainly been examined as distinct concepts in literature and official documents. The majority of papers in this field are aimed at investigating the impact of smart city implementation on attaining net-zero emissions in urban areas. For example, P5 conducted quantitative research demonstrating the impact of digitalisation, through the deployment of smart cities, on achieving net-zero city targets based on data collected from 353 cities in China. The findings indicate that adopting digital governance through smart city construction pilots has led to a 6.6% reduction in regional carbon emissions, and this positive impact is expected to be maintained continuously.

P6 attempts to identify potential solutions based on AI that could be utilised in smart cities as a helpful technique towards becoming a net-zero city. In six main domains of smart cities including smart people, smart transportation, smart living, smart environment, smart economics, and smart governance, the importance of AI-based solutions in achieving zero carbon policy and neutrality in carbon emissions has been investigated. Through conducting a review study, the authors prove the beneficial impacts of AI-based technologies, particularly green coins, in increasing public awareness regarding climate change and promoting the transition towards smart net-zero cities.

P7 investigates the contribution of employing digital technologies to move smart cities towards net-zero cities. They conducted an extensive evaluation of how machine learning, deep learning, and remote sensing technologies may facilitate the transformation towards net-zero cities. This study investigates some domains where machine learning is applied, including the assessment of energy consumption, the monitoring of facilities, the enforcement of legislation, and the implementation of energy-conserving strategies that can facilitate the transition to net-zero cities.

In P8, an analysis was conducted to determine the viability of converting city districts into self-sufficient net-zero energy districts (NZEDs) by utilising locally generated renewable energy and smart city technology. They utilised simulation methodologies to examine the model for achieving carbon neutrality across several scenarios, considering variables such as geographic location, climate conditions, individual energy usage, and the spatial arrangement of the district. The model demonstrates that when the population reaches a particular level, a residential area that currently relies on fossil fuels for household energy, city lighting, and transportation can transform into a self-sustaining NZED with zero yearly carbon dioxide emissions. This transformation is achieved by utilising locally generated renewable energy from solar panels. They highlighted that the performance of the model relies on the combination of human behaviours, communal situations, and technological capacities.

P9 focuses on integrating intelligent technology and the importance of data analytics in advancing towards smart net-zero cities. In addition, they developed a framework to demonstrate this integration. This paper considers cities as complex systems of systems, and the main focus of this paper is on how analysing data will provide an opportunity to understand dynamic interaction in city systems. Finally, the authors advocate for additional research to address the data limitations, and the environmental, social, and technological transformation issues involved in achieving a smart net-zero city. In addition, integrating advanced digital technologies such as digital twins has been proposed as another opportunity for future research.

P10 explores the existing challenges to the development of smart net-zero cities and proposes new practical indicators associated with green buildings (GBs) and electric vehicles (EVs) with the goal of net-zero in smart cities. The study highlights the significance of implementing practical measures such as developing zero-energy buildings, using effective design indicators for GBs and EVs, reducing manufacturing costs of EVs without compromising quality, managing electricity demand, and integrating EVs into the grid for the development of smart cities. The authors also emphasise the significance of government-led strategies to enhance communication, collaboration, awareness, and engagement to achieve net-zero smart cities.

By analysing data from Chinese cities between 2003 and 2016, P11 investigates the impact of smart cities on the net-zero development of cities. The objective is to establish a relationship between smart city initiatives and the promotion of net-zero objectives. The results indicate that smart cities can facilitate the development of technologies for net-zero goals that will contribute to progress towards net-zero development in three main aspects, including industrial structure, production, and environmental performance. In addition, they provide a specific definition of net-zero development as the allocation of resources towards renewable energy, the abandonment of polluting technologies, and the transformation of the economy to be environmentally friendly, energy-efficient, and environmentally clean in its production processes. Also, the government's involvement in promoting policies and citizen participation in fostering technological innovation to achieve green development is emphasised.

P12 undertook a systematic review to assess the potential effects of adopting smart city techniques in urban sectors to achieve net-zero cities. The results show that smart solutions and technology can improve predictive capability, enabling frisk planning and preparation. They further increase operational efficiency, improve resource management to improve stakeholders' environmental awareness and enable integrated city management.

3.4. Smart Net-Zero City Development

Although the majority of research in the field concentrates on the influence of smart city implementation on the development of net-zero cities, a limited number of studies went a step further and attempted to establish a framework for smart net-zero cities.

Analysis of the Smart Net-Zero City Development Papers

P13 attempts to analyse the relationship between net-zero cities and smart cities' objectives by employing similarities and convergence theory as an approach. The suggested framework integrates the human and technological characteristics of smartness with the human and environmental aspects of net-zero goals to establish shared objectives for the economy, population, housing sector, transportation, and environment. In addition, the authors prove that utilising a smart-centric approach will provide an opportunity to improve this integration. The result underscores the necessity for improved harmonisation between net-zero objectives and smart technological solutions to achieve smart net-zero cities in the future.

P14 conducted research on the sustainable development of modern urban areas and proposed a framework for developing smart net-zero cities. The major principles highlighted were environmental management of resources, societal and geographic coherence, smart, circular, integrated economy, and city intelligence. In the developed framework, the integration of these key solutions is represented. However, the authors acknowledge that verification is necessary since the proposed framework is conceptual. Also, the paper underscores the significance of cross-sectoral collaboration in reaching the objectives of smart net-zero cities.

P15 suggested a framework that integrates various disciplines to develop smart net-zero cities, with a focus on energy at the community level and by utilising technology and infrastructure. The proposed framework has five primary stages, including initial evaluations, political assessment, requirements analysis, virtual modelling, cyber-physical systems, and economic investigation, and each stage encompasses a set of strategies that are discussed in detail. The integration of new technological advances, such as IoT, big data analysis, and AI solutions, is emphasised as critical for improving the framework's potential. The authors suggest that further research is required to enhance the framework's effectiveness, and they emphasise the importance of validating the proposed framework through a real-world case study.

P16 developed a framework for smart net-zero cities and attempted to extract the key factors from implementing the framework in a case study in Denmark. These significant factors were exported to be utilised in other cities undergoing the same transformation. The framework has been proposed in four steps, which encompass theoretical investigation, testing and deployment, monitoring, and exchange of information. During the initial phase, some measures, such as the revision of standards, the creation of new business models, and the formulation of policies to enhance citizen participation, are proposed. The second stage (implementation) is dedicated to net-zero solutions for energy, infrastructure, and transformation, with an emphasis on people's engagement. In addition, impact assessment, monitoring of the project, and evaluation are examples of measures implemented during the third stage. Finally, the last stage is dedicated to applying tools and techniques for sharing the knowledge from the other stages and finding the potential for utilising them. The authors conclude that integrating energy planning through urban development, implementing energy efficiency programs, and improving citizen knowledge and collaborations are the three important identified key factors.

3.5. Digital Transformation for Smart Net-Zero Cities

3.5.1. Overview

Digital transformation encompasses a continuous movement to successfully respond to rapid technological advancements [101]. According to [24], digital transformation comprises three primary stages: digitisation, digitalisation, and digital transformation. The technological process of transforming analogue data into digital format is referred to by the authors as digitisation. In addition, digitalisation refers to the utilisation of digital technology to improve current business procedures [102]. On the other hand, the approach of digital transformation is holistic and revolutionary, encompassing fundamental changes in organisational culture, structure, and services [103].

Initially, digital transformation was introduced in enterprises to enable the implementation of strategic changes in the business model by adopting digital technologies [102]. Ref. [104] approach a city as an enterprise and demonstrate that different city sectors, such as transportation, healthcare, power, and education, can be compared to business systems such as human resources, sales, and finance departments. Therefore, digital transformation, originally developed for utilisation and managing fundamental business changes, can be applied to achieve holistic transformation in cities. Digital transformation in cities enhances city societal and economic operations, infrastructures, and governance by utilising data and digital innovations to enhance urban administration efficiencies and the quality of life [12].

Digital transformation can facilitate the integration of several digital technologies in the cities. For example, IoT enables devices to establish connections with the internet, hence facilitating the collection and processing of data for decision-making and policymaking purposes [105]. IoT sensors, including temperature, humidity, light, and motion sensors, can be employed to enhance energy efficiency in the energy sector [106], provide real-time tracking and traffic management in transportation processes [107], and monitor, protect, and enhance natural resources in the environment [108].

AI is another digital technology that refers to the capacity of a system to accurately comprehend external data, understand the data, and apply the gained insight to accomplish specific objectives [109]. AI can be utilised in transportation for tasks such as modelling and simulation, dynamic routing, traffic management, and control, enabling the development of an intelligent transportation system [110]. Employing AI algorithms in the energy sector can bolster cybersecurity, enhance energy efficiency, and facilitate efficient operation of smart grids [111]. AI can be utilised in the environment to enhance the detection of air pollution [112]), forecasting of weather conditions, processing of images [113], and management of natural disasters [114].

Blockchain is another advanced technology that is a decentralised, shared database that has transformed the way users automate payments, communicate, and monitor transactions without requiring central administration to manage the transactions [115]. Through implementing distributed management of data and decentralised peer-to-peer connection among IoT devices, blockchain technology provides reliable, transparent, strong, and validated data transmission in smart cities [116]. Ref. [117] discussed the advantages of utilising blockchain technology for smart transportation systems, demonstrating that it can contribute to enhanced efficiency, cost reduction, and reliable delivery of services to customers. In addition, through ensuring decentralisation, transparency, and secure transactions, blockchain technology will enable customers to have a more participatory role in the energy market, fostering a shared economy within the energy sector [118].

3.5.2. Digital Transformation Elements

Major recognised elements of digital transformation are people, technology, processes, and data [24]. Some examples of people as a key element of digital transformation in cities include access to digital technologies, ethics, responsibility, and maintaining physical and mental health [119]. The technology element that is a critical driver of digital transformation is the utilisation, adoption, and development of digital technologies such as blockchain, artificial intelligence, and the Internet of Things [120]. The process element of digital transformation encompasses many activities, such as process change, automation, reengineering, and optimisation [121]. Finally, data lifecycle management, encompassing data collection, analysis, explanation, prediction, and utilisation, has been highlighted as the pivotal aspect of the data component in digital transformation [122]. Therefore, technology alone is not sufficient, and it is crucial to address each component in order to accomplish an effective digital transformation [24].

Analysis of Papers on the Digital Transformation for Smart Net-Zero Cities

Limited studies investigate the development of digital transformation for smart net-zero cities. P17 developed a digital transformation model for smart net-zero cities, including people, technology, processes, and cities. In the technology aspect of this model, the authors suggested integrating various technologies, such as data management systems, digital solutions, and the development of environmentally friendly products. In the people component, critical thinking, knowledge, and education are among the social dimensions of the digital transformation that are being addressed. Also, the process component of the transformation model provides some solutions, such as digitalising and integrating the process to move towards smart net-zero cities. Finally, within the city domain, certain policies are suggested that necessitate development by individuals in positions of authority at the municipal level. They also emphasised the importance of including aspects such as modularity, openness, interoperability, integrating virtualisation, autonomy, and real-time management into the model. Furthermore, in addition to establishing the term "eco-transformation", the authors identified four primary development stages, which include an engaged municipality, a creative municipality, incorporating citizens, integrating, and, finally, a smart net-zero city. For further investigation, they highlighted the importance of conducting more research in the four main domains of the model (people, technology, city, and process).

P18 is he most relevant paper to this study by developing Cities4ZERO, a step-by-step digital transformation roadmap established to support the successful transformation of cities into smart net-zero cities. This roadmap has been developed by thoroughly examining five European cities over four years and is proposed in three main stages including the strategic stage, the design stage, and the intervention and assessment stage. Each stage comprises various parts that have been thoroughly discussed. Five cities have collaborated extensively to develop and execute the proposed method. Furthermore, around 60 cities have already initiated the process of implementing the approach within their local contexts.

The article identifies several key features of smart net-zero cities, which encompass strategies for enhancing energy efficiency in buildings, integrating energy systems, optimising mobility, and integrating information and communication technologies (ICTs). For the building sector, the authors proposed some solutions, such as the utilisation of renewable energy sources, retrofitting building envelopes, and implementing heat pumps. As potential solutions for the energy sectors, some strategies such as converting waste to energy, thermal storage, and electrical energy storage are suggested. Regarding the transportation sector, the authors have suggested some options, including the utilisation of electric, hybrid, and environmentally friendly cars, the enhancement of bicycle infrastructure, and the development of car-sharing services. Furthermore, the project recommends the integration of ICT in various sectors, such as city planning, building energy systems, and smart electrical grids.

3.5.3. Analysis of the Government Documents

Following the Paris Agreement, many strategies to achieve net-zero have been established by countries such as the European Union (EU), China, the United States (US), and the United Kingdom (UK). Table 3 provides a comparison of these strategies' target year, objectives, key sectors, and key policies. China is the only country that sets 2060 as its target year, while other countries acknowledge 2050 as their target year. However, there is a slight difference in the countries' objectives. For example, the UK has set an objective to reduce GHG by at least 68% by 2030 while the percentage is expected to be 50–52% lower than 2005 levels in the US by 2030. The recognised key sectors that are required to achieve decarbonisation in all the countries are the same, including energy, transportation, building, and industry. However, for example, the US refers to agriculture, forestry, and land use as separate sectors from industry. As another example, the UK considers fuel supply and hydrogen as the separate sector from energy. They also contemplated a distinct sector for greenhouse gas removals, natural resources, waste, and fluorinated compounds.

Table 3. Comparing the four net-zero strategies.

Country	Target Year	Objectives	Key Sectors Covered	Key Policies
P19 (EU)	2050	-To achieve a reduction in greenhouse gas (GHG) emissions ranging from 80% to 100% in comparison to the levels recorded in 1990. -A climate-neutral economy by 2050	-Energy -Building -Transportation -Industry -Environment	-Global collaboration -Empowering society -Improving system integration by developing a digital market -Integrating research and innovation -Ensuring equal taxation -Public and private investment -Smart and interconnected infrastructure ...
P20 (US)	2050	-Global greenhouse gas (GHG) emissions reduction of 50–52% below 2005 levels in 2030 -Achieving net-zero greenhouse gas emissions on a global scale by 2050 or shortly thereafter, with a subsequent transition to net-negative emissions	-Energy -Transportation -Building -Industry -Agriculture, forestry, and land use	-Federal involvement in establishing policies, partnering to accelerate market transformation, investing in clean technologies, and incorporating climate issues into financial systems -Integrating and supporting technological innovations -Subnational policies in local and non-federal systems ...
P21 (UK)	2050	-Achieving a minimum reduction of 68% in economy-wide greenhouse gas emissions by the year 2030 -Reducing its overall emissions by 100% by the 2050s	-Energy -Fuel supply and Hydrogen -Industry -Heat and building -Transportation -Greenhouse gas removal -Natural resources, waste, and fluorinated	-Private and public investment -Government support and involvement -Local action -International collaboration -Technological solutions -Empowering society and businesses -Systems thinking ...
P22 (China)	2060	-Achieving CO_2 emission peak before 2030 -Achieve net-zero before 2060	-Power and heat -Fuel supply -Industry -Transport -Building	-Private and public investment -Restrictive regulations for metals and carbon -Supporting innovation -Systemic transformation -International collaboration

In the key policies, multiple similarities have been identified. For example, supporting and developing technological solutions and innovations is a significant key policy that has been highlighted in all strategies. This common policy highlights the significant role of technology in facilitating the progression towards net-zero cities. As an example, the EU emphasised the incorporation of smart and connected infrastructure as an important policy. Improving investment, international collaboration, and developing effective policies to support transformation are the other similarities in most policies. In addition, systematic integration is considered essential in the UK, EU, and China as a key policy for progressing towards net-zero cities. The UK strategy emphasises that the application of systems thinking is essential for urban transformation aimed at attaining net-zero emissions by 2050 as it allows policymakers to better understand the intricate interdependencies among sectors like energy, transport, and housing while recognising opportunities for leverage and harmonising strategies for a sustainable, zero carbon future.

Therefore, integrating a systemic approach alongside technological innovations is the common key policy emphasised in the majority of net-zero cities' strategies.

Several studies have been undertaken in academic investigations on net-zero cities. Some of these studies concentrate on providing a framework or implementation plan towards developing net-zero cities.

3.6. City as a System

A system is a collection of interconnected and interdependent components that operate within specific boundaries in space and time, are impacted by their surroundings, and can be described by their structure and purpose, which are manifested in their functioning [123]. Smart cities are complex systems that encompass physical components such as transportation and buildings, as well as digital components such as ICT, which enable connections and interactions between the city system components [124]. In addition, cities have a dynamic nature as their components undergo continuous evolution and alteration [125]. Any modification in a single subsystem will have an impact on the operation of other subsystems and a holistic impact on the system function [35]. For example, although electric vehicles have a beneficial effect on energy efficiency and emission reduction during operation in comparison to conventional combustion engines, they do have a substantial environmental impact during the manufacturing process [126].

Ref. [127] analysed the smart city from the perspective of the complex system of systems by considering the city sectors as the subsystems and discussing the operational and managerial independence, connectivity, evolution, emergent behaviour, and dynamic complexity. Operational and managerial independence refers to the city's sectors (for example, energy, transportation, and building) operating as separate subsystems, with each sector accountable for delivering its services, achieving its unique goals, and overseeing its resources.

Connectivity as another important element refers to the interconnection between the system's elements. In smart cities, there is a collaboration of interconnected smart systems that interact, communicate, and exchange information, which enables the use of services across different sectors [128]. Evolution, in contrast, refers to the continuous development of each subsystem in response to various changes, including those in the environment, component systems, or its purposes [127]. For example, integrating renewable energy into transportation will support the sector in evolving into a more sustainable, efficient, and resilient version [129].

Emergent behaviour in systems thinking refers to the change that arises from the real-time collaboration between the individual components of the systems, which cannot be achieved by individual components in isolation [130]. As an example of emerging behaviour in smart cities, smart buildings decrease electricity consumption during periods of high energy demand [131], electric vehicles can decrease energy usage [132], and solar panels can optimise the energy output [133]. Therefore, the behaviour of managing energy consumption arises from the collaboration between the city's sectors as the subsystems.

Dynamic complexity refers to unpredictable systems change and adaptation in real-time [127], which can be understood in the context of smart cities. If there is a reduction in the generation of renewable energy, it leads to a sudden decrease in power supply and the smart grid needs to quickly adjust by obtaining power from alternative sources or utilising energy storage technology. However, this can create feedback loops and impact other sectors within the city [134].

Therefore, smart cities as complex systems cannot be understood in isolation and require a systematic approach to enable effective transformation [36]. Several papers have emphasised the significance of incorporating a systems approach while analysing smart cities or proposing new methods in this field [35,127,135–138]. However, very limited publications in the field of this study have focused on incorporating a system thinking approach.

3.7. Thematic Analysis of All Papers

Table 4 provides detailed explanations of how digital transformation elements, framework/model/roadmap, and systems thinking themes are being applied in the selected resources through a thematic analysis. Table 5 represents a summary of the thematic analysis of all state-of-the-art review papers.

Table 4. The detailed results of the thematic analysis.

	Digital Transformation				Framework/Model/Roadmap	Systems Thinking
	People	**Technology**	**Process**	**Data**		
P1	Policy support, people's behavioural change, and public participation	Limited information on implementing new technologies	Very limited focus on the process	Very limited information on the data	General and conceptual framework representing city sectors and a summary of academic resources	The interdependency between city systems acknowledged without integrating systems thinking principles
P2	Behavioural change, social participation	Limited information on implementing emerging technologies	Very limited focus on the process	Limited information on data collection and monitoring	A conceptual and systems-based framework for demand reduction, switch to net-zero energy, carbon uptake enhancement, and seven pathways to achieving them	The necessity of cross-sectoral interventions and systemic change
P3	Community empowerment	Limited information on implementing emerging technologies	Very limited focus on the process	Limited discussion regarding the utilisation of digital tools for data management	A six-step cycle principle to guide the development of net-zero cities by incorporating innovative technologies, renewable energy, and partnerships between the private and public sectors	Emphasis on a systemic approach by allocating two phases of the framework to identify system boundaries and approaches for systems integration
P4	Public participation and awareness, engagement of local authorities, policy support	Limited discussion on implementing emerging technologies	Limited focus on the process	Limited focus on data	A conceptual framework including three levels of systems integration (single sector, limited cross-sectoral, and advanced urban system integration)	Focus on the importance of cross-sectoral interventions in the city system
P5	Regional governance and policy support	Limited discussion on the role of emerging and digital technologies	Very limited focus on the process	Data-driven governance	Not proposed	The interconnected nature of the city system highlighted without specifically operationalising the systems thinking
P6	Citizens' empowerment and involvement through education	Some discussions on utilising digital and AI-enabled tools and techniques, specifically GreenCoin	Limited focus on the process	The data collection and analysis are highlighted	A conceptual framework including the smart city sectors and AI-enabled technologies	Emphasising the significance of attaining a holistic view of the city by employing AI-enabled approaches
P7	Very limited discussions on the role of people	Focus on integrating machine learning, deep learning, and sensing technologies	A limited discussion on process automation and efficiency	Some discussions on the importance of data-driven decision-making	Not proposed	The interconnectedness of the urban system is highlighted without providing a practical integration of the systems approach

Table 4. *Cont.*

	Digital Transformation				Framework/Model/Roadmap	Systems Thinking
	People	**Technology**	**Process**	**Data**		
P8	Citizens' engagement, participation, and behavioural change	A range of digital and emerging technologies, such as smart grids, renewable energy technologies, and nature-based solutions integrated into digital technologies, are discussed	Limited information regarding the process	Discussions regarding data collection and data-driven decision-making	A conceptual model proposed to support the transformation of urban districts into net-zero energy districts, including district analysis, energy and emission analysis, transition measures, and creating a balance between energy and CO_2 emissions	Limited addressing of systems thinking by emphasising the interconnectedness of city systems
P9	Citizens' participation, collaboration, and behavioural change	The necessity of implementing digital and emerging technologies, such as AI, digital twin, and smart systems	Very limited information regarding the process	Some discussions about data integration, visualisation, and using data for monitoring	A theoretical framework proposed to illustrate the interaction among data, analytical tools, and actions inside urban environments	Cities are considered as systems-of-systems with interconnected social, digital, and physical elements, and the necessity of utilising a holistic approach is emphasised
P10	Public participation through education and engagement	Smart technology implementation to support green buildings and electric vehicles	Very limited information regarding the process	The role of data-driven policies, utilising data analysis methods to monitor energy consumption, emissions, and city service performance	Not proposed	Not discussed
P11	The role of citizens, policymakers, and businesses is highlighted	The importance of utilising green technological innovation is highlighted	Limited mention of the process	Emphasis on data-driven decision-making, specifically in monitoring and evaluating policies	The conceptual framework representing green industrial infrastructure and production along with environmental monitoring as potential enablers of green development in smart cities	Not offered
P12	An emphasis on policymakers, urban planners, and businesses, and the need for behavioural change and public awareness to improve citizens' participation	An extensive discussion regarding smart technologies such as IoT, AI, smart grids, digital twins, machine learning, and blockchain	Limited discussion about the process	Emphasis on data-driven decision-making to improve energy efficiency, risk management, and resource optimisation	There is no unified framework; rather, it examines the application of smart city solutions across urban systems for climate change adaptation	Underscoring a systems approach by highlighting how the integration of smart solutions, including IoT sensors, machine learning algorithms, and big data analytics, facilitates a holistic understanding and management of complex city interactions
P13	Citizens' engagement and behavioural change	Highlighting the utilisation of ICT, IOT, AT, big data, sensors, cloud computing, and smart grids	Limited discussion on the process	No discussion	A framework proposed utilising similarity and convergence theories to reflect the relationship between smart and net-zero cities towards sustainable development	Not mentioned
P14	Citizens' and local communities engagement and collaboration	The utilisation of smart city technologies such as IOT, AI, big data, and digital twins	Limited discussion on the process	Utilising data-driven governance, real-time monitoring, and analytics	A conceptual framework representing smart city sectors and general instructions for solutions	Systems thinking, mainly suggested by their focus on integration and collaboration among diverse stakeholders

Table 4. *Cont.*

	Digital Transformation				Framework/Model/Roadmap	Systems Thinking
	People	**Technology**	**Process**	**Data**		
P15	Willingness, acceptance, awareness, and participation	The utilisation of smart technologies such as IOT, digital twin, automation, ICT infrastructure, and real-time monitoring	Some discussions around the assessment of the policies and government frameworks	Data-driven decision-making with an emphasis on real-time monitoring, data fusion, and predictive analysis	The conceptual framework is divided into several stages, encompassing initial evaluations, technology and infrastructure mapping, review of policies, and economic assessment, including some decision-making steps for a smart transportation plan	Systems thinking is explored by conceptualising cities as interconnected systems that integrate technology, individuals, and processes across multiple disciplines
P16	Stakeholder engagement and community participation by highlighting behavioural change and improving awareness	Utilising smart technologies such as smart grids, IoT, AI, digital twin, and real-time monitoring technologies for effective predictive analysis is highlighted	The necessity of developing integrated policy frameworks and models as well as financing mechanisms is highlighted	Emphasis on data-driven decision-making through real-time monitoring, impact assessment, and AI-driven analysis	The framework is a conceptual model for transforming metropolitan regions into smart net-zero cities focusing on urban decarbonisation through the integration of smart technologies, renewable energy systems, and stakeholder participation	The complex interaction between smart city sectors is acknowledged without integrating the systems approach in the proposed framework
P17	The importance of citizens' engagement through improving awareness, education, and digital tools	Utilising smart technologies to manage the data lifecycle and develop digital solutions	Limited discussion about the process	Focus on data-driven decision-making in governance and performance monitoring	A conceptual framework for transforming towns into green smart cities by utilising technology, citizen interaction, and process optimisation by proposing some steps for people, technology, and processes	The city is acknowledged as an interconnected system of processes, technology, and citizens
P18	People's behavioural change and acceptance and the participatory governance models	Emphasis on integrating smart city technologies and utilising digital tools for real-time monitoring	Limited discussion about the process	Digital decision-support system and real-time monitoring through data analysis	A step-by-step framework, including strategic stages, design stage, and assessment stage, integrating smart technologies, stakeholders, and a governance and data-driven decision-making system	Systems thinking acknowledges the necessity of cross-sectoral integration and feedback analysis
P19	People engagement and behavioural change through improving lifestyle choices and inclusive governance	Innovative technologies such as IoT, energy-efficient smart grids, and AI	Taxation reform, green business models, and improving governance frameworks	Some discussions on data-driven policies and regulations, AI predictions, real-time monitoring, improving connectivity between energy networks, digital grids, and AI-based predictions	Including seven pillars: energy efficiency, renewable energy integration, clean transportation, smart infrastructure, bioeconomy, circular economy, and carbon capture	Systems thinking is applied through integrating technologies, policies, economy and people engagement, and cross-sectoral integration; also, a feedback loop between policies, technological innovations, and economy adoption is highlighted
P20	Citizens' engagement and stakeholders' participation through training and economic inclusion with a focus on health benefits for all communities	Integration of technological innovations such as smart grids, AI, and energy management systems, highlighting carbon capture, renewable energy, electrification and hydrogen integration, and research and development solutions for the clean transformation	Some discussions around integrating financial, regulatory, and market systems, along with the industrial process transformation	Emphasising data-driven decision-making in energy, transportation, emission monitoring, and policy evaluations	A cross-sectoral framework focusing on electricity decarbonisation, electrification, energy efficiency, reducing methane and improving CO_2 removal through policies, innovative technologies, and local authorities' and citizens' participation	Systems thinking is highlighted by identifying the interdependencies and cross-sectoral integration between city sectors, and feedback loops between policies, technologies, and industry

Table 4. *Cont.*

	Digital Transformation				Framework/Model/Roadmap	Systems Thinking
	People	**Technology**	**Process**	**Data**		
P21	Citizens' engagement and behavioural change, local actions, developing skills, ensuring equality in transformation, and improving green choices	Utilising smart technologies such as AI, IoT, and digital infrastructure, clean energy technologies, carbon capture technologies, and digital monitoring	Regulation reforms, green business models, improving process efficiency through process automation, digitalisation, and carbon pricing	Data-driven decision-making, real-time monitoring, and predictive analysis for policy refining	A cross-sectoral framework highlighting renewable energy integration, zero-emission industry, green transportation, smart buildings, sustainable management of urban resources, and investment in innovative solutions	The cross-sectoral interdependencies and feedback loops between governance, technologies, and economy are recognised
P22	Stakeholders' participation and behavioural change, including citizens, businesses, and government, as well as training programs for workforce and improving public health and the local economy	Electrification and renewable energy technologies, digital infrastructure, smart technologies such as smart grids, carbon capture and energy storage systems, AI-driven solutions for energy consumption management and monitoring	Some discussions on industrial process transformation, policy, and finance system reform	Advocates for data-driven energy efficiency, predictive analysis for demand forecast and urban planning, real-time tracking of emissions and energy, and AI-driven decision-making	Including two phases, the Announced Pledge Scenario for reaching net-zero by 2060 and the Accelerated Transition Scenario for a faster decarbonisation process emphasising renewable energy integration, improving energy efficiency and carbon capture in industry, transportation electrification and decarbonisation, building electrification, retrofitting, and integrating district heating	Sectoral interdependency is recognised, highlighting feedback loops between government policies, investment, and innovative solutions, emphasising cross-sectoral collaborations

Table 5. Thematic analysis results (✓ shows that the theme included in the paper, – represent that the theme is not included in the paper).

Paper Code	Themes							
	Net-Zero City	Smart City	Digital Transformation				Framework/Model/Roadmap	Systems Thinking
			People	Technology	Process	Data		
P1	✓	✓	–	–	–	–	✓	✓
P2	✓	✓	–	–	–	–	✓	✓
P3	✓	✓	–	–	–	–	✓	✓
P4	✓	✓	✓	–	–	–	✓	✓
P5	✓	✓	–	–	–	–	–	✓
P6	✓	✓	–	✓	–	–	✓	✓
P7	✓	✓	–	✓	–	–	–	✓
P8	✓	✓	–	✓	–	–	✓	–
P9	✓	✓	–	✓	–	–	✓	✓
P10	✓	✓	–	✓	–	✓	–	–
P11	✓	✓	–	–	–	✓	✓	–
P12	✓	✓	✓	✓	–	✓	✓	✓
P13	✓	✓	–	✓	–	–	✓	–
P14	✓	✓	–	✓	–	✓	✓	–
P15	✓	✓	–	✓	✓	✓	✓	✓
P16	✓	✓	–	✓	✓	✓	✓	✓
P17	✓	✓	–	✓	–	✓	✓	✓
P18	✓	✓	–	✓	–	✓	✓	✓
P19	✓	✓	✓	✓	✓	✓	✓	✓
P20	✓	✓	✓	✓	✓	✓	✓	✓
P21	✓	✓	✓	✓	✓	✓	✓	✓
P22			✓	✓	✓	✓	✓	✓

Results

The results of the overview of the focused documents indicate that smart cities and net-zero cities are the key themes that have been discussed. Some research studies underscore single-sector interventions, while others promote integrated, cross-sectoral solutions through a systems thinking approach.

Several studies concentrate on implementing interventions to reduce carbon in specific urban sectors, proposing strategies like the incorporation of EVs and heat pumps. For example, P18 emphasises the significance of electric vehicles in mitigating emissions in urban transportation, particularly when integrated with energy from renewable sources. Likewise, P2 highlights the significance of decentralised energy alternatives, such as heat pumps, to improve energy efficiency in building heating systems or smart environmental energy monitoring systems to manage energy consumption as proposed in P5. These interventions effectively address sectoral energy demands; however, while each sector functions independently, they are mutually impacting other city sectors that must be considered for a systemic transformation.

On the other hand, some studies employ a more holistic approach, advocating cross-sectoral interventions leveraging interdependence in the urban system. For example, P8 proposes district energy that combines low heating, cooling, and electricity to improve energy system efficiency. P17 explores waste-to-energy solutions that convert urban waste into heat or electricity. Another example of cross-sectoral interventions is the adoption of the circular economy, which has been proposed in P6. A digital twin for simulating the urban energy system in real-time is proposed in P18. These techniques indicate that achieving smart net-zero cities requires a systematic design of interventions to exploit synergies and mitigate inefficiencies across urban sectors.

However, there is a significant gap in the utilisation of systems thinking to formulate an effective transformation towards smart net-zero cities. Although some studies present cross-sectoral interventions—such as digital twin implementation for managing urban energy systems, improving the waste-to-heat system, or circular economy, there is a lack of investigation into interventions that holistically address all the systems thinking elements (independency, connectivity, evolution, emergent behaviour, and dynamic complexity) of urban systems. A few of them attempted to address the systemic approach by proposing interventions that involve multiple sectors (emergent behaviours in systems thinking) rather than single-sector interventions. This is despite the significant emphasis on delivering system thinking through many papers. The lack of integrating systems thinking for understanding the city system's behaviour will result in isolated interventions rather than holistic solutions that can optimise the resources and maximise the efficiency across urban sectors.

Digital Transformation Elements: Examining the studies through the digital transformation elements (people, technology, process, and data) indicates that the majority of studies generally mention these digital transformation elements without providing a detailed explanation of how to effectively integrate and resolve them. This demonstrates a significant gap as effective digital transformation necessitates a harmonious and integrated combination of the elements, enabling a balanced digital transformation approach.

Some studies highlight the significance of public participation and changing behaviours as crucial elements of successful digital transformation. For example, the Cities4ZERO methodology proposed by P18 incorporates substantial community engagement, involving local stakeholders in planning and continuous monitoring, establishing a sense of responsibility for cities' journeys towards decarbonisation. Similarly, the GreenCoin system discussed in P6 encourages citizens' accountability for emissions, which strengthens people-driven climate action. Some studies highlighted the significance of process change in this field. For example, P17 promotes ongoing process adaptation as cities progress through digital transformation phases, with each phase necessitating changes in processes to reduce carbon emissions in smart cities.

Most of the studies emphasise technological developments as the main driver for the digital transformation towards smart net-zero cities. Technologies such as IoT, AI, and smart energy systems provide the foundation for solutions like smart grids, EV integration, and energy-efficient building systems. For example, P7 discussed how machine learning algorithms can be employed to monitor air quality and estimate energy demand. According to P6, AI-based models monitor traffic, optimise transportation flow, and provide predictive abilities to improve utilising the alternative modes of transportation, reducing energy consumption.

Although data are essential for smart cities, a limited number of studies specifically address the data role in advancing urban decarbonisation. Some investigations emphasised AI-enabled solutions and machine learning in cities, demonstrating how data analytics may enhance urban systems by forecasting energy consumption, monitoring air pollution, and providing effective utilisation of urban resources. However, the lack of focus on the effective utilisation of data lifecycle in forming digital transformation highlights a fundamental gap in the research, particularly in how cities should employ data to make adaptable, informed decisions for cities to move towards smart net-zero cities.

4. Discussion

Reviewing the literature indicates a significant lack in the effective integration of the four components of digital transformation—people, technology, data, and processes—with a systemic approach for smart net-zero cities implementation. While many studies suggest frameworks for developing smart net-zero cities, there is a need for more investigations into providing comprehensive frameworks that thoroughly integrate every element of digital transformation with systems thinking elements. A systematic framework could enable cities to move beyond isolated changes, fostering a holistic understanding of the urban ecosystem, which supports a complex balance between people, technology, processes, and data. Figure 3 represents the proposed framework in this study that attempted to address the discussed issue related to smart net-zero city development.

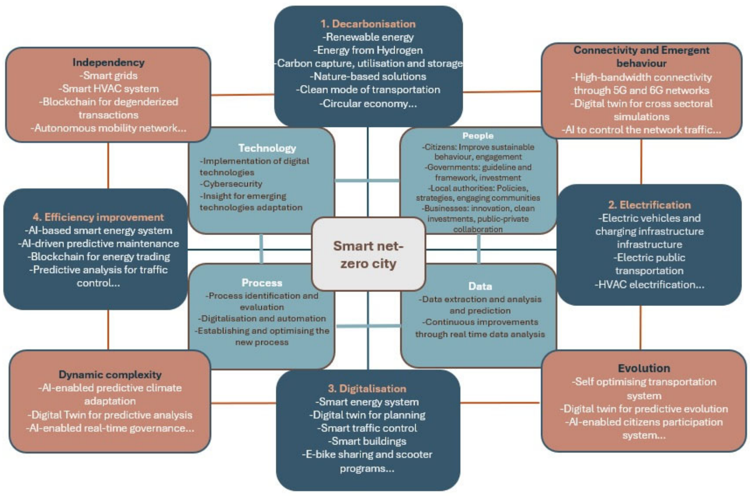

Figure 3. The proposed smart net-zero city integrated and multi-layered framework includes digital transformation elements (technology, people, data, and process), four key categories of key interventions (decarbonisation, electrification, digitalisation, and efficiency improvement) and systems thinking components (independency, connectivity, emergent behaviour, evolution, and dynamic complexity). Source: Developed by the authors.

4.1. Integration of Digital Transformation Elements

The proposed framework represents the digital transformation elements and provides a comprehensive understanding of their requirements and components (Figure 3). While technology has received the most attention in the reviewed investigations, it still needs to be explored more. The main focus of the reviewed papers was implementing new technologies such as smart technologies, while some measures such as cybersecurity and insight for utilising emerging technologies for the future, can be considered as another important component of the technological element of digital transformation (Morze & Strutynska, 2021 [24]), are overlooked. Implementing appropriate cybersecurity protocols will prevent vulnerabilities, safeguarding the system's resilience and users' privacy. Also, continuous assessments of innovative technologies are necessary to ensure the readiness to adopt future trends that need to be considered in the technology element of digital transformation [139], (See Figure 3).

People as another element of digital transformation gained some focus in the literature. However, people as stakeholders need some clear categorisations that clarify the responsibilities and components of each category. Citizens as the biggest category of stakeholders need to improve their engagement and practice sustainable behaviour through their daily choices. Governments are required to improve investment in the sustainable development of cities and develop governance guidelines and frameworks to implement the strategies. These strategies enable local authorities to effectively engage local communities and citizens. Local communities can support seamless transformation by conducting educational campaigns and encouragement programs to improve participation and provide green practice choices. Businesses are required to utilise innovation, investing in clean technologies and energies, alongside enabling effective collaboration between public and private sectors.

Data as an essential element of smart net-zero cities' digital transformation needs to be discussed through their lifecycle, including data collection, explanations, analysis, and predictive decision-making. Most of the investigations concentrate on the predictive analysis of the role of data in digital transformation. However, it is crucial to gain more understanding of the tools, techniques, requirements, regulations, and policies regarding data collection, explanations, analysis stages, and challenges, alongside data security measures in digital transformation [122].

Process as the final element of digital transformation requires specific components to be effectively covered and addressed. It is crucial to understand that implementing new technologies requires changing and adopting the process according to the new specific requirements. The components of the process of digital transformation include the process of identification and evaluation and establishing a new process [29]. In process identification and evaluation, the existing process will be assessed to identify any requirements for improvement or replacement. This stage will determine if the process needs any optimisation, digitalisation, automation, or entire replacement [24]. Then, a new process will be established to maximise efficiency in the adaptation of new technologies.

4.2. Four Main Elements of Smart Net-Zero City Interventions

While the literature attempted to discuss various interventions for smart net-zero cities, there is no practical categorisation of the interventions, which has led to a heterogeneous approach and inconsistency in the proposed frameworks. This research provides four main categories of smart net-zero city interventions and integrates them into the framework, including decarbonisation, electrification, digitalisation, and efficiency improvement that need to be implemented and integrated into a sequence (Figure 3). Decarbonisation refers to all the interventions that contribute to carbon reduction in the city. Renewable energy integration, energy from hydrogen and carbon capture, utilisation, and storage are some examples of this category.

The interventions that are categorised in electrification aim to replace fossil fuel-based operations with clean electricity. Examples can be electric vehicles, charging infrastructure, and public transportation electrification. Digitalisation is the next step, which refers to the process of integrating digital technologies into city services and sectors such as smart energy systems and the digital twin for planning and smart traffic control.

The last stage is efficiency improvement, which advocates for utilising emerging technologies such as AI and blockchain to enhance the efficiency of the implemented digital technologies. Examples can be integrating AI in energy systems, predictive maintenance in the city sector, and services monitoring.

4.3. The Integration of Systems Thinking Elements

As it has been discussed, systems thinking has mainly been assessed in the literature through the necessity of considering the interconnection and cross-sectoral interventions (connectivity and emergent behaviour). However, cities as a complex system can be examined through a comprehensive systemic view that includes all the systems thinking elements (independence, connectivity, emergent behaviour, evolution, and dynamic complexity). Figure 3 represents how these elements can be integrated into the smart net-zero city framework.

Independency as the first element of systems thinking in digital transformation represents how each sector and service in the city (as the complex system elements) are capable of independently operating and managing themselves to move towards the smart net-zero city objectives (the systems aim). This element can be considered as the single-sector interventions such as smart grids for the energy sector, autonomous electric vehicles for transportation, and smart HVAC systems for the building sector.

Connectivity refers to the interconnection and interdependency between city system elements that facilitate effective connection. The 5G and 6G network for high bandwidth connectivity is an example of this element in the city system. Emergent behaviour is defined as any behaviour that arises from the connectivity between the city system elements. Cross-sectoral interventions and real-time collaborations such as implementing a digital twin for cross-sectoral simulations can be considered in this category, which will enable effective collaboration between the sectors.

Evolution explains how each subsystem continuously develops and evolves. Some city services and interventions can be categorised in this category such as self-optimising transportation systems and digital twins for predictive evolution.

Dynamic complexity as the final element of systems thinking refers to the unexpected behaviour in the systems. This element can be achieved through some interventions, such as a digital twin for predictive analysis and AI for predictive maintenance.

5. Conclusions

The critical value of implementing comprehensive digital transformation and systems thinking in achieving the goal of smart net-zero cities is underscored in this state-of-the-art review. The examination of resources highlights that, although several frameworks are available, mainly with theoretical applications, the majority do not provide a comprehensive strategy that adequately harmonises the fundamental components of digital transformation—people, technology, data, and processes—across complex city systems.

This gap proves the necessity for developing a practical digital transformation framework integrated with system thinking that harmonises technology, people, processes, and data to improve efficiency and sustainability.

5.1. Contributions of This Research

This research provides the following contribution to the field of digital transformation for smart net-zero cities. Firstly, it offers a structural approach that presents the required stages that need to be followed for the city interventions, including decarbonisation, electrification, digitalisation, and efficiency improvement. This categorisation can serve as a strategic guideline for policymaking, urban planning, and research. Secondly, although most of the review papers mainly concentrate on single-sector interventions for smart net-zero cities, this research advocates a holistic approach that integrates the main elements of systems thinking into the city transformation, emphasising independency (single-sector interventions), connectivity and emergent behaviour (city connection infrastructure and cross-sectoral interventions), evolution (continuous development of city services and interventions), and dynamic complexity (unexpected city system behaviour).

Thirdly, most of the studies offer a few components of digital transformation elements (people, technology, process, and data), that are required to be investigated. However, this study took a step further and proposed more components for each element. These components represent all the measures that are necessary to take in each element, facilitating a more comprehensive view of the digital transformation elements.

5.2. Limitations of This Study

There are some limitations related to this research that can be investigated in future research. The first limitation is that the proposed framework is not validated through a case study or real-world implementation that is required to support the framework's applicability in cities' digital transformation. Furthermore, this research advocates for integrating a systemic approach through the highlighted system thinking elements. However, the practical challenges related to this integration in real-world applications need further analysis and research.

5.3. Recommendations for Further Research

Several directions can be recommended for future research in this area. First, more research should be conducted to analyse the proposed framework's feasibility in real urban applications. Also, there is an opportunity for future investigations to transform the proposed framework into a practical, step-by-step roadmap that can be utilised as an implementation guideline in cities. Finally, future studies can investigate the systemic transformation in cities by attempting to address how city sectors, services, and interventions can be independently operated while interconnected. For this purpose, they can analyse the application of systems thinking elements through emerging technologies such as artificial intelligence for predictive maintenance and digital twins for real-time simulation of urban systems.

Author Contributions: Conceptualisation, V.J., H.S., F.M.J. and M.M.G.; Methodology: F.M.J.; Investigation, F.M.J.; Original draft preparation, F.M.J.; Review and editing, V.J.; Supervision, V.J., H.S. and M.M.G.; Project administration, V.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study did not require ethical approval.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the findings of this study are available from publicly accessible sources. All relevant references have been cited in the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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