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REVIEW

Blockchain technology as an enabler for cross-sectoral systems integration for developing smart sustainable cities

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Abstract

Smart cities driven by modern technologies are the need of the day to alleviate the urbanisation challenges and improve the overall experience of the citizens. As the role of data-sharing to facilitate systems integration across city sectors for developing smart cities has grown ever so profoundly, there is a need for decentralisation, transparency, and openness in terms of integration of city sectors to have efficient data diffusion among them. This is extremely important as the requirements of smart sustainable cities are open data sharing to allow service providers to better serve the citizens. Blockchain technology offers these characteristics with the extremely important added advantage of maintaining data security via an immutable record. However, the notion of the use of Blockchain for smart sustainable cities is still in the early years and requires extensive efforts to research and test it. In this research, a state-of-the-art review is conducted to explore the usefulness of Blockchain technology in smart sustainable city development with a specific focus on cross-sectoral systems integration, highlighting the gaps in the existing body of knowledge. This leads to the proposal of a novel framework for the use of Blockchain for smart sustainable cities, linking together service providers and citizens.

KEYWORDS

blockchain, data sharing, smart cities, smart city development, sustainable, systems integration

1 | INTRODUCTION

In November 2022 the world's population reached 8 billion people [1]. The rapid rate of urbanisation depicted in a study by the United Nations suggests that by 2050, 68% of the world population will be residing in cities which is a 55% increase in urban population as compared to 2018 [2]. This tremendous growth in population and that too in specific urban areas pose great challenges in terms of transportation, public safety, health, education, jobs, housing etc. These city systems need to be smart with proper planning and management and must ensure that sustainable measures are taken place in order to cope with these challenges [3].

To reap the benefits of smart cities in a true sense, it is of extreme importance that the different sectors within a city can freely communicate with each other and are able to disseminate data. For a pragmatic deployment of a smart city, data sharing is one of the basic requirements [4]. Traditionally, smart city designers have always been considering a centralised policy in terms of data sharing with all 'read' and 'write' transactions being done on a centralised server. This structure is likely to be opposed by city sectors and agencies mainly because of privacy issues, as well as their willingness to share. Moreover, the structure is prone to a threat by hackers as well as poses a single point of failure as all operations and controls are done on a single centralised node [5]. Even from a cost-benefit perspective, the implementation of a centralised server is much more costly in terms of initial deployment as well as maintenance as the number of connected devices continues to grow [6].

[7] emphasise that Blockchain technology eradicates the need for a centralised entity between the contributor systems and gives all the nodes equal opportunities to control and manage the overall operations of the network. The main aim is to develop completely autonomous and decentralised

applications which are capable of executing secure transactions using an encrypted algorithm. In addition, this technology also allows storage of the data on the distributed nodes instead of a central server. Blockchain has become increasingly important and relevant because of its advantageous qualities such as audibility, transparency, immutability, and decentralisation, hence, blockchain has what it takes to be the next technology enabler in order to provide fast, secure, and open infrastructure [8]. After enabling the digital cryptocurrency market for a couple of years, Blockchain technology has shown numerous capabilities to be used as a basic technology enabler for multiple applications like smart grid [9], transport and logistics [10], financial [11], and health care [12]. Another aspect of the use of Blockchain is the automation of various steps for the manufacturing industry, the features like decentralisation, distribution, transparency, and traceability [7].

In traditional systems, smart city devices such as sensors, cameras, and other connected devices, collect data and store it on a central server, where it is stored for processing and analysis. This central server is typically owned and operated by the government or other stakeholders involved in the management of the city infrastructure. The data collected may include information on traffic patterns, air quality, energy consumption, waste management, and other aspects that impact the city's sustainability and liveability. However, this approach has several limitations. Firstly, it can be costly to maintain and manage a centralised server infrastructure. Secondly, the central server may not be able to handle large amounts of data in real-time, leading to delays in processing and analysis. Additionally, there may be concerns around data privacy and security, as sensitive information is stored in one location, making it a prime target for cyber attacks. It means that smart city devices and central servers are vulnerable to a variety of threats, including the leaking of sensitive information because of hacking [3].

Blockchain technology has the potential to address these issues by providing a decentralised system for storing and managing data. In a blockchain-based smart city system, data collected by smart devices is stored in a decentralised ledger, making it more secure and private. Additionally, blockchain technology can enable secure and efficient transactions between smart devices and other entities in the smart city ecosystem, such as service providers and government agencies. Therefore, the use of blockchain technology in smart city development can lead to more secure, efficient, and transparent systems. Blockchain is a decentralised, widely available, and irreversible distributed database that has eliminated the need for a central authority to manage transactions. Even though there is a lot of literature available on smart cities and blockchain, however, there is very little insight available on the use of blockchain for smart sustainable cities. Furthermore, when we focus on cross-sectoral systems integration for smart cities, the availability of literature becomes very scarce specifically where Blockchain technology is used as an enabler. [13] endorse the fact that the literature available for smart cities development specifically focusing on systems integration is not enough and have therefore taken an approach to consider cities like enterprises and have tried to focus on the same model of enterprise systems integration (ESI). The gap in this underpinning concept of the use of Blockchain for smart sustainable cities development focusing on inter-systems/cross-sectoral integration is evident as either the Blockchain technology till now is being researched to fulfil one sector of a smart city at a time or used as one of the technologies to enable smart cities along with internet of things (IoT), Big Data, Artificial Intelligence etc. However, for a future-proof smart sustainable city, multiple sub-systems must collaborate in order to serve their customers with high-quality and real-time services [14]. Therefore, it is of critical importance to explore the use of Blockchain technology as an enabler to bridge the silos existing in different sectors (systems) in a smart city. As explained earlier, these silos can hinder efficient data sharing and collaboration between different systems, leading to suboptimal performance and decision-making. Blockchain technology offers a potential solution to overcome these silos and enable cross-sectoral integration. By providing a decentralised platform for data sharing and collaboration, blockchain can facilitate the creation of a unified, transparent, and secure database for all systems in a smart city. It can facilitate seamless data sharing and collaboration between different systems, leading to more effective decision-making and improved overall performance of the city.

Nevertheless, despite the growing interest in the use of blockchain technology for smart city development, there is a limited understanding of the state of our knowledge and a comprehensive view of the research that has already been conducted in this field. Hence, there is a need for a state-of-the-art review of the existing literature to identify the gaps and limitations of previous studies and to develop a comprehensive understanding of the potential of blockchain technology for smart city development. Such a review will help to address the current lack of clarity in the field and pave the way for future research that can advance our understanding of this emerging area. This project will review the recent literature available on this subject and will set the stage for future research aspects keeping in view the gaps that would become clearer as an outcome of the state-of-the-art literature review.

1.1 | Research background

Numerous studies have examined the interplay between Smart Cities and Blockchain, with a plethora of publications delving into their respective architectures, frameworks, implementation, and use cases. Despite these efforts, the extent to which Blockchain can serve as a critical component in the creation of smart, sustainable cities remains a relatively nascent inquiry. Moreover, when cross-sectoral integration is brought into the equation, the availability of literature on this subject diminishes significantly. As such, this section aims to commence by exploring recent literature that covers the fundamentals of smart cities and blockchain, laying a foundation for a more comprehensive review.

1.1.1 | Smart sustainable cities

The term is used all around the world with various taxonomies, contexts, and meanings. A variety of conceptual versions are easily constructed by substituting the word 'smart' with adjectives such as 'digital' or 'intelligent' or 'urban' or 'knowledge'. Several definitions have been proposed by authors (see Table 1) and have been proposed and accepted for usage in both practical and academic settings. The table shows both the definitions that are relatively older as well the more up-to-date definitions considering ICT as an enabler for smart cities.

In addition, several frameworks have been developed for smart cities and we have reviewed them. For example, [17] built an integrative framework to describe the linkages and impacts between these characteristics and smart city projects (Figure 1). They have identified 8 factors that impact the model,

TABLE 1 Smart cities definitions.

Definitions of a smart city	Reference	Type
'A city well performing in a forward-looking way in economy, people, governance, mobility, environment, and living, built on the smart combination of endowments and activities of self-decisive, independent and aware citizens'	[15]	Traditional
'The use of smart computing technologies to make the critical infrastructure components and services of a city, which includes city administration, education, healthcare, public safety, real estate, transportation, and utilities more intelligent, interconnected, and efficient'	[16]	Traditional
"A city striving to make itself 'smarter' (more efficient, sustainable, equitable, and liveable)"	[17]	Traditional
'Smart city does not have an absolute concept, rather, it is interpreted as a process towards creating a sustainable and resilient city'	[18]	Modern
'The smart city refers to a local entity, that is, a distinct city, region or small locality which takes a holistic approach to employ information technologies with real-time analysis that encourages sustainable economic development'	[19]	Modern
'The smart city is a territory with a high capacity for learning innovations, built on the creativity of its residents, their knowledge development, and their digital infrastructure for communications and knowledge management'	[20]	Modern
'Smart city has high productivity as they have relatively higher educated people, knowledge-intensive jobs, output-oriented planning systems, creative activities and sustainability-oriented initiatives'	[21]	Modern
'A system of systems in which cross-sectoral city systems integration has been accomplished, enabling access to real-time information and knowledge by all the city sectors, providing integrated services, and enhancing liveability, workability, and sustainability for the citizens'	[22]	Modern
'A smart city is a sustainable city that solves urban problems and improves citizens' quality of life through the fourth industrial revolution technology and governance between stakeholders'	[23]	Modern

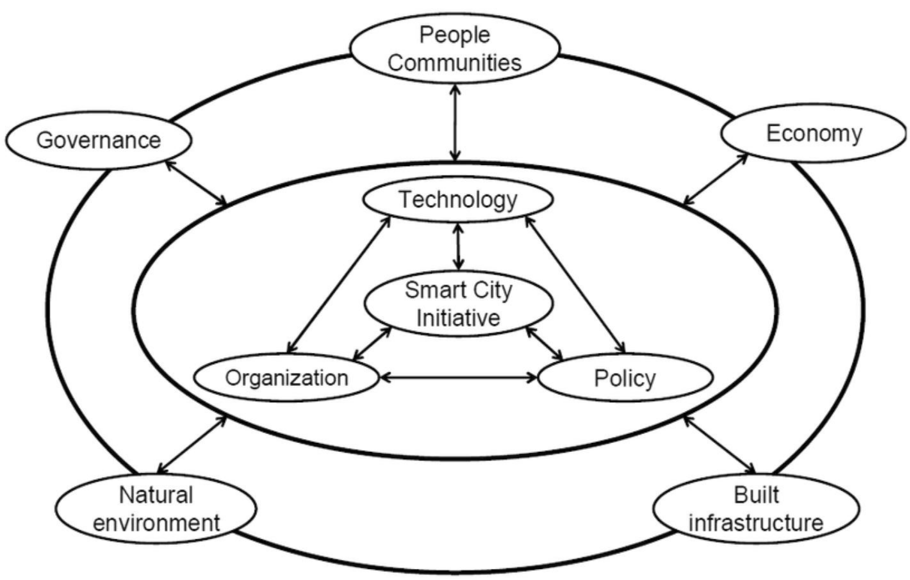

FIGURE 1 Smart city initiatives framework - *Source*: [17].

application and use of smart city initiatives. All these factors are influencing in one way or another to each other which is depicted in two-way arrows in the diagram. The inner circle shows the factors that are more influential than the ones mentioned in the outer circle. Among all these factors, technology is the most important factor which is impacting all other factors as most of the initiatives for smart cities are heavily dependent on the use of technology.

ASEAN smart cities framework specifically developed by ASEAN member countries [24] includes three core outcomes as follows: quality of life, economy, and sustainable environment (Figure 2). The framework is a layered architecture that sheds light on the factors of enablers in terms of infrastructure and funding, diverse focus areas covering all aspects of citizens' needs in a smart city, and enforcing a governance layer as well. The framework can be considered one of the few smart sustainable city frameworks.

The PAS181 [25] is also a framework covering aspects of people, process and technology, however, this by far is the most comprehensive framework as it goes the extra mile as compared to other frameworks listed above and covers dimensions like success factors and benefits realisation strategies (Figure 3).

Upon examining the prevailing definitions and frameworks pertaining to smart and sustainable cities, it becomes evident that the integration of systems across various sectors necessitates the vital aspect of data sharing. However, as previously elucidated, the preservation of data privacy and security poses a substantial challenge that must be effectively confronted. This is primarily due to the extensive collection, processing, and sharing of vast amounts of sensitive data across interconnected systems and from various applications for delivering meaningful services. Hence, the protection of this data becomes paramount to safeguard citizen privacy, preserve the integrity of critical infrastructure, and mitigate the risks posed by cyber threats [26]. Robust encryption techniques, secure storage systems, and access control mechanisms are essential to safeguard sensitive data from unauthorised access and breaches. Additionally, measures like data anonymisation and de-identification techniques help protect individual privacy while allowing for meaningful analysis and utilisation of the collected data.

Research in this field has addressed these security concerns and proposed solutions to ensure the protection of smart city systems. For example, the authors in refs. [27, 28] highlight the importance of addressing security concerns in smart cities. Shankar et al. [27] propose the Secure Smart City Infrastructure using Blockchain and Deep Learning framework, which combines blockchain and deep learning to ensure privacy and trustworthiness in IoT communication. The framework demonstrates high security, low latency, and efficient resource utilisation, offering significant benefits for smart city infrastructure. Another research [29] explores the concept of the smart city, characterised by its IoT infrastructure and intelligent systems. They argue that while smart cities offer various benefits, security and privacy concerns arise due to the collection of sensitive information and control over city facilities. The article investigates security and privacy challenges in smart city applications, focusing on healthcare, transportation, and smart energy. It also presents research efforts to address these challenges and identifies open issues for future research, which fits well with the purpose of our research. Study conducted by the authors in ref. [30] also explain that while smart cities bring convenience and improved experiences, they also

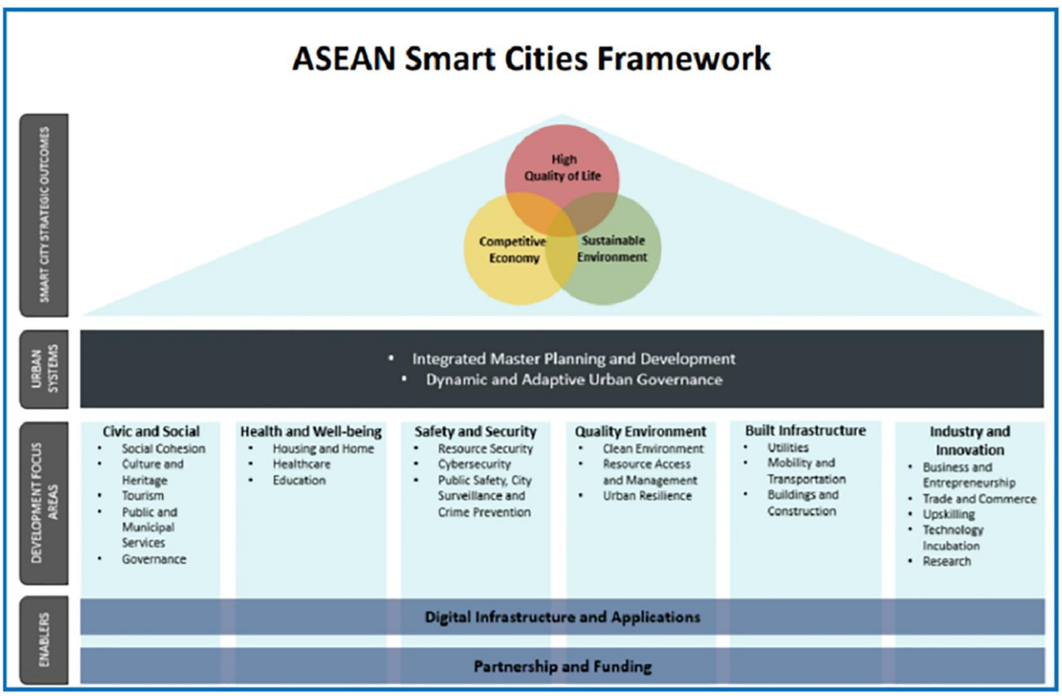

FIGURE 2 ASEAN Smart Cities framework - *Source*: [24].

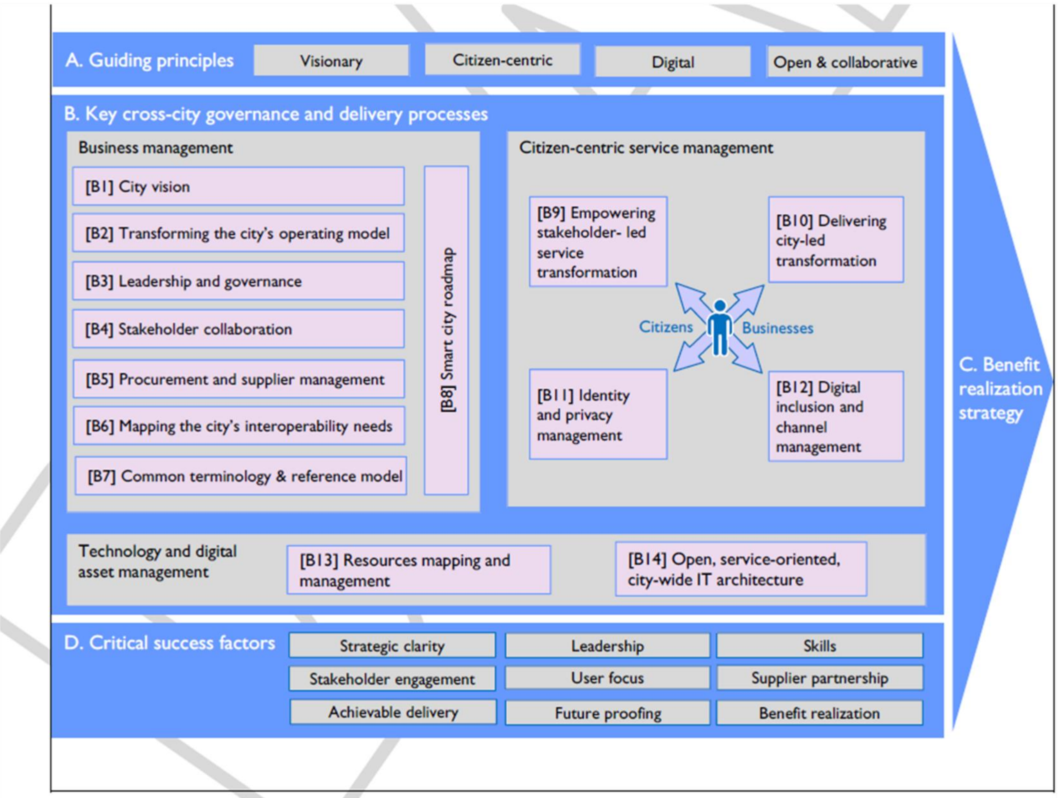

FIGURE 3 High-level SCF [PAS 181]—*Source*: [25].

pose threats such as information leakage and cyber attacks. The paper provides an overview of smart cities, cyber security, and deep learning concepts. It also reviews various deep learning models and explores their applications in cyber security within smart cities. The paper concludes by discussing the future development trends in smart city cyber security. Accordingly, Farahat et al. [31] propose a system for securing WiFi-based data transmission in smart cities, employing encryption and encoding techniques to control data access and protect citizen data and maintain their privacy throughout the data transfer process. Furthermore, Toh [26] has comprehensively explained the necessity of ensuring security in smart cities. To ensure the security of data, the author has explained that several measures can be implemented, such as access control, encryption, authentication, data signatures, and privacy protection. Different types of data in smart cities, including transport, health, finance, utility, and telecom, require specific security measures. He has also highlighted that data breaches in recent years have emphasised the need for robust data protection policies and frameworks, with governments taking responsibility for safeguarding a significant portion of the data. Accordingly, the European Union introduced regulations like the General Data Protection Regulation, while the United States has enacted laws such as the Electronic Signatures in Global National Commerce Act (ESIGN) and the Homeland Security Act. These legal measures, alongside technological solutions, are essential for ensuring data security and compliance in smart cities.

The strength of blockchain technology lies in its utilisation of public-key encryption and consensus protocols to verify transactions and authenticate a decentralised ledger, eliminating the need for a centralised authority. Hence, Blockchain technology has the potential to provide a secure and decentralised platform for cross-sectoral data sharing, addressing some of the challenges in maintaining data integrity and privacy in smart city applications [26].

1.1.2 | Blockchain

Zheng et al. [32] emphasise that Blockchain is a public ledger where all entered transactions are kept as a list of blocks, it has distributed consensus and encrypted information in order to have a secure flow of information inside the network. Decentralisation, persistence, and anonymity are a few of the critical factors which make this technology incredibly safe and secure to operate on. Shen et al. [33] emphasise that blockchain provides a network of independent nodes which reach a consensus conclusion within themselves, therefore, eliminating the need for a central authority. There has been a remarkable evolution of Blockchain over the years, since its inception when it was primarily used for financial transaction, the technology has really evolved to be useful in many other applications, this evolution of Blockchain from phases 1.0–5.0 are defined from a number of distinct perspectives including functionality, features, strengths, security issues which are addressed and are applications which are served [7]. These evolution stages are summarised in Figure 4.

Typically, a Block inside a Blockchain consists of the following components, mentioned in Figure 5.

Table 2 shows each component with its characteristics.

Mingxia et al.[34] highlight the importance of the use of consensus algorithms within a Blockchain network, as the main driving force behind the quick adaptability of Blockchain is the inherited nature of decentralisation and distribution, however, as there are many nodes involved to create the peer network, the chance of eavesdropping and malicious attack is very high, therefore, the use of a strong and effective control mechanism

TABLE 2 Block components [32].

Component	Characteristics
Block version	Indications set of block validations rules to follow
The Merkle tree root hash	A hash value of transactions
Timestamp	The current time as compared to Jan 01, 1970
nBits	Target threshold of a valid block hash
Nonce	A field that increases its 4-byte value with every hash calculation
Parent block hash	A 256-bit hash value that links to the previous block

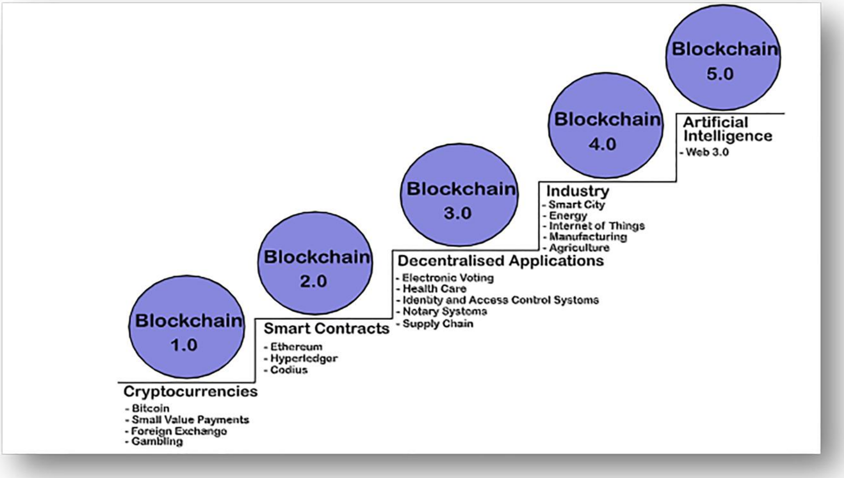

FIGURE 4 Blockchain evolution—*Source* [7].

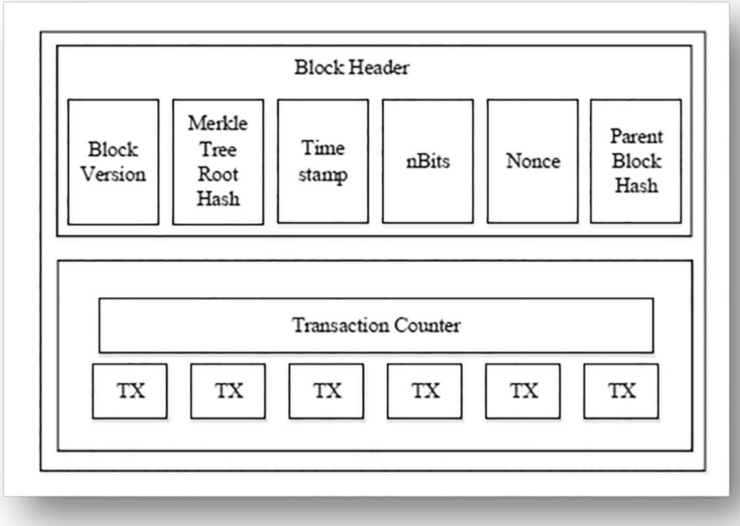

FIGURE 5 Block components—*Source*: [32].

through the use of consensus algorithm is necessary to maintain the integrity of the overall transactions of the Blockchain. To maintain this there are several types of consensus algorithms summarised in Figure 6.

Based on the technologies, the main types of Blockchains are described in the Table 3.

1.1.3 | Blockchain and smart sustainable cities

Rawat et al. [36] emphasise that Blockchain can be applied where a need for a trusted third-party centralised ledger is not required, and a peer-to-peer arrangement of network nodes can handle the operations and management of transactions between the connected nodes. Looking at the development timeline of Blockchain shows that 2018 onwards have seen plenty of Blockchain applications in smart sustainable cities, cyber security, and real estate by using smart contracts, and Blockchain enabled governments in order to make the data available for the public ensuring trust and transparency etc. [37]. Some proposed applications of blockchain in smart cities include decentralised identity management systems, secure payment platforms for municipal services, resilient energy grids, peer-to-peer transport platforms, efficient waste management systems, streamlined government services through smart contracts, disruptive innovations in the insurance industry, and enhanced security for healthcare records [26]. In November 2018, Riad Salameh, the Governor of Lebanon's central bank, disclosed ongoing investigations into the potential implementation of a digital currency with the aim of fulfilling the same functions as Lebanon's national currency, the 'Lira'. Similarly, The Central Bank of Bahamas introduced the 'Sand Dollar,' a central bank digital currency, in 2017 to modernise the financial system, reduce operational costs, and improve transaction efficiency domestically [38]. Furthermore, Estonia has been at the forefront of distributed ledger technology adoption since 2012, successfully implementing it across diverse sectors such as healthcare, judicial and legislative services, personal data management, and identity verification. Other countries have also embraced blockchain technology for specific applications, such as Sweden for real estate transactions, the UK for grant distribution, Ghana for tamper-resistant property ownership records, Russia for secure trading and shareholder transactions, Singapore for trade invoice fraud prevention, and Korea for the development of a blockchain-based ecosystem within the banking sector. China has likewise made significant strides in leveraging blockchain technology, incorporating it into various domains ranging from education to legal frameworks, and actively supporting its own smart contract platforms such as TRON, NEO, VeChain, and Qtum [26, 38].

However, as explained by Toh [26], the Blockchain technology still holds great potential for revolutionising various aspects of smart sustainable cities, which are unexplored. It can offer the following principles:

TABLE 3 Blockchain types.

Blockchain type	Characteristics
Public	Open for all, any individual can check and verify the transaction, for example, bitcoin and ethereum
Consortium	Usually used in B2B models, not fully decentralised as the authority is for limited agreed users, for example, hyperledger and R3CEV
Private	Strict data access controls. Not open for participation for all the nodes.

Source: [35].

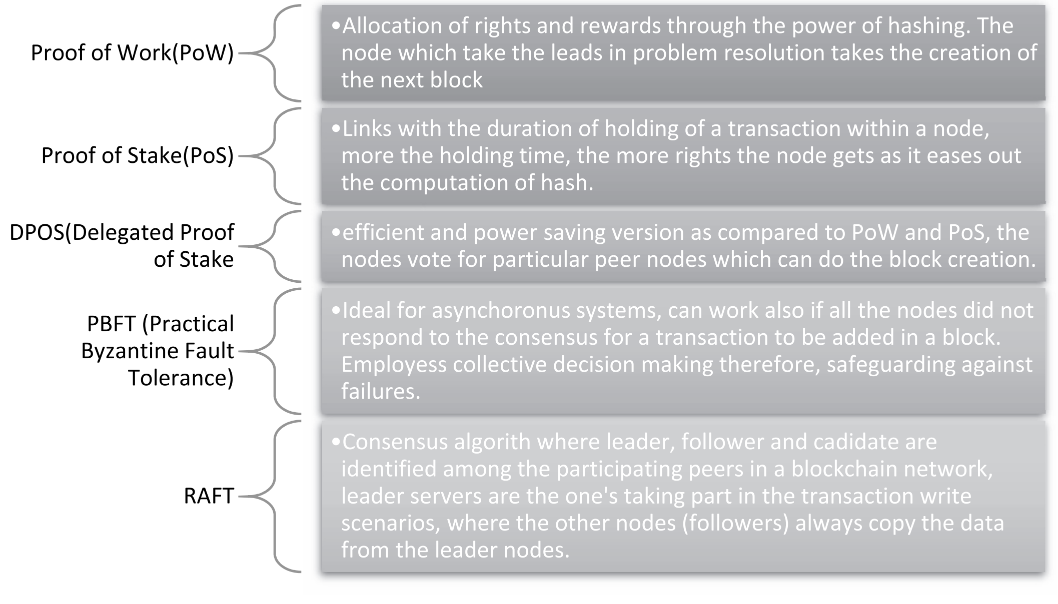

FIGURE 6 Consensus algorithms for blockchain.

- Transparency: everybody can access the records
- Democracy: consensus algorithms work together to allow a block to enter the chain.
- Security: no single point of failure
- Immutability: the shared ledger cannot be changed as all transactions are digitally signed.

Because of these benefits, the application of blockchain technology to smart sustainable cities can guarantee data integrity, encourage organisations and individuals to share data and make shared decisions, empower translucent management, and endorse the enactment and deployment of a trustworthy, secure, and democratised smart city. These are aligned with the following challenges in the development of smart sustainable cities, highlighted by [39]:

- Reliable data collection, maintaining the authenticity and anonymisation
- An exponential increase in the number of connected devices.
- Complexity and fluctuations in the number of connected devices call for decentralised management.
- Allowing citizens to participate requires transparency in how the data would be used.
- The sharing of M2M devices, organisational data, and personal data needs a trustworthy technological infrastructure

Hence, Blockchain technology may be able to offer a promising solution to these challenges, facilitating the implementation of smart city solutions using a secure and efficient data management system to ensure the privacy and security of citizens' data. For instance, since it is based on a distributed ledger system, it can store data in a tamper-proof and immutable way, making it ideal for managing sensitive data. Furthermore, blockchain technology enables smart contracts, which are self-executing contracts with the terms of the agreement directly written into lines of code, further improving transparency and efficiency.

Therefore, integrating blockchain technology into developing smart and sustainable cities can provide a secure and efficient data management system, enhance transparency and traceability, and facilitate decentralised decision-making. Furthermore, it can enable the creation of decentralised marketplaces for various services, providing citizens with a greater range of choices and promoting innovation.

However, the integration of blockchain technology into smart cities must be done carefully and thoughtfully. It requires an understanding of the potential applications and the areas of usefulness, such as cross-sectoral process change and data sharing across various sectors of a city, which are significant necessities for developing smart and sustainable cities [40]. In addition, it requires fully comprehending the challenges and limitations of the technology and careful consideration of the specific needs and requirements of smart city systems. However, the current knowledge regarding the amount of research work on these matters is scarce. In addition, very limited to no research has been conducted, guiding the integration of blockchain technology into smart sustainable cities to address these challenges and limitations. Moreover, the body of knowledge does not set the stage for future research and advancements in the use of Blockchain technology for developing smart sustainable cities. Hence, the main question of this research is formulated as follows:

'Would the existing literature offer sufficient knowledge to understand the usefulness of Blockchain technology for cross-sectoral systems integration in developing smart sustainable cities?'

1.2 | Aims and objectives

As we progress and discuss the future of smart cities, emphasis on sustainability, interconnectivity, and cross-sector communication becomes more prudent, without which it would be difficult to fulfil the end-user expectations in a smart sustainable city. Therefore, this research aims to understand the state of the current literature regarding the use of Blockchain technologies for developing smart sustainable cities with a focus on cross-sectoral systems integration. To fulfil this aim, the following objectives are addressed in this study:

- To conduct a state-of-the-art review of the literature regarding the utilisation of blockchain in developing smart sustainable cities, especially for data sharing for the purpose of cross-sectoral systems integration, by
    a. Identifying the most effective search terms to find relevant literature for review
    b. Identifying the publication trend to realise the earliest publication year for conducting the review
    c. Formulating the inclusion and exclusion criteria based on the initial search and according to the relevance of the topics
    d. Formulating the filtration criteria
- To categorise the blockchain use cases for various components of smart sustainable cities such as smart healthcare, transportation, energy, and so on
- To develop a framework for blockchain technology to serve smart city requirements, covering the integration of sectors keeping in view the existing shortcomings/challenges in terms of cross-sectoral integration of smart cities.

2 | METHODOLOGY

To address the research question and fulfil the aim and objectives, a State-of-The-Art (SoTA) literature review is used to narrow down the research objective with a goal-oriented mode of action which is clear for all involved stakeholders about the possible final output and the addition of this research will make to the body of knowledge.

Scopus was selected as the main database for the SoTA. The following search string was used with final permutations and combinations:

('blockchain' OR 'block' AND 'chain') AND ('smart' OR 'intelligent' OR 'knowledge' OR 'digital') AND ('sustainable' OR 'liveable' OR 'maintainable') AND ('city' OR 'cities' OR 'places' OR 'communities' OR 'urban' AND 'areas') AND ('cross-sectoral' OR 'across' AND 'sector' OR 'between' AND 'sectors').

Without having any alias for smart cities and sustainable as well as systems integration on Scopus revealed only one document with the string (blockchain AND smart AND cities AND sustainable AND cross-sector). Therefore, the final search term as shown above was used with an alias for all possible search terms to increase the inclusion criteria, so that we could realise the coverage of the cross-sectoral city systems integration and the usefulness of Blockchain technology for it by the review of the relevant papers.

The initial search with the string on Scopus revealed 1,108 documents. Further limitations in terms of time window were done for the last 5 years only (i.e. 2017 to 2022 based on the generated graph shown in Figure 7). In addition, rigorous exclusion and inclusion criteria were applied based on the subject area, source type, keywords, language, and publication stage was done limiting the documents to 181. Further sorting of the documents and going through the abstract and conclusions with actual blockchain-smart cities reduced the number of papers for detailed review to 23. There were documents included manually as well by going through the bibliography and reference documents of some of the most relevant articles and journals.

The search time window was selected from 2017 to 2022 and the inclusion and exclusion criteria for the papers were devised as shown in Table 4.

The detailed filtration done on Scopus is highlighted in Table 5.

After reading the abstracts, the accessible publications are downloaded and recorded as annotated bibliographies for a comprehensive examination. Figure 8 shows the steps that are carried out to fulfil the SoTA literature review.

3 | RESULTS

There is a considerable number of research articles regarding blockchain and smart sustainable cities, written in the past 5 years. However, drilling down on the use of Blockchain technology for smart city enablement takes down the overall number of published articles. Therefore, to segment the results with a more categorised viewpoint, the results are grouped together in two different dimensions namely, data diffusion and the use of Blockchain to serve a certain component/sector/used case within smart cities as depicted in Figure 9. The main aim for this thematic analysis is because of the skewness of the available literature, as the main feature and characteristic of Blockchain is easiness in data sharing without the need for a centralised authority, this distinction of Blockchain is leveraged inside smart cities as well. However, most of the literature available is emphasising vertical sectors (e.g. smart transport, smart healthcare etc.).

According to the findings of this study, the elimination of a single point of failure and distribution of resources to enhance the overall storage and processing/computing capabilities within a smart sustainable city is at the core of the studies being

TABLE 4 Inclusion and exclusion criteria for the research.

Inclusion criteria	Exclusion criteria
English articles only	Data from blogs, Wikipedia etc,
Only full-access articles	Websites
Conference proceedings	Outdated articles and books
Journals articles & high-rank conference papers	Assignments, thesis, not cited low-quality conference papers
White papers	
Publication date from 2017 to 2022	

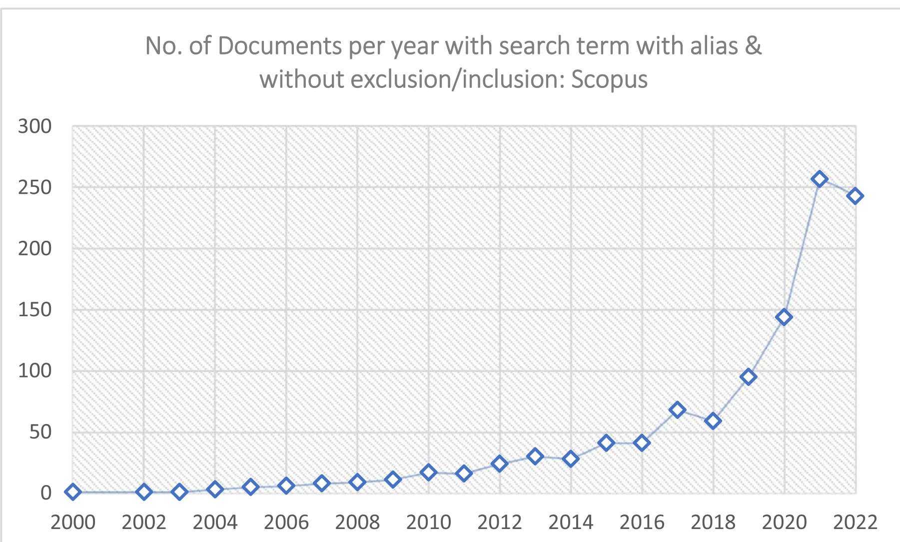

FIGURE 7 No of documents per year from Scopus.

done for Blockchain-smart cities from a capacity and dimensions perspective, the authors in refs. [41, 42] emphasise on the enhancement of compute resources being incrementally increased by using Blockchain-smart cities as the resources are spread across the network and it is easier to scale up by adding new nodes all the time, this is critical as the number of connected devices is increasing continuously within the smart cities. Similarly, the amount of data with the increase in devices is increasing as well, the storage of this data is still a challenge, and the issue of retention time is still a debatable question. The other crucial aspect is the management of the databases in the Blockchain network in a decentralised way, this notion is at the heart of the research done by several studies, such as refs. [38, 41, 43, 44]. These studies emphasise that the use of Blockchain-smart cities limits the failure chances both in case of a node failure or unlawful intrusion in the network by many folds due to the decentralised control.

Smart cities' incorporation with Blockchain has also been addressed by other papers, mainly discussing different flavours of Blockchain implementation for smart cities, either in the form of layers, or differentiation based on the basis of consensus algorithms, type of Blockchains or using a Cloud Service Provider to integrate Blockchain for smart cities. Sharma et al. [45] presented the Blockchain for smart cities from an architectural standpoint, where they divided the architecture into two distinct groups, the Core network and the Edge network, the core network is the main Blockchain network which validates and manages the data received from the edge nodes, the edge nodes reside locally with each of the smart cities devices. There is a centralised node introduced within the edge node which acts as a firewall for the filtration of the data.

Makhdoom et al. [46] proposed a fragmented approach within the Blockchain-smart cities where multiple channels of Blockchain within the network are created each of them handling a different kind of data, these behave completely independently of each other with predefined nodes within each of the channels responsible for data authenticity and addition of transactions within the blocks. Another approach of distributed data storage is introduced by Cha et al. [47], they introduced the CSPs which take out the storage issue of data within the Blockchain, in their point of view, this takes out the pressure of data retention on the Blockchain itself where the cloud resources are used primarily for storage and for computation and processing as well in some scenarios.

TABLE 5 Detailed filtration of the Scopus results for the Research.

Criteria	Filtration
Year	2017, 2018, 2019, 2020, 2021, 2022
Subject area	Environment science, engineering, social sciences, business, management and accounting, decision sciences, multidisciplinary
Document type	Article, review, conference paper
Publication stage	Final
Keyword	'Blockchain', 'systematic literature review', 'sustainability', 'sustainable development', 'industry 4.0', 'internet of things', 'systematic review', 'literature reviews', 'technology adoption', 'literature review', 'decision making', 'innovation', 'block-chain', 'information management', 'smart city', 'conceptual framework', 'digitalisation' 'digital technologies', 'blockchain technology', 'review', 'digital transformation', 'smart cities', 'conceptual frameworks', 'smart contract', 'technology', 'internet of things (IoT)', 'applications', 'internet of things (IoT)'
Source type	Journal, conference proceeding
Open access	All open access

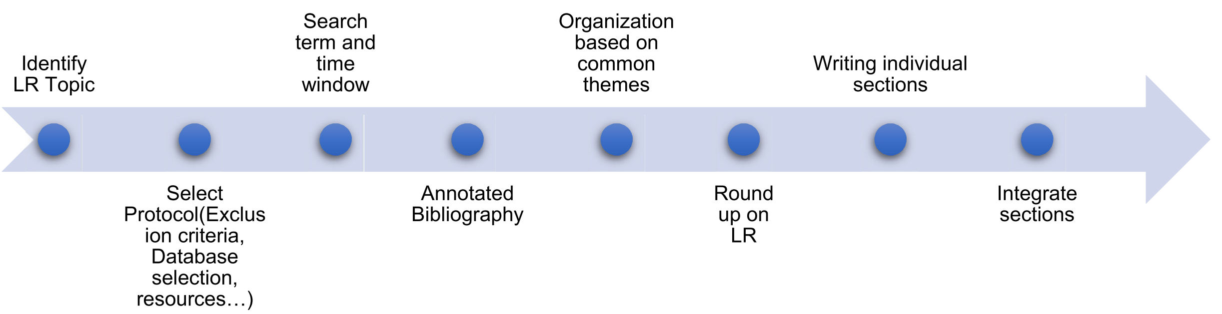

FIGURE 8 Steps for SoTA literature review.

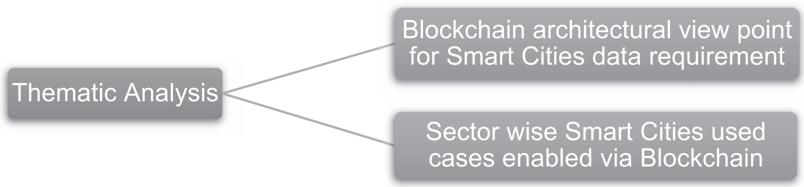

FIGURE 9 Segmentation for thematic analysis of the literature.

In addition to the architectural aspects of the use of Blockchain, Shen et al. [33] introduced another viewpoint on the use of Blockchain in smart cities, in their systematic literature review on the blockchain, they made the classification of the previous academic papers in this domain into two distinct subject areas, 'role-based' which incorporates the aid of Blockchain as an 'improver', an 'enabler' and a 'transformer', the other side of the classification talks about the papers where Blockchain serves smart cities from a 'business model' based perspective, where the Blockchain enables smart cities via providing a platform for collective decision making based on the trustworthy data, maintaining the access controls, data records which cannot be altered without legitimacy and lastly allowing the growth in peer-to-peer markets. Furthermore, Hakak et al. [43] highlighted the smart cities' data security challenges and the use of Blockchain to address these challenges, they emphasised the technological requirements needed to implement Blockchain in its true sense to overcome these challenges, likewise, Ahmed et al. [48] explored the bottlenecks with different applications of smart cities sector's and systems, and how Blockchain can help in resolving these obstacles. Kumari et al. [44] picked up the smart cities sectors of energy, transportation and healthcare, and have proposed an architecture of Blockchain to be used in these sectors individually.

Apart from the architectural implementation of Blockchain, the other theme that has been found as a result of the literature review is the use of Blockchain to enable specific sectors within a smart city. Some of those sectors have been explained in the following sections, according to the findings of this research.

3.1 | Healthcare sector

Electronic health records, smart wearables, and medical devices with integrated sensors recording patient vital signs have become critical in today's Healthcare sector specifically in a smart city. Since all the above devices and facilities receive, record and transmit a large number of transactions, Blockchain can be a vital enabler for the providers and city planners to have proper checks in place in terms of patients data privacy, legitimacy of the records without any tampering, and make an efficient network of nodes which rule out any chances of a single point of failure. McGhin et al. [49] emphasised the role of Blockchain in making the transactions within the healthcare sector more transparent as well as raising the accessibility of medical records to patients in a more convenient way, this surely enables the patients about the progress of their treatment and can support them to have more informed decision making collectively with the service providers. Zhang et al. [50] proposed a scheme based on Blockchain to fulfil the needs of healthcare infrastructure organisations, this allows the planners to confidentially receive patients' data and link it with a suitable service provider. Griggs et al. [51] proposed the use of Blockchain as an enablement technology for the real-time patient monitoring system, smart contracts were used via adopting the consortium type of Blockchain in Wireless Body Area Networks. This enables continuous monitoring as the signals are transmitted via wearable devices from patients to the medical service provider. The ability through smart contracts is to allow medical professionals to set certain thresholds which can generate alarms in case of a breach from the normal readings. In addition, multiple works have been done by the authors in refs. [52, 53] around smart contracts incorporating Electronic health records with varying levels of access controls as well as the kind of data to be shared with different stakeholders involved in the smart healthcare sector. Finally, Hameed et al. [7] has visualised a Blockchain-enabled healthcare system where patients, doctors, medical researchers and governance bodies are linked together, and data is shared via a Blockchain network (Figure 10).

3.2 | Energy sector

By virtue of the decentralisation management of data and offering a complete layer for smart contracts, Agung et al. [54] present smart grids based on Blockchain technology enabling data sharing between the users and service providers, the transactions between the entities are metre readings which are generated from smart metres and are shared with the grid, the proposed architecture is shown in the figure below where the grid act as a miner and is responsible for full control of the transactions being operated in the network (Figure 11).

Furthermore, the use of Blockchain in the Smart energy sector can enhance efficiency and transparency by eliminating the need for a central authority, similarly, energy trading among the users and providers via smart contracts has now enabled home users to sell their energy back to the grid as more and more households are shifting towards the use of renewable energy sources such as solar power, this increases the overall efficiency and optimise the utilisation of the energy resources [53]. The authors in refs. [55, 56] emphasise the balanced use of energy by focusing on having real-time communication between the users and the grid in order to ensure the demand and supply are balanced. They have suggested the use of smart contracts with public blockchain type using either PoS or PoW protocols respectively. Zheng et al. [57] proposed a consortium-based Blockchain network among energy suppliers, using the PoS protocol. Yang et al. [58] proposed a proof-of-authority consensus protocol to design the distributed energy resources mechanism leveraging the smart contract feature of Blockchain, it minimises the operational costs via system automation and provides an end-to-end mechanism to enhance energy optimisation and efficiency.

3.3 | Education sector

He et al. [59] have proposed role-based access control for the smart classroom where IoT sensors are used to record information like attendance, lecture notes, audio and video, this data is stored in a central location in a cloud-based data centre and access is granted to legitimate users only after the validity

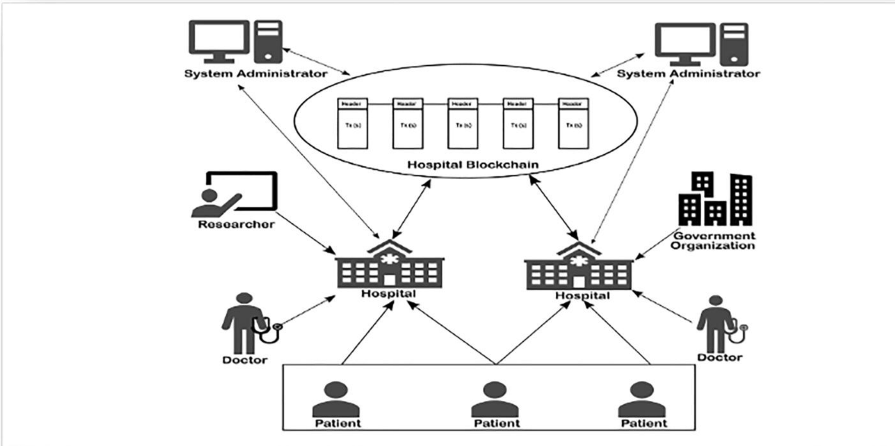

FIGURE 10 Blockchain-enabled smart healthcare—*Source*: [7].

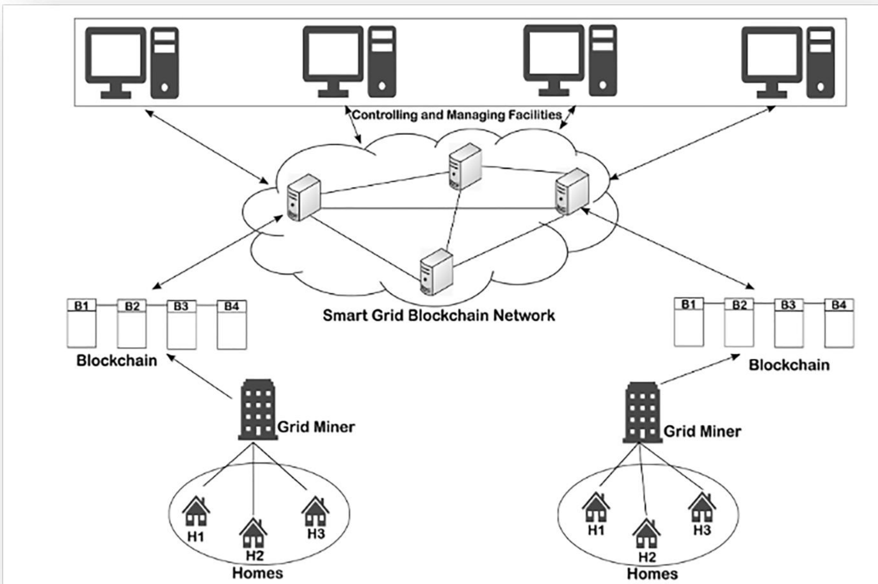

FIGURE 11 Smart grid blockchain network—*Source*: [54].

credentials are checked through Blockchain, this ensures the permission to access the data is granted on role basis rather than per user, the proposed Blockchain is the public type with a PoW consensus protocol. Bore et al. [60] have proposed the idea of a school information hub via using Blockchain, this is primarily effective for less developed countries where the data collected with the schools are still kept manually in registers and papers, they proposed to leverage smart contracts to manage the data accessibility to enhance the overall learning environment in the school (Figure 12). This data could be gathered from multiple schools and can be transferred to the education ministry and governance bodies to have statistical analysis for further planning and research. Therefore, the Blockchain can be managed on multiple levels, firstly within a single school where peers will be different classes and secondly, the schools can act like a peer in another level of the Blockchain network where they can feed the information to government institutions.

Han et al. [61] proposed that the user-level records in terms of degrees and certifications be kept in a trustworthy online repository using Blockchain, this can be specifically helpful in situations where the certificates are obtained from multiple educational institutions. Due to the inherited nature of Blockchain in maintaining the integrity of the records, the

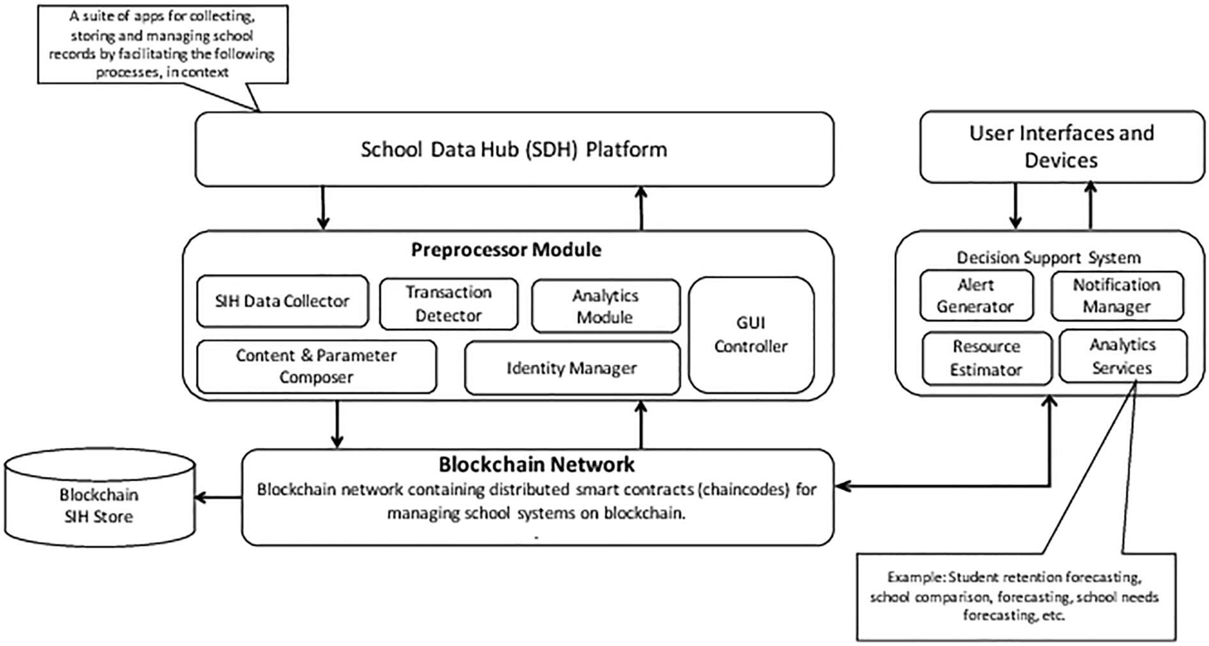

FIGURE 12 School information hub (SIH)—*Source*: [60].

authenticity of the certificates is un-challengeable. The study suggested the use of smart contracts where the institution that issues the certificates has full authority over the records, they can extend the 'read' only authority to prospective employers who can view the certificates to get confident about a prospective employee. This is based on a private Blockchain type using PoW consensus protocol.

3.4 | Transportation sector

The transportation sector within the smart city consists of logistics (freight forwards and goods-movers as well as connected cars, traffic route optimisation and roads and infrastructure linkages). Blockchain can be beneficial with all these interconnected segments as there is a large number of connected devices sending real-time data feeds at all times, for freight management. Remarkable work carried out by the authors in ref. [62] leveraging the decentralisation phenomenon of Blockchain network with secure and anonymous sending of the information of goods and containers keeping the goods to all involved parties, as the freight is between a defined sender and receiver, the sender sends the goods with encrypted data over the Blockchain network which can only be decrypted by the governance bodies (i.e. customs or the receiver entity). This is beneficial to reduce the turnaround time on ports as the secure checking of goods via the customs official is fully automated. They propose to use Hyperledger Fabric which is a component of Blockchain which can scale up to support more than 1,000 transactions per second. Li et al. [63] introduced the concept of CreditCoin, which is an incentive-based Blockchain scheme for smart vehicles, based on the principles of cryptocurrency, each participating vehicle can earn coins based on the number of transactions added for safety messages, consensus mechanism used is derived from the basis of BFT. Figure 13 shows the high-level network diagram of the CreditCoin network where vehicles communicate with roadside infrastructure units (RSUs), these RSUs further relay the data to the Blockchain network, and the traffic authorities can get this valuable information and can take the necessary actions wherever required. Further improvements were suggested by Kang et al. [64] through an improved Delegated PoS consensus protocol where the RSUs do the block validation and can appoint further nodes within the network which can take part in the validation exercise. Javed et al. [65] suggested another dimension for vehicles sharing the data with RSUs where they suggested a consensus protocol which uses Proof-of-Authority (PoA) which is an enhancement over PoW, the RSUs select the miner based on the reputation of the node from a historical standpoint.

3.5 | Building sector

Smart contract abilities within Blockchain offer a variety of advantages when it comes to the maintenance and governance of Smart buildings for both residential and commercial buildings. Lin et al. [66] proposed 'HomeChain' a novel Blockchain-based remote authentication mechanism which helps data diffusion and validates the users to access the data shared by smart home sensors like cameras, temperature sensors, fire alarms, door locks etc. For smart homes, security is of paramount importance in order to protect against unlawful access to the data as it could lead to remotely logging into the system and making changes or even giving physical access to unlawful persons. The 'HomeChain' system enables smart homes via

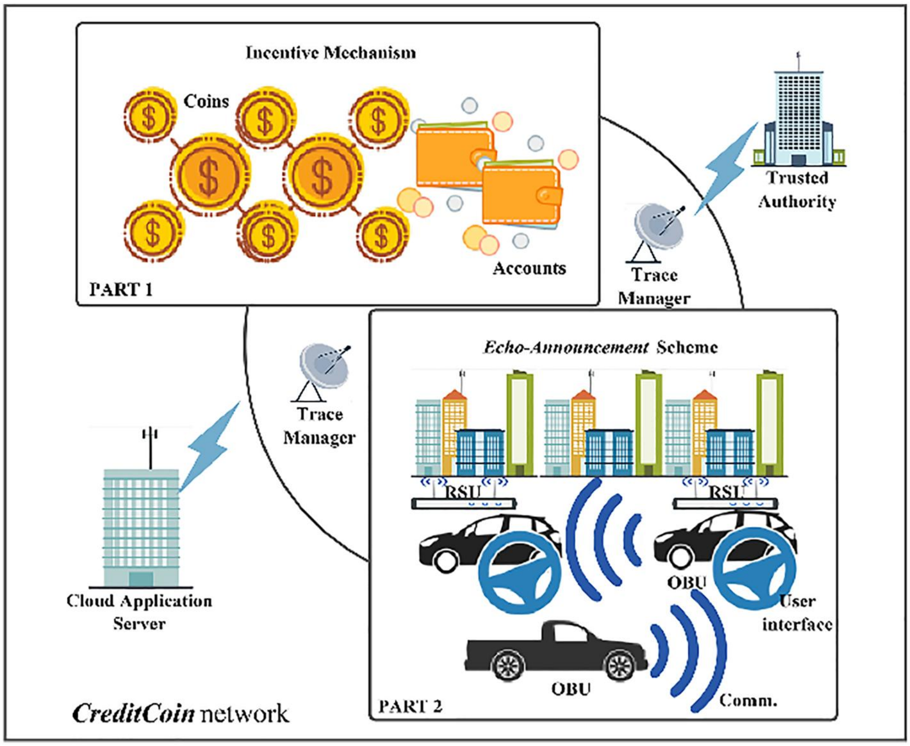

FIGURE 13 CreditCoin network for traffic data sharing via Blockchain—*Source*: [63].

authentication and group signature to provide the legitimacy checks between the remote users and home gateway, Blockchain enables integrity for end-to-end data for each transaction and stores the response from the gateway as well, this allows close monitoring of the history logins and communications of users. The solution is using the PBFT consensus algorithm. Qashlan et al. [67] also used smart contracts for privacy management for smart homes, attribute-based access control framework is proposed on top of Ethereum based Blockchain platform with dual smart contracts used for policy management and registration of common attributes and characteristics of the end users and smart home devices, the second contract works on the actual access arrangement of the end users to the home devices. Wan et al. [68] suggested a framework for a smart factory, the main characteristic of the Blockchain network introduced in the framework is the storage of data in a cloud platform which eases out the capacity requirements in terms of storage of data within Blockchain itself, this is extremely crucial when talking about industrial applications within smart factories as even a single unit can contain thousands of sensors relaying real-time data to the central control servers. The framework suggests the use of a Blockchain ledger to contain the access records only. Another remarkable work for smart factories has been done by Huang et al. [69], who propose a PoW consensus protocol giving credit to the nodes which are having a green history in terms of mining, the credit is inversely proportioned to the complexity given to solve the hash calculation for good nodes and very high complexity to malicious nodes.

4 | DISCUSSION

As introduced in the previous section, the majority of the literature, identified through the SoTA in this study can be distributed in two distinct themes:

- The architecture viewpoint of Blockchain implementation enabling smart cities: this viewpoint encapsulates the types, consensus protocols, layers and different implementation approaches in general.
- The usage of Blockchain as an enabling technology for different applications/sectors/components of a smart city.

The former theme is richer and more holistic in terms of the availability of the literature as multiple research articles were found to serve a single sector of a smart city. The main difference in the approaches was the way Blockchain was implemented to serve a certain sector. However, none of the literature we have analysed speaks about a holistic framework or artefact guiding the use of Blockchain for cross-sectoral systems integration within a smart sustainable city.

4.1 | Linking the findings to the main research question

Sharma et al. [45] have also highlighted the limitation of research being done in the Blockchain-smart cities domain to be either too general or too specific to solve a certain problem only, therefore they also proposed a centralised hybrid network based on Blockchain for a smart sustainable city, however, the limitation of the proposal lies in extreme dependency of data retention schemes on edge node covering each of the sectors of a smart city. In addition, the architecture is limited in a way that it still introduces kind of a centralised 'core network' of Blockchain nodes replaying the data from each of the edge networks. The possibility of failure in case anything happens within the core network is still significant.

Furthermore, the work done by Cha et al. [47] introduces cloud service providers for the fulfilment of data retention and storage limitations of the Blockchain, however, they fail to shed light on what consensus protocol to be used. In addition, there is no model or framework introduced. The fragmented approach introduced by Makhdoom et al. [46] for access control is beneficial for securely preserving user data, however, due to the introduction of added fragments, the resource requirements have increased to a much larger scale. Shen et al. [33] suggested the role-based and business model-based use of Blockchain in smart cities and reviewed the technology in terms of a theoretical standpoint only with no emphasis on proposing a model or framework for cross-sectoral integration. In addition, the technical aspects in terms of types of Blockchain and consensus protocols are also not part of this systematic literature review.

Hakak et al. [43] have presented quite conclusive evidence-based outputs in terms of research challenges and the future of Blockchain-smart cities by studying the actual deployment of smart cities used cases in 'French City Brain', 'Smart Dubai' and 'Limestone Network'. However, they did not suggest remedies or a comprehensive framework to overcome these challenges. A systematic literature review was provided by Ahmed et al. [48] mentioning the security challenges of smart cities and how Blockchain can help in different domains, however, a holistic approach was found to be missing. Moreover, no information about the cross-sectoral data diffusion within a smart city could be found. Kumari et al. [44] discussed in detail Blockchain-based frameworks for Smart Health, Smart transport, and Smart energy, each of the frameworks shed focused light on how to tackle the challenges within these sectors and how to use Blockchain to maintain decentralised, transparency and immutability. However, the research is too focused on specific sectors only and again lacks cross-sectoral flavour.

The other papers, presented in the above section, discuss a single sector within a smart city, some of them are found to be very comprehensive proposing a holistic approach backed by experimental analysis and framework to use Blockchain as a technology enabler for smart city use cases. However, none of them answers the problem statement and research question in this project, our primary concern is how useful Blockchain can be for a smart sustainable city for integration of different sectors within the smart sustainable city. The papers which were studied and analysed during this project failed to fulfil this research question in totality. These are summarised in Table 6.

4.2 | Proposed framework

As evident in the last section, the literature including SoTA, systematic literature review papers, as well as papers presenting novel solutions and frameworks, leveraging Blockchain to serve smart cities sectors reveal that none of them is addressing our research question, which is focusing on cross-sectoral systems integration within a smart sustainable city. Therefore, based on the findings of this research, we are proposing a framework that can help future researchers, smart city developers/planners/consultants, entrepreneurs, inventors, and solution providers to focus on cross-sectoral systems integration as an important component of developing a smart sustainable city. This is critical as the sectors always need to share data to serve the end-user that is, a citizen in a better way, as example, parents going to pick up and drop their kids at school daily can share their real-time traffic feeds to the transportation authorities to better plan the routes within the city specifically in the morning and evening hours. Similarly, the connectivity of transportation with the healthcare sector in real-time can guide the emergency services that is, ambulance and rescue workers to better traverse the roads in the city to optimise the time it takes to reach the affected location. Relatedly, although Sharma et al. [45] have proposed a framework for smart cities based on Blockchain., their framework also distributes the sectors and links them with edge nodes and all the processing of the messages is being done in another central network. This distribution allows flexibility, however, at the same time it introduces bottlenecks as each edge node is linked with each of the sectors. In addition, there is no mention of the schemes and techniques to be used within the sector.

The aspiration of the framework is derived from the consideration of thinking of a smart city as an integrated enterprise and using the concepts of ESI. This proposal and consideration initially surfaced by Javidroozi et al. [14]. The same inspiration to overcome data silos within a smart city is at the heart of the proposed framework as shown in Figure 14.

The framework proposes authentication, registration, and onboarding of 'users' located within a sector of a smart sustainable city using a smart contract, once onboarded, they create and send the transaction to the corresponding Blockchain 'nodes', the data flow within the Blockchain will take place on a predefined consensus protocol. In other words, this process is accomplished through the use of smart contracts, which allow for the creation and sending of transactions to the corresponding Blockchain nodes. Once the user is onboarded, they can upload data to the centralised Blockchain network using a predefined consensus protocol, regardless of whether the user is an individual, a building, or a classroom.

The 'user' here can be a person, for instance, this framework enables individuals to share traffic information from their smartphones or relay data from wearable devices to healthcare providers, while also allowing for entire buildings within the smart building sector and classrooms within the smart education sector to upload information onto the centralised Blockchain network. This approach enhances transparency, security,

TABLE 6 Analysis of reviewed literature.

Reference	Area of study	Covering cross-sector (Y/N)	Model/framework proposed (Y/N)	Remarks
[3]	SoTA literature review, data dissemination within smart cities via blockchain	N	Y	Good base providing an up-to-date review of literature for blockchain-smart cities. However, no proposed frameworks for cross-sectoral integration.
[7]	Security aspects of blockchain-based industry 4.0 applications	N	Y (per application/ sector)	Provides detailed security aspects of industry 4.0 applications using blockchain, however, no end-to-end framework is proposed for cross-sectoral integration.
[45]	Hybrid network architecture for blockchain-based smart city	N	Y (per application/ sector)	A good approach linking edge and core networks of blockchain to enable smart cities, however, fails to provide a cross-sectoral approach
[47]	Inclusion of CSPs within the blockchain network for smart cities	N	Y (per application/ sector)	Addresses the issues of data retention on blockchain via the introduction of CSP. However, do not have an end-to-end approach. No consensus protocol was proposed.
[46]	Fragment-wise approach for secure data transfer via blockchain for smart cities	N	N	Fragmented approach for the data security within the blockchain-smart cities network, however, the approach adds extra workload on the compute and storage resources and fails to address cross-sectoral integration.
[33]	Role-based and business-model-based approaches for blockchain to serve smart cities used-cases	N	N	Theoretical approaches are presented only, types and consensus protocol for any other artefacts are missing
[43]	Reviewed actual challenges in the implementation of blockchain-smart cities used cases in 3 different locations	N	Y (for some sectors)	Have a very good analysis based on actually used cases, however, no remedy or solution in a framework or artefact form is provided to overcome the issues.
[48]	Discuss security and privacy issues within various sectors of smart city	N	N	Only provides theoretical approach, type of blockchain or consensus is missing
[44]	Covered health, transport and energy sectors using blockchain for a smart city	N	Y (health, transport, and energy)	Detailed framework and technical approach articulated for blockchain network, only limited to three sectors.
[40]	Discuss the security and privacy of EHR via private blockchain	N	Y (healthcare)	Detailed analysis and frameworks for the healthcare sector including EHR, patient records and medical IoT.
[49]	Research challenges and opportunities for blockchain in healthcare applications	N	N	Literature review about the latest academic papers available for patient health records automation via blockchain, highlighting security, interoperability, data sharing and access. No consensus or blockchain type was mentioned to be used.
[50]	Secure sharing of clinical data through blockchain application	N	Y (healthcare)	Introduces detailed architecture with all technical details and consensus protocol, in addition, a digital health application is suggested with user authentication based on blockchain
[51]	Real-time monitoring of patient vitals through blockchain enabled WBANs	N	Y (healthcare)	Complete framework leveraging consortium blockchain using PBFT consensus protocol, using a smart contract to securely link wearable devices from patients to healthcare providers in real-time.
[54]	Application using blockchain for the smart grid for home-users	N	Y (energy)	Comprehensive framework provided with application development linking home users to the energy provider that is, grid. The grid acts as a miner and controls the onboarding of new blocks to the network after having authentication through smart contracts

TABLE 6 (Continued)

Reference	Area of study	Covering cross-sector (Y/N)	Model/framework proposed (Y/N)	Remarks
[58]	Using smart contracts to overcome the need for a central authority in energy distribution	N	Y (energy)	Private-type blockchain by using a PoA consensus protocol, optimised energy resources via the reduction in operational cost via complete automation using smart contracts
[59]	RBAC for smart classrooms, privacy protection provided by blockchain	N	Y (education)	A complete framework linking the IoT sensors within the smart classroom to the teachers and students via role-based access control to the user level by using public blockchain and PoW consensus protocol
[60]	Blockchain-enabled school information hub.	N	N	Leveraging smart contracts within blockchain to create a complete solution of SIH, shortcomings are no mention of a model or consensus protocol.
[61]	Management of individual educational certifications	N	N	PoW usage in private blockchain to maintain the records of individual persons for the certificate authentication issued from multiple educational institutes. No detailed design and framework were introduced.
[66]	Remote authentication of home users to connect to the smart home gateway to access the IoT devices within the home environment	N	N	Introduction of 'HomeChain' a novel blockchain-based solution for authentication of users, leveraging PBFT consensus protocol and private blockchain type.
[67]	Attribute-based access control (ABAC) for smart homes using a private blockchain.	N	N	Explores a real-time model for smart home users to authenticate register and access IoT devices within the smart home. No model or framework proposed
[68]	Blockchain usage in smart factories	N	Y (building)	Introducing cloud-based integration of blockchain, taking out the issue of data retention within blockchain. Usage of public type blockchain with a PoW consensus protocol.
[62]	Proposed 'defend' blockchain-based solution for the freight industry.	N	Y (transport)	Comprehensive solution for smart transportation specifically talking about the freight sector, secure communication between sender, receiver and the government customs. Scaling up possibilities using hyperledger with transaction speeds up to 1000+ transactions per second.
[63]	Smart vehicle connectivity via data diffusion using blockchain, cryptocurrency-based CreditCoin concept.	N	Y (transport)	Incentive-based technique CreditCoin was introduced to encourage the participating vehicles to contribute more and more towards sharing of traffic-related messages, a public type blockchain with consensus based on BFT. The incentive-based scheme can incur significant delays when deployed on a commercial scale

and traceability within the system, reducing the risks of data tampering, and creating a more efficient and integrated system for smart city development.

The framework presented is a generic framework that opens new opportunities and avenues for further work to be done in a more detailed way and using actual data from smart sustainable city systems for in-depth analysis. The proposed framework offers a promising avenue for the development of smart sustainable cities by leveraging the potential of blockchain technology. The framework provides a comprehensive and systematic approach to authenticate, register, and onboard users within a specific sector of a smart city system. By using smart contracts and a predefined consensus protocol, the framework ensures secure data flow and enhances transparency, traceability, and efficiency in the system. Moreover, the framework offers a generic solution that can be applied across various sectors of smart sustainable cities, such as transportation, healthcare, education, and buildings. This allows for the integration of different sectors and the creation of a more cohesive system that can better serve the needs of citizens. The proposed framework also presents opportunities for future research and development. The framework can be further studied and refined by incorporating actual data from smart city systems for in-depth analysis. This will enable a

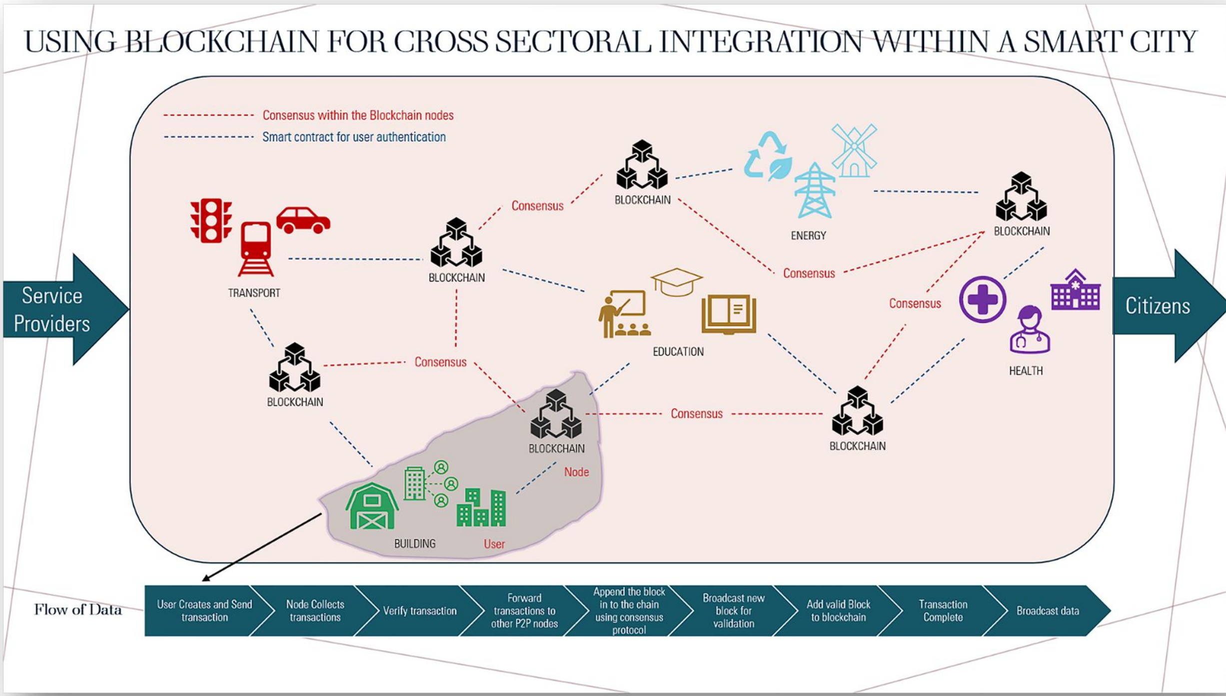

FIGURE 14 Proposed framework for Cross-sector integration of smart cities leveraging Blockchain.

more detailed understanding of the framework's capabilities, limitations, and potential improvements. Furthermore, future research can explore the applicability of the framework in real-world settings and assess its impact on the development of smart sustainable cities.

Table 7 summarises the limitations and future recommendations for the use of this framework. It proposes the dimensions, which we recommend being further studied to have a practical solution that can be readily implemented for smart sustainable cities.

5 | CONCLUSION

This state-of-the-art research reviewed the existing research regarding the use of blockchain technologies for developing smart sustainable cities, especially from cross-sectoral systems integration and the requirements of data and process sharing a viewpoint. This was conducted through the implementation of a comprehensive search protocol using relevant keywords and formulated search terms.

This research explained that in the contemporary world, modern technologies have become imperative to overcome the urbanisation challenges and enhance the living standards of the citizens. With the ever-increasing role of data-sharing in facilitating systems integration across various city sectors for smart and sustainable city development, there is a need for decentralisation, transparency, and openness in terms of integration to ensure the efficient diffusion of data among the city sectors. It is crucial to ensure open data sharing as it can enable service providers to provide better services to citizens. Blockchain technology can offer these characteristics with the added advantage of maintaining data security via an immutable record.

However, according to the findings of this research, the use of Blockchain for smart sustainable city development specifically with a focus on cross-sectoral systems integration is still a reasonably new idea that needs much attention from researchers and city planners, necessitating extensive research and testing. Hence, this research aimed to conduct a state-of-the-art review to explore the utility of Blockchain technology in developing smart sustainable cities, focusing on cross-sectoral systems integration while highlighting the gaps in the current knowledge. This led to the proposal of a novel framework for the application of Blockchain technology in developing smart sustainable cities, creating a link between service providers and citizens, which can be used as a basis for further research and development in this area. To summarise, in this study, a detailed literature review has been done on the subject, the objective was to explore smart cities definitions, trends, sectors, and various smart cities frameworks, followed by an exploration of blockchain technology including architecture, consensus protocols, applications, trade-offs, and challenges. Furthermore, a review was presented on the utility of blockchain in various smart city use cases. The literature review section covered all of these objectives, and then in the methodology section, details of the research including the search strategy and project synthesis were presented. The results section included the details of the papers which were extensively reviewed. The discussion section

TABLE 7 Limitations and Future Recommendations for the proposed framework.

Limitations	Future recommendation
Focusing on the technical aspects only: the framework addresses the technical concerns only, however, for complete implementation of this framework, business process re-engineering has to be done, in addition, the people aspect has to be considered as well	Study the impact of process change and the people aspect linked with this framework needs to be evaluated. People's readiness to adopt blockchain as the mechanism for data exchange and move towards smart contracts is essential. In addition, a study on the current processes to be completely re-engineered has to be done for each sector.
Data architecture is not considered: The framework did not discuss the required data architecture that would be required to maintain the data sharing.	Research on the data architecture needs to be carried out can fulfil both the needs of the corresponding sector as well as of the centralised blockchain nodes which will be responsible to authenticate and broadcast the data.
Architecture and consensus protocols for blockchain: The framework is a general guideline only, not having details on which type of blockchain and consensus protocol to be used	Further research is recommended to study the suitable architecture which can fulfil each sector as well as the consensus protocol which will work for the nodes handling different sectors within the smart city
Dimensions and scalability: The sizing and dimensioning have not been studied for commercial deployment in a used case.	Commercial deployment of the framework needs to be studied as this would require to have scalability features within the blockchain. As each sector depending upon the size of the end-users contributing could add different payloads of transactions, in addition, some of the used cases would require real-time data sharing which would require lightweight blockchain to be considered.
	Since the cost of implementing such innovative technology for developing smart and sustainable cities is an important aspect to consider, it is also recommended that a comparative analysis on the deployment cost, benefits and return on investment is conducted to better understand the commercial viability of using blockchain technology for developing smart sustainable cities.
User data privacy, security & legislation: Data privacy and security aspect is not considered in the framework	As blockchain is an open decentralised architecture, this poses a threat to maintaining the user's data privacy and security, in addition, future research should discuss the legal aspect in terms of government legislation for the data being shared through blockchain networks, this is required to ease-out the adaptability of the technology on a commercial and mass deployment scale.
Focusing on blockchain only: considering other technologies (e.g. Big data analytics and data streaming) to be integrated with blockchain technology	Further research is needed to examine the merits and demerits of integrating other technologies with blockchain for developing smart sustainable cities, especially in the aspect of cross-sectoral data sharing for city systems integration

highlighted in detail the overall analysis of the reviewed papers specifically linking the analysis with the problem statement and research question. It is evident from the discussion section that the current literature does not fully answer the request question as cross-sectoral systems integration leveraging Blockchain was not found to be covered in the reviewed papers. Therefore, the gap in the existing literature in the discussion section leads to the proposal of a novel framework that will be useful for the cross-sectoral integration of smart sustainable city development.

Overall, the proposed framework represents a significant contribution to the field of smart sustainable city development and sets the stage for future research and advancements. This project's contribution to this subject re-accentuates as follows:

- The proposed framework for smart sustainable cities, leveraging the potential of blockchain technology, presents a promising avenue for addressing the challenges of urbanisation. This can be elaborated further by conducting more research on specific challenges;
- By providing a systematic and comprehensive approach to authenticate, register, and onboard users within a specific sector of a smart city system, the framework ensures secure data flow and enhances transparency, traceability, and efficiency in the system. As a result, the framework can serve as a catalyst for the development of smart cities, improving the overall experience of citizens;
- The generic nature of the framework allows for its applicability across various sectors of smart sustainable cities, such as transportation, healthcare, education, and buildings. This opens up the possibility of integrating different sectors and creating a more cohesive system that can better serve the needs of citizens;
- The proposed framework's contribution also extends beyond its immediate application:
  a. The framework presents opportunities for future research and development, where its capabilities, limitations, and potential improvements can be further studied and refined by incorporating actual data from smart city systems;
  b. Future research can explore the applicability of the framework in real-world settings, assess its impact on the development of smart sustainable cities, and investigate the potential for scaling up the framework to a city-wide level.

Accordingly, the framework can also have the following practical contributions/applications, especially in the various city sectors:

- The framework can enhance the efficiency and effectiveness of public services in smart cities, such as waste management, traffic management, and emergency response;
- The framework can facilitate secure and efficient energy trading among prosumers, allowing for the development of decentralised energy systems and reducing reliance on traditional energy sources;
- The framework can improve the quality of healthcare services in smart cities by enabling secure and transparent sharing of patient data between healthcare providers, patients, and other stakeholders;
- The framework can enhance the safety and security of smart city systems by providing a tamper-proof and auditable record of all transactions and data flows;
- The framework can promote greater citizen engagement and participation in smart city decision-making processes by providing a secure and transparent platform for citizens to provide feedback and suggestions to city authorities.

As in the case of any research, this research as well cannot be deemed complete due to multiple reasons, specifically the time limitation, the selection of literature in the English language only, and peer-reviewed journals and conference proceedings. Consequently, it is urged that future researchers should focus on the limitations and recommendations mentioned in Table 7.

AUTHOR CONTRIBUTIONS

Sarmad Khawaja: Conceptualisation; data curation; formal analysis; investigation; methodology; project administration; resources; visualisation; writing—original draft. **Vahid Javidroozi**: Conceptualisation; methodology; project administration; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

We, the authors have no conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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