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Blockchain Applications in the Development of Smart Cities

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Abstract: Blockchain technology, with its decentralized nature, immutability, and transparency, has emerged as a promising tool to address challenges in smart city development. This review paper examines the applications of blockchain across multiple sectors, including waste management, finance, voting, real-estate, and energy management. Drawing from current research, the paper demonstrates how blockchain can enhance conventional approaches to improve efficiency, transparency, and security. While blockchain holds significant promise, this paper also explores the constraints hindering its mass adoption, such as scalability, energy consumption, and regulatory challenges. By incorporating perspectives from both industry and academia, it provides a balanced analysis of the opportunities and challenges associated with blockchain adoption in smart cities. Ultimately, this paper aims to offer valuable insights to policymakers, researchers, and stakeholders, helping them better understand how blockchain can be strategically leveraged to create more sustainable, secure, and efficient urban systems.

Keywords: Blockchain; Smart City; Distributed ledger technology; Ethereum; Energy Trading; Waste Management; Finance; Voting; Real Estate.

1 INTRODUCTION

The rapid urbanization of the global population has placed unprecedented demands on city infrastructures, resources, and services, necessitating innovative solutions to enhance efficiency, sustainability, and quality of life. In response, the concept of smart cities has emerged, leveraging advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics to optimize urban operations. However, the integration of these technologies often raises challenges related to data security, transparency, and interoperability [1,2]. Distributed Ledger Technology (DLT), commonly exemplified by blockchain, which we will focus on in this paper, has gained significant attention as a transformative tool to address these challenges [3]. By providing a decentralized, tamper-proof, and transparent framework for record-keeping, blockchain offers a robust solution for managing the complex and interconnected systems that underpin smart cities.

This review paper critically examines the growing body of research on the potential uses of blockchain in smart cities, synthesizing insights from academic studies, industry reports, and real-world implementations. As a review, it does not present new experimental data but instead evaluates and consolidates existing work to identify trends, gaps, and future directions. The paper explores the diverse applications of blockchain in urban contexts, such as facilitating secure peer-to-peer energy trading, enhancing waste management systems, transforming banking systems and enabling Central Bank Digital Currencies (CBDC), revolutionizing real-estate markets, and ensuring voting transparency.

By providing a comprehensive analysis of the current state of research, this paper aims to serve as a valuable resource for researchers, policymakers, and urban planners. It not only underscores the transformative potential of blockchain in addressing urban challenges but also calls for further interdisciplinary research to overcome existing barriers and unlock the full potential of this technology in building smarter, more resilient, and inclusive cities.

The rest of this paper is organised as follows. Section 2 provides an overview of blockchain technology and its utilization in smart cities, highlighting its key features and potential benefits. Section 3 delves into the applications of blockchain in various fields, including waste management, finance, voting systems, energy management, and real estate. Each subsection explores how blockchain addresses specific challenges and enhances efficiency, transparency, and sustainability in these domains. Finally, Section 4 presents a discussion of the findings, synthesizing the opportunities and challenges of blockchain adoption in smart cities, and concludes with future research directions and broader implications for the development of smarter urban ecosystems.

2 BACKGROUND THEORY

In this section, we explore the fundamentals of blockchain technology, including its definition, significance, and various types. Following this, we delve into the concept of smart cities, discussing their meaning and importance, and briefly discussing how blockchain technology can contribute to the development of these futuristic urban environments.

2.1 Blockchain

Blockchain technology is one of the most significant innovations in recent years, as it has redefined trust, ownership, digital identity, and financial systems. Blockchain operates as a decentralized and distributed ledger system, specifically designed to securely record, validate, and maintain transaction data. Instead of being managed by a single centralized authority, such as a bank, blockchain records are monitored and maintained by a decentralized network of participants. No individual entity has exclusive control over the system, and once a transaction is recorded, it cannot be altered or erased, ensuring immutability and security within the network [4,5].

The term "blockchain" refers to a chain of cryptographically linked blocks, where any modification to a single block invalidates all subsequent blocks in the chain [6]. The primary function of a blockchain network is to ensure that independent and untrusted nodes within the system achieve consensus on a single, immutable record of transactions [7]. This function is fulfilled by consensus mechanisms, which establish the rules for maintaining consistency across the network. The first widely recognized consensus algorithm, Proof of Work (PoW), was introduced with the launch of the Bitcoin blockchain. Since then, multiple consensus algorithms have been developed to enhance scalability, efficiency, and security in various blockchain applications [5]. Some examples of consensus algorithms include Proof of Stake (PoS), practical Byzantine Fault Tolerance (pBFT), Proof of Elapsed Time (PoET), and many more [8].

Blockchain technology is primarily classified into two main types: private blockchain and public blockchain. However, depending on specific criteria and analytical perspectives, blockchain can also be categorized into consortium blockchain and hybrid blockchain models [9]. In public blockchains, the network is open and accessible to anyone who wishes to participate in transactions, without requiring special permissions. Examples of public blockchain are Bitcoin, Ethereum, Cardano, etc. On the other hand, private blockchains are restricted-access networks, meaning they are not open to the public. Participation is limited to authorized users who are granted access by a central authority or system administrator. Despite being permissioned, private blockchains still leverage cryptographic security and decentralization to some extent, while ensuring greater privacy and control over data management [9]. Hyperledger Fabric, Corda R3, Hyperledger Sawtooth, IBM Blockchain include some of the well known examples of private blockchain [10]. A combination of features of public and private blockchains resulted in hybrid blockchains. This type of blockchain allows selective transparency, where certain data is made publicly accessible while other information remains restricted to authorized participants. Examples of hybrid blockchains include IBM Food Trust and XinFin [11]. A consortium blockchain is a type of semi-decentralized blockchain where multiple organizations collectively manage and control the network. Unlike public blockchains, which are fully open, or private blockchains, which are restricted to a single entity, consortium blockchains allow a group of pre-selected entities to govern the system [9]. Corda R3, Quorum and Energy Web Foundation (EWF) are some of the most common examples of consortium blockchains [12].

Blockchain technology has evolved into multiple specialized platforms, each serving distinct purposes. Among the most widely recognized are Bitcoin, Ethereum, and Hyperledger Fabric, which cater to different use cases, from cryptocurrency transactions to smart contracts and enterprise solutions [8].

Bitcoin is the world's first and most dominant cryptocurrency. It was introduced in 2008 by Satoshi Nakamoto as the first successful implementation of blockchain technology. Bitcoin revolutionized digital finance, enabling peer-to-peer transactions without reliance on banks or governmental authorities [13].

In 2013, Vitalik Buterin introduced Ethereum, which significantly expanded blockchain technology by enabling the execution of smart contracts on a decentralized platform. Unlike Bitcoin, which primarily serves as a digital currency, Ethereum functions as a programmable blockchain that allows developers to create markets, build decentralized applications (DApps), and execute automated transactions without requiring intermediaries. A key innovation of Ethereum is its smart contract functionality, which enables self-executing agreements that automatically enforce terms without the need for third parties. These smart contracts are written in Solidity, Ethereum's purpose-built Turing-complete programming language, designed to facilitate secure and transparent decentralized execution of blockchain-based applications [8].

Hyperledger Fabric, a modular and permissioned blockchain platform, was introduced in 2016 under the Linux Foundation's Hyperledger project, with key contributors including IBM. Unlike public blockchains, Hyperledger Fabric processes transactions using an execute-order-validate model, which eliminates the need for traditional consensus algorithms by relying on a predefined ordering service to arrange transactions. It also allows smart contracts to be written in multiple programming languages like Node.js, Java, and Go, making it highly flexible for enterprise applications. A key distinction is that all nodes have assigned identities, ensuring controlled access, which enhances security, privacy, and regulatory compliance for business use [14].

Building on the advancements of blockchain platforms, such as the ones described in the previous paragraph, blockchain technology has become a cornerstone of financial innovation, transforming payments, cross-border transactions, decentralized finance (DeFi), and digital asset management by ensuring security, transparency, and efficiency. However, its impact extends far beyond finance, with applications in supply chain management, healthcare, identity verification, real estate, voting systems, the Internet of Things (IoT), and many more, where trustless and tamper-proof solutions are increasingly valuable. As blockchain technology continues to evolve, its versatility and potential for disruption across multiple industries are expected to drive further adoption and innovation [5].

2.2 Smart City

With the fast-growing population in urban areas, new challenges are emerging, which might require a "smarter" approach. According to the United Nations, it is projected that around two-thirds of the global population will live in urban areas by 2050 [15]. In these high population density areas, citizens are faced with many factors limiting their quality of life, such as inefficient waste management systems, energy demand fluctuations and inefficiencies, increasing real estate prices, voting processes vulnerable to fraud and low participation, slow and limited financial systems etc. These are some of the issues that a smart city aims to address. Although the term "smart city" has been in use for some time, it has only recently gained wider recognition among the public. The term can be challenging to define due to discrepancies in the literature and rapid technological advancements. This inspired our study to look into specific use of different technical (smart) solutions which can make a life in modern cities more convenient.

A key characteristic of smart cities is the integration of advanced Information and Communication Technology (ICT) to enhance the quality of life for its citizens and promote a sustainable urban environment [16]. Building on this foundation, smart cities aim to establish a development model based on utilization of human, collective, and technological capital in order to drive growth and prosperity in urban areas. Greater transparency in public governance, active citizen participation, efficient traffic and public transport management, optimized resource utilization, enhanced environmental protection, seamless integration of smart devices, and improved services in healthcare, energy, and education are just a few of the numerous beneficial attributes smart cities are offering [17].

2.3 Blockchain in Smart Cities

Amidst a wave of innovations and technological advancements, blockchain has emerged as a promising technology for the development of smart cities. Alongside Artificial Intelligence (AI) and other emerging technologies, blockchain holds significant potential to enhance the quality of life of smart city residents. In an era of increasing demand for reliable information, ensuring its transparency and accuracy is crucial for societal prosperity. Systems that depend on such information - such as traffic management, waste management, energy distribution, healthcare, public dispute resolution and voting - can greatly benefit from blockchain's components, including smart contracts, consensus mechanisms and cryptographic verification.

The technology offers "trust-free trust", enabling decentralized governance without third-party intermediaries. Its impact can be seen in four key areas. First, the network effect of trust enhances societal, governmental, and industrial functions by reducing corruption, tackling online disinformation, and improving transparency in public administration. Second, empowering individuals and strengthening the economy allows citizens to have control over their digital identities and personal data. Third, the sharing economy benefits from blockchain’s ability to remove intermediaries, lowering costs for services like real estate, transportation, and hospitality. Lastly, the liquid economy is shaped by tokenization, where assets and services are digitized for seamless trading and investment [18].

3 BLOCKCHAIN APPLICATIONS IN SMART CITIES

The integration of blockchain technology into smart cities is transforming various sectors by enhancing transparency and security in urban management. As cities become more interconnected, decentralized ledger technology provides innovative solutions for handling critical areas such as waste management, real estate, finance, voting, and energy management. This section explores how blockchain is applied across different fields, highlighting its impact and potential for future urban development.

3.1 Waste Management

The increased urbanization, economic growth, population increase, and high living standards in developing countries have contributed to an increase in the amount of waste [19]. Waste management involves several processes, including collection, segregation, transportation, treatment, and final disposal or recycling of waste products [20]. Traditional waste management systems face several key challenges, including:

- **Lack of transparency and traceability.** Traditional waste management systems often fail to track the movement of waste, which leads to illegal dumping and unrecorded waste.
- **Data manipulation and fraud risks.** Use of paper records and centralized databases exposes waste data to the risk of manipulation and falsification.
- **Ineffective waste collection and sorting.** Lack of effective monitoring systems and manual sorting procedures leads to ineffective recycling.

- **Ineffective enforcement of regulations.** Most of the existing waste regulations lack effective means of enforcement, and therefore polluters cannot be held accountable.

- **High operational costs and financial inefficiencies.** Costs of waste collection, transport, and recycling are high due to inefficient manual processes.

- **Limited scalability in growing cities.** Increasing urban waste volumes overwhelm urban waste management systems, leading to overutilization of landfills and unsustainable waste disposal practices [20].

Blockchain technology offers various solutions to these issues by introducing transparency, automation, and decentralized control. Through the utilization of immutable records, smart contracts, and token-based incentives, blockchain has the potential to promote accountability, optimize waste management processes, and foster sustainable behavior in smart cities [19].

Transparent waste tracing and auditing features can be useful to verify the authenticity of waste management data. The immutable ledger aspect of blockchain guarantees that all transactions are accurately documented and monitored in real-time. Thus, in effect, promotes increased accountability on the part of waste management companies and lowers the possibility of fraudulent activities, such as misreporting disposal locations [20]. For instance, PlasticBank employs blockchain to track plastic waste collection operations and ensures that collected material is legally processed. This approach primarily addresses the lack of transparency and traceability in traditional waste management, as well as the data manipulation. However, its effectiveness depends on adoption rates and token usability [21].

Blockchain-based systems can motivate people and businesses to take part in proper waste disposal and recycling by issuing digital tokens that can be exchanged in terms of goods or services. Hence, cities and organizations can promote sustainable behavior while ensuring that waste ends up in appropriate recycling facilities instead of landfills [19]. Most solutions leverage Ethereum's ERC-20 tokens, which provide an efficient way to distribute incentives securely and transparently. One example is Recerum, a blockchain-based system that incentivizes proper waste disposal by rewarding users with digital tokens. Tokens can be used as a discount in the bill for energy, gas, garbage disposal, or other Recerum's partner services. It represents a solution for ineffective waste collection and sorting. Effectiveness of this approach depends on the stability and widespread acceptance of the token-based economy [22].

Smart contracts can also trigger real-time penalties when waste management companies or individuals fail to meet predefined terms or violate regulations (e.g. dumping of waste illegally, failure to meet recycling targets, or misrepresentation of waste) [19]. In the study "Industrial Wastewater Management using Blockchain Technology: Architecture, Requirements, and Future Directions", the authors proposed a blockchain-based solution for management of industrial wastewater. While the primary focus is on monitoring and tracking wastewater disposal, the architecture also supports the integration of smart contracts. These smart contracts can be programmed to automatically enforce compliance by imposing penalties on entities that violate environmental regulations. However, the implementation of such a system may face challenges, including high operational costs due to the need for advanced technological infrastructure and potential scalability issues [23].

Additionally, blockchain can enhance waste management regulations efficiency through smart contract automation. Blockchain-based solutions minimize manual verification efforts and eliminate intermediaries, which decreases administrative costs and increases overall accountability of services [19]. A practical example of this is IBM's partnership with PlasticBank, where smart contracts ensure that plastic waste collectors are paid fairly and transparently. This addresses inefficiencies in regulation enforcement, ensuring transparency and compliance with established rules. However, this approach depends on the adoption rate, because traditional methods may remain more practical due to lower technological requirements [21].

Blockchain-based solutions for waste management provide numerous benefits but also suffer from some limitations. Adoption barriers remain a significant hurdle, as most municipalities and traditional waste management businesses are hesitant to transition from traditional systems to decentralized ones. Thus, most of the aforementioned projects are currently in the pilot or prototype phase [21, 22, 24, 25, 26]. Most of these projects are based on the Ethereum platform, which faces scalability issues and high transaction fees [24, 25, 27, 28]. In contrast, other prototypes utilize Hyperledger Fabric due to its permissioned network structure and lower transaction costs [21, 29]. Also, IoT and smart bin integration is a significant step in waste management since it can enhance operational efficiency. But it requires enormous investment in infrastructure. Despite these limitations, the potential of blockchain to revolutionize waste management using AI and IoT can also enhance efficiency and enable more sustainable and transparent waste management solutions.

Blockchain-based tracking, incentivization, automation of smart contracts, and transparency in supply chains can significantly improve waste management systems of smart cities. Not only do they encourage environmental sustainability, but they also lower operational costs and bring about increased accountability at all levels of waste management.

3.2 Finance

Blockchain technology has its roots in finance, beginning with the creation of Bitcoin [30]. In the context of smart cities, blockchain's application in finance is a natural extension of its original purpose. Smart cities rely on interconnected systems and data-driven decision-making, which require trust, transparency, and efficiency - qualities that blockchain inherently provides.

Some of the issues traditional finance faces that can be solved by the usage of blockchain:

- **Money embezzlement.** Traditional finance relies on centralized systems, often scattered across multiple and private databases, allowing bad actors to manipulate records or divert funds without detection.

- **Money laundering.** Lack of real-time transparency and reliance on intermediaries in traditional systems make it easier to obscure the origins of illicit funds.

- **High transaction costs.** Traditional finance involves multiple intermediaries, manual processes, and complex verification systems, all of which drive up costs.

By integrating blockchain into financial systems, smart cities can tackle issues like corruption, inefficiency, and financial exclusion, paving the way for more equitable and sustainable urban development.

Blockchain ensures transparency and immutability, which significantly reduces the risks of money embezzlement and laundering [31]. The authors also highlight how blockchain can simplify crowdfunding by providing a secure and transparent platform for raising funds. Additionally, it becomes easier to determine users' credit scores, as all their transactions are recorded on a public ledger, ensuring accuracy and reliability [32]. Furthermore, blockchain eliminates the need for intermediaries, reducing transaction costs, particularly for cross-border payments [32].

A promising approach to enhance financial systems in smart cities is moving fiat money to blockchain [33], such as usage of Central Bank Digital Currencies (CBDCs) [34]. CBDCs are digital versions of a country's fiat currency, issued and regulated by the central bank. By replacing physical cash with CBDCs, smart cities can achieve greater efficiency, security, total transparency, and inclusivity in their financial ecosystems. Examples of operational CBDCs include the Sand Dollar [35] (built on NZIA Cortex DLT) and the eNaira [36] (built on Hyperledger Fabric). Meanwhile, the eAUD [37] (built on Quorum) is in its pilot state, and the development of Digital Euro [38] and Digital Dollar [39], and many more, is currently under research. The number of countries exploring CBDCs is steadily increasing and can be tracked [40, 41].

This approach is not without its own challenges. First one is regulatory compliance [32], which can be overcome by using private blockchains controlled by the government. Some authors [31, 32] question blockchain's ability to handle a sufficient number of transactions per second. However, this issue can be mitigated by using blockchain implementations with improved scalability. An added benefit of such implementations is their lower energy requirements for node operations, making the system more environmentally friendly [31].

3.3 Voting

Elections and other forms of anonymous voting are fundamental to democracy, the most prevalent form of governance worldwide. However, traditional voting methods have encountered numerous challenges, particularly in balancing privacy with transparency [42]. While privacy is essential to maintain the anonymity of votes, transparency is crucial to ensure that all votes are recorded accurately and remain unaltered. Traditional approaches often require a central authority to maintain this balance, but this can compromise transparency and does not inherently prevent issues such as vote duplication or unauthorized access to preliminary results [43]. The advent of electronic voting systems promises to address these complexities by offering new mechanisms for secure and verifiable voting processes, where each eligible voter can only vote once and results are safeguarded until the official count is completed.

In the context of smart cities, electronic voting systems can deliver additional benefits. Firstly, they reduce costs and increase efficiency, potentially reducing pollution as fewer physical materials and less transportation are required for setting up and conducting elections. This aligns with the broader smart city objectives of efficiency and environmental sustainability. Secondly, the enhanced accessibility and convenience of electronic voting can lead to greater voter participation, allowing residents to easily engage in the democratic process from remote or mobile locations [44]. Moreover, the interoperability of these systems with other smart city services facilitates a more integrated approach to urban management, enhancing the overall efficacy of public services. Additionally, the reduced operational costs associated with electronic voting can enable more frequent elections and referendums, allowing communities to engage more dynamically with issues as they arise. This can lead to a more responsive and adaptive form of urban governance, reflective of citizens' needs and preferences in real-time.

Blockchains offer enhanced privacy[30] with such techniques as blind signatures, homomorphic encryption, and mix networks[42], and they permit this without the need for a central controlling entity. As the theoretical framework of blockchain-based voting systems has shown promise, numerous implementations have emerged globally. In the following, specific solutions will be explored, highlighting their unique approaches to challenges and their use in real-life applications, distinct from the commonalities previously discussed:

- Follow My Vote [45] uses the Bitcoin blockchain framework and employs cryptographic verification along with a polling box suite to mathematically verify votes. The solution is designed for online voting.

- Voatz [46] is built on Hyperledger Fabric and incorporates biometric authentication, including fingerprints and retinal scans, alongside cryptographic verification to enhance security. It implements device security checks and restricts voting to one device per voter to prevent fraud. The system is used for mobile-based voting.

- Polyas [47, 48] operates on a private blockchain and utilizes cryptographic proof mechanisms for verification. It has been certified by the German Federal Office for Information Security and is used in Germany and other parts of Europe for electronic voting.
- Luxoft's [49] blockchain voting system runs on Hyperledger Fabric and uses smart contracts for consensus and vote auditability. It is implemented in Switzerland for government-backed voting projects. The system allows hybrid voting, combining e-voting with traditional voting methods, and has received very positive user feedback.
- Polys [50] is based on Ethereum and employs cryptographic privacy mechanisms for vote verification. It is backed by Kaspersky Lab and is used in student councils, unions, and local authorities for voting. The system also supports hybrid voting processes.
- Agora [51] uses a custom blockchain built on Bitcoin and incorporates "Vote" tokens to facilitate elections. It implements a legitimate consensus mechanism and participatory security to ensure a secure voting process. Agora was used in the 2018 presidential election in Sierra Leone.

Despite blockchain-based voting systems, so far looking very promising, they all have an unsolved problem - scalability [42]. These systems are not efficient at handling millions of transactions on a national scale, since there are limitations inherent in current blockchain frameworks like Bitcoin, Ethereum and Hyperledger Fabric, which cannot handle the transaction volumes compared to systems like Visa which processes a vast number of transactions daily. There is also a problem that occurs in traditional voting methods - coercion and vote-buying. At the moment there is no way to prevent individuals from giving away their keys, and allow others to use or check their vote.

The concept of a blockchain-based voting system, along with the solutions it has inspired, demonstrates a robust foundation capable of potentially replacing traditional election methods. These innovative approaches promise to offer a reliable and secure voting method, fostering greater trust among voters. As this technology continues to evolve, it holds the potential to transform electoral processes worldwide, ensuring more transparent and equitable voting practices.

3.4 Real Estate

The real estate sector plays a crucial role in a city's economy. While digitization of real estate offers significant benefits, it also demands careful consideration, as drastic changes could have unintended consequences and prove unsustainable for the economy. Research has shown that blockchain technology could add great value to the real estate sector in three categories: land administration, transaction efficiency and tokenization.

One of the primary challenges in real estate transactions is adverse selection. This term refers to a situation where sellers may possess superior information about property characteristics, potentially placing buyers at a disadvantage. The problem occurs when the buyer cannot access or verify information about an asset. This is particularly relevant in less developed countries where oral or locally registered contracts prevail [52].

Blockchain technology is proposed as a solution, offering a transparent and immutable digital ledger able to record every transaction with a timestamp and date, thereby reducing fraud and increasing trust among all parties, including banks, real estate agencies, buyers, and sellers. Additionally, it offers benefits even when compared to existing centralized record keeping systems, since it offers more security against cyber attacks and corruption.

Several successful projects have demonstrated the integration of blockchain technology into land registries, with notable examples in Sweden, Ghana, Georgia, and Afghanistan [53]. During the early stages of development, Sweden's land registry project faced setbacks when brokers and other organizations introduced their own platform to consolidate their market share and mitigate potential disruptions from the new technology [54]. Despite these challenges, this collaborative project by Lantmäteriet, Telia Company, ChromaWay, and Kairos Future, manages to improve transparency and trust by enabling all interested parties (buyers, sellers, banks, agents) to access data on a shared, immutable ledger. This significantly reduces the burden of manual verification and, in turn, speeds up the process of property transactions. Additionally, incorporating digital signatures offers major security improvements. An application was developed to facilitate interactions among all stakeholders. Property owners can verify ownership, agents can manage listings, buyers can access property information, and banks can conduct necessary checks - all within a unified digital platform [55].

Another notable initiative is goLandRegistry, developed by UN-Habitat in collaboration with the United Nations Office of Information and Communications Technology (OICT) and implemented in Afghanistan [56]. This project leverages LTO Network's hybrid blockchain solution [57], which enables adaptation and integration in various nations. With the Afghan government serving as a key stakeholder, the project underscores the critical role of collaboration and coordinated efforts in facilitating the successful adoption of blockchain-based land registry systems [58].

With increases in transparency and trust brought by blockchain-based registration of properties, we could expect a positive impact on transaction efficiency as well. The benefits may include reduced time for transactions, fraud reduction, simplified administrative processes, and even reduced need for intermediaries [52]. The potential of blockchain technology to enhance real estate transactions remains largely unrealized.

Theoretical frameworks support the concept of automating purchase and rental agreements through the use of Ethereum-based smart contracts, with the aim of streamlining transaction processes and reducing associated costs. However, these frameworks emphasize optimization rather than disintermediation of the process [59].

The concept of transforming real estate assets into digital tokens representing fractional ownership has been proposed as a means to enhance market accessibility, liquidity, and efficiency by reducing transaction times and associated costs. This innovation could broaden access to real estate investments for a wider range of investors [52]. Despite the intuitive appeal of the concept, regulatory complexities pose significant challenges, contributing to a limited body of literature on the topic. Notably, companies like RealT (RealToken) have made strides in addressing these challenges. RealT purchases residential properties and tokenizes legal entities that hold the deeds of the property according to US regulations. Management, maintenance, and rent collection of the properties are outsourced to a third party. After subtracting costs, the collected rent for the specific property is paid to token holders [60]. However, limited information is available regarding the underlying technology supporting this system, as the primary focus has been on regulatory compliance.

Numerous studies indicate that developing countries that have recently digitized their land registries using centralized databases have experienced significant instances of fraud and cyber attacks, leading to widespread disputes. This highlights the potential of blockchain even when compared to existing centralized record keeping systems, since it offers more security against cyber attacks and corruption. However, the implementation of such technologies poses significant challenges, primarily due to the fragmented nature of the system, which comprises numerous disconnected groups of stakeholders. Additional challenges for the adoption of blockchain-based systems may arise from third parties who don't fully recognize the benefit of more reliable information, or think their role in the system may be compromised. Regulations pose another issue, as some applications require legal amendments. For example, in Sweden, the application could not move to production because electronic signatures were not legally valid for real estate transactions. These challenges are particularly pronounced in the context of tokenization, as legal frameworks vary significantly across jurisdictions, even within the European Union. This regulatory fragmentation creates considerable barriers to the facilitation of cross-border transactions [54].

Given these factors, many blockchain-based real estate solutions remain largely at the conceptual stage. However, several established projects have demonstrated the potential for these systems to add tangible value to the industry. It is also important to note that the technological frameworks underpinning various real estate solutions often differ significantly. This lack of technological uniformity may stem from the infrequent nature of real estate transactions and the low likelihood of refunds, reducing the weight of specific blockchain technology choices in determining a project's success. Alternatively, the limited visibility into technological details may be attributed to proprietary corporate practices. Despite these challenges, the advancements made thus far highlight the promise of blockchain in enhancing transparency, efficiency, and accessibility in the real estate sector - paving the way for future research and innovation.

3.5 Energy Management

The way in which the energy sector has functioned so far and how electricity is generated, distributed, and consumed is not in line with the requirements of smart cities. This is because smart cities aim to improve quality of life, sustainability, and efficient resource utilization [61]. A few reasons why traditional, centralized energy systems are not adequate include:

- **Energy waste.** Energy is being overproduced in order to avoid power outages and energy loss during long-distance transmissions [61].
- **Environmental impact.** Centralized power plants mostly use non-renewable fossil fuels and therefore pollute the air, water, and land [62].
- **Single point of failure.** Failure of a major power plant can cause widespread blackouts and grid disruptions [63].
- **Higher costs.** Due to the high transaction costs associated with energy trading, ineffective administration, and requirement for middlemen to conduct transactions, centralized energy systems result in higher costs [63].

To address these challenges, researchers are attempting to transform centralized energy systems into decentralized ones. Due to the decentralized nature of blockchain, this technology is regarded as a promising solution for the development of distributed energy systems [61, 64].

Blockchain technology has introduced a user-friendly and efficient approach to establishing secure and reliable decentralized energy trading markets [65]. This development has been facilitated by the rise of smart grid technology, which enables individual users to generate energy from renewable sources [66]. These users can then either feed excess electricity directly into the main grid [67], engage in peer-to-peer energy trading [61], or pursue a combination of both options [65]. The energy trading process typically involves auction mechanisms with participants acting as both bidders and sellers. To facilitate these transactions, various auction methods have been utilized, including Vickrey second-price auction methodology [68] and double auction systems [63]. Although many of these proposed solutions such as [61, 65, 68] were not fully implemented in real-world scenarios, there have been a few successful implementations, such as Power Ledger [69], Brooklyn Microgrid [70], and Enerchain [71].

Power Ledger, an Australian technology company, developed a blockchain platform which enables households to trade energy.

This platform is used in Fremantle, Western Australia, where households generate solar energy and sell the excess to other households that offer to buy it [69]. Similarly to Power Ledger, the Brooklyn Microgrid represents another successful implementation of P2P energy trading. In Brooklyn, New York, neighbors use solar panels to generate energy and trade surplus with each other through the blockchain platform [70]. Enerchain is yet another proof that blockchain-based solutions for P2P trading can be successful, even though it works differently than Power Ledger and Brooklyn Microgrid. Enerchain is not intended for energy trading between neighbors but between energy companies. It has been implemented in Europe, where 45 leading energy companies participate in decentralized electricity and gas trading [71].

Blockchain solutions can encourage users to produce or consume energy from renewable sources by issuing digital tokens as rewards. NRGcoin and SolarCoin are both blockchain-based digital currencies that serve as great examples of token-based reward systems. A user is awarded one NRGcoin for every kilowatt-hour (kWh) of green energy supplied. These tokens can then be sold in currency markets or traded for green energy consumption [72]. On the other hand, SolarCoin is promoting only solar energy production and awards a user with a SolarCoin (SLR) for every megawatt-hour (MWh) of verified solar energy produced [73].

Although energy management systems based on blockchain technology offer several advantages, they also face certain challenges and drawbacks. One of the problems with blockchain technology is that some of the algorithms it uses, such as the proof-of-work consensus mechanism, require substantial energy. Specifically, the traditional auction methodologies used in these P2P trading platforms demand significant computational power, resulting in considerable energy usage. This high energy consumption directly opposes some of the reasons for implementing these blockchain solutions in the first place. As a result, researchers are currently exploring more effective decentralized auction methods for energy-trading applications [74]. Regulatory and legal challenges present additional barriers to the widespread adoption of this technology. Current regulations in many areas prohibit consumers from trading electricity directly with one another. For example, the application of blockchain technology in China is hindered by the country's monopolistic energy supply market structure, although the growing clean energy sector presents a significant opportunity for implementing blockchain [75]. In addition, the adoption of blockchain technology may require costly new infrastructure, including specialized hardware and software. Currently, smart meters deployed in the energy industry lack significant computational capability. Consequently, integrating the existing smart metering and grid infrastructure with distributed ledgers can result in substantial expenses [64].

In conclusion, the adoption of blockchain technology and the transformation of centralized energy systems are still in the early stages, with new research consistently being published. Many challenges still need to be addressed. However, the successful real-world implementation of various solutions has shown that this technology has the potential to support the creation of decentralized energy systems and smart cities [64].

4 DISCUSSION AND CONCLUSION

In this paper, we reviewed the current body of research on the application of blockchain technology in development of smart cities. Focus of the research was on five distinct sectors of a smart city, including waste management, finance, voting systems, real estate, and energy management.

Our research showed that blockchain brings significant improvements in security and transparency across various sectors. By decentralizing data storage and eliminating intermediaries, blockchain enhances trust and accountability, which is particularly beneficial in fields such as finance, voting, and waste management. The ability to create tamper-proof records ensures fraud prevention and reduces the risk of manipulation, which is a crucial advantage over traditional systems. Additionally, blockchain's transparency fosters greater public trust, as citizens and organizations can verify transactions and activities without relying on a central authority.

Despite these advantages, adoption remains limited, with most solutions still in the prototype or pilot phase. Table 1 highlights that many blockchain applications in smart cities face scalability issues, regulatory challenges, and infrastructure costs that hinder widespread implementation. For example, while blockchain can streamline real estate transactions by reducing reliance on intermediaries, compliance with government regulations remains a major barrier. Similarly, in the finance sector, blockchain reduces cross-border payment fees and fraud risks, yet its adoption largely depends on government incentives and acceptance. These findings suggest that while blockchain has the potential to improve urban management, its real-world implementation is still in its early stages.

A key observation across different fields is the distinction between permissioned and public blockchains. While Ethereum is commonly used for decentralized finance, incentive mechanisms, and peer-to-peer energy trading, Hyperledger Fabric is preferred in applications that require enterprise-level control and regulatory compliance, such as waste tracking and financial transactions within government systems. This suggests that blockchain adoption in smart cities will likely follow a hybrid approach, where both permissioned and public blockchains coexist depending on the specific use case and regulatory requirements.

The impact of blockchain varies across sectors, introducing new functionalities and efficiency improvements. In waste management, blockchain enables tokenized incentives for recycling and automates compliance enforcement. In voting systems, blockchain eliminates the need for a trusted authority, ensuring privacy, security, and fraud prevention, although scalability remains a challenge. Similarly, in real estate, blockchain enhances efficiency in property transactions but still requires high levels of coordination due to legal and regulatory constraints. The energy sector benefits from peer-to-peer energy trading, allowing for decentralized energy markets that optimize grid efficiency and reduce costs. Across all these applications, blockchain offers fraud prevention, automation, and cost reductions, demonstrating its broad applicability to smart city development.

However, one of the most pressing challenges remains scalability. Table 1 indicates that every sector, but real estate, faces issues related to handling high transaction volumes, which limits the practicality of blockchain in large-scale applications. Blockchain networks such as Ethereum are still working on scaling solutions, but current limitations prevent them from fully replacing traditional centralized systems. Additionally, regulatory and legal barriers continue to slow adoption, particularly in finance, real estate, and voting, where government intervention is necessary.

Future research should focus on developing scalable blockchain solutions while addressing regulatory and security challenges. Additionally, further exploration is needed on how blockchain can be seamlessly integrated into existing city infrastructure and how to develop more energy-efficient solutions to enhance sustainability. Nevertheless, substantial research efforts and a handful of successful real-world implementations of blockchain-driven solutions indicate that this technology will play a critical role in the future development of smart cities.

Table 1 Overview of Blockchain Applications and Adoption

Sector	Benefits	Challenges	Technology	Impact	References
Waste Management	Improved transparency and tracking, introduction of incentives and penalties	Scalability, regulatory compliance, IoT integration, adoption rate	Ethereum, Hyperledger Fabric	Incentives, compliance	Mostly in research
Finance	Improved transparency, prevents money laundering, money embezzlement and fraud, lowers transaction cost, improves credit score calculation	Regulatory compliance, scalability	Permissioned blockchains, e.g. Hyperledger Fabric, Quorum	Money laundering, embezzlement and fraud elimination, cheaper transactions, precise credit scores	Mostly in industry
Voting	Improved anonymity, automated and precise vote counting, fraud prevention	Privacy, transparency, scalability	No the technologies are standing out as favorites	Automated and precise vote counting, fraud prevention	Mostly in research
Real Estate	Reduced costs and time required, introduces partial real estate ownership	Regulatory compliance, adoption	Ethereum, LTO network	Partial real estate ownership	Mostly in research
Energy Management	Improved transparency, lower costs, minimal transmission losses, optimal grid efficiency	Transaction energy consumption, costly infrastructure, regulatory and legal challenges	Ethereum, Hyperledger Fabric	Incentives	Mostly in research

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