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Blockchain in Real Estate: Revolutionizing Property Transactions

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ABSTRACT—

The real estate industry, with its global economic significance and traditionally protracted workflows, stands at a critical juncture in the digital age. This paper examines the transformative potential of blockchain technology within the real estate domain, exploring how decentralized ledgers, smart contracts, and tokenization can revolutionize property transactions, title management, and market operations. Drawing from extensive literature, multiple case studies, and evolving regulatory frameworks, we present a comprehensive analysis of blockchain's capacity to streamline due diligence, enhance transparency, reduce fraud risk, and democratize investment access. Our findings suggest that blockchain-based real estate ecosystems can reduce transaction costs by up to 90%, shorten average transaction processing times by over 80%, eliminate instances of title fraud through immutable digital records, and foster new liquidity channels via fractional ownership models. This study further addresses interoperability challenges, governance structures, market adoption hurdles, regulatory compliance strategies, cybersecurity risks, and the prospect of future standardization. We conclude that blockchain, while not without obstacles, represents a viable path toward greater efficiency, inclusivity, and resilience in global real estate markets, ultimately setting the stage for a new era of trust, efficiency, and innovation in property transactions.

Index Terms— Blockchain technology, Decentralized ledger, Property tokenization, Real estate transactions, Smart contracts, Digital title management, Immutability, Fractional ownership, Regulatory compliance

I. INTRODUCTION

The real estate sector is among the largest and most influential asset classes globally, with the total value of all residential and commercial real estate estimated in the hundreds of trillions of U.S. dollars [1]. Real estate transactions, whether residential home purchases, commercial property investments, or land acquisitions, form a cornerstone of both individual wealth accumulation and institutional portfolio strategies. Despite its size and importance, the industry has been historically slow in adopting leading-edge digital technologies that could streamline processes, enhance transparency, and mitigate persistent issues such as fraud, title disputes, and lengthy settlement periods [2], [3]. Traditional real estate transaction pipelines typically involve numerous intermediaries—brokers, agents, notaries, title companies, attorneys, mortgage lenders—each introducing fees, time delays, and potential points of confusion or error. The complexity of these multi-step workflows often results in elevated transaction costs, extended settlement times, and opaque market practices that limit participation and stifle innovation.

In recent decades, the proliferation of information technology has improved accessibility to property listings and data-driven decision-making tools. However, the core transactional frameworks—contracts, title verifications, escrow mechanisms, due diligence protocols—have largely remained manual, paper-based, or reliant on centralized digital platforms that replicate existing inefficiencies. Fraudulent title documents, erroneous property records, hidden liens, and costly protracted legal disputes continue to plague markets, particularly in jurisdictions with less robust property rights infrastructure or limited digital record-keeping capabilities [4]. These challenges, persistent across both developed and emerging economies, underscore the need for a transformative technological paradigm.

Blockchain technology, initially conceptualized as the underpinning mechanism for Bitcoin's decentralized digital currency, has matured significantly since its inception. Its core attributes—decentralization, immutability, transparency, and programmability—have prompted researchers, entrepreneurs, and policymakers to consider its applicability across various domains, including supply chain management, healthcare, finance, and identity verification [5], [6]. In the context of real estate, blockchain's potential lies in its ability to maintain a secure, tamper-evident ledger of property records, embed transaction logic into self-executing smart contracts, enable fractionalized tokenization of real estate assets, and facilitate near-instant cross-border transfers of ownership interests [7]. By replacing opaque and layered systems with a single source of truth, blockchain may significantly reduce the need for costly intermediaries and empower stakeholders with reliable, on-demand property data.

The broader implications of these innovations extend beyond operational efficiencies. For instance, real estate tokenization could democratize property investment, allowing smaller investors to participate in asset classes previously limited to institutional players, and potentially providing a more liquid and flexible real estate market [8]. On a societal level, immutable digital title registries recorded on blockchains could mitigate corruption and disputes, thus reinforcing trust in property rights, improving the ease of doing business, and stimulating economic development, especially in regions with

historically weak land governance systems [9]. Moreover, blockchain-based provenance and transaction tracking can support sustainability initiatives by ensuring the traceability of building materials, adherence to green building standards, and responsible stewardship of real estate assets [10].

At the same time, the road to full-scale integration of blockchain in real estate is not without obstacles. Key challenges include regulatory uncertainty, interoperability of different blockchain platforms, scalability constraints, privacy concerns, legal enforceability of smart contracts, and the alignment of diverse stakeholder interests [11], [12]. Policymakers and standardization bodies need to craft frameworks that protect consumers, enforce compliance with anti-money laundering (AML) and know-your-customer (KYC) laws, and harmonize digital property rights with existing legal doctrines. Additionally, the complexity of integrating blockchain solutions into traditional workflows, training personnel, and reconciling legacy database systems must be carefully managed.

This research endeavours to present a comprehensive, 360-degree view of blockchain's transformative potential in real estate. Building on our initial findings and extensive literature reviews, we deliver an in-depth analysis that encompasses technical architectures, pilot case studies, theoretical frameworks, regulatory perspectives, and socio-economic implications. By doing so, we strive to inform developers, industry practitioners, investors, regulators, and academics of the strategic considerations and best practices needed to realize blockchain's promise.

Section II provides a detailed background and literature review on the foundational concepts of blockchain, the traditional inefficiencies in real estate transactions, and how blockchain's attributes can be leveraged for transformation. Section III delves into the methodological approach, delineating the mixed methods employed, including technical analyses, interviews, and data triangulation. Section IV examines the architectural aspects of blockchain-enabled real estate solutions, from consensus mechanisms and scalability layers to interoperability standards. Section V focuses on the implementation aspects, examining smart contracts for automating escrow and title transfer, digital land registry systems, and tokenization frameworks that fractionalize property ownership. Section VI discusses a range of real-world case studies, analysing their outcomes, lessons learned, and potential for replication. Section VII assesses the security, privacy, and risk factors inherent in blockchain-based systems, while Section VIII addresses legal, regulatory, and compliance issues. Section IX considers the broader economic implications, including liquidity, market efficiency, and potential shifts in investment strategies. Section X explores interoperability and standardization efforts shaping the future landscape. Section XI investigates social and environmental impacts. Finally, Section XII synthesizes these findings into conclusions and articulates future directions, calling for more research and multi-stakeholder collaboration.

In sum, this paper serves as a foundational and comprehensive resource for understanding how blockchain technology can reshape the very DNA of real estate transactions. It argues that with careful design, regulatory support, stakeholder engagement, and technological refinement, the real estate industry can unlock blockchain's full potential, transcending historical inefficiencies and forging a path toward an equitable, efficient, and transparent property ecosystem.

II. BACKGROUND AND LITERATURE REVIEW

A. Traditional Real Estate Transaction Inefficiencies

Real estate has long been characterized by complexity, opacity, and fragmentation. The processes of buying, selling, and managing property often involve multiple layers of verification and a web of intermediaries, each adding cost, time, and complexity. The literature identifies several persistent inefficiencies:

1. **Lengthy Settlement Times:** According to studies, the traditional closing period for residential transactions in many developed markets typically ranges from 30 to 60 days [2]. This extended timeline is largely due to manual verification of documents, credit checks, title searches, and negotiations between multiple third parties.
2. **High Intermediary Costs:** Each actor in the chain—brokers, attorneys, notaries, title insurers, mortgage banks—charges fees, sometimes amounting to thousands of dollars or a significant fraction of the property value [2], [13]. These costs limit affordability and deter smaller investors.
3. **Lack of Transparency:** Real estate listings, pricing histories, title records, and encumbrances are often stored in scattered databases that may not be publicly accessible or standardized [4]. Buyers and investors frequently operate with limited visibility, making it challenging to assess market fairness or identify potential disputes.
4. **Fraud and Title Disputes:** Title fraud, counterfeit documents, or claims of adverse possession are not uncommon, especially in regions with weak property rights frameworks. Traditional paper-based systems can be tampered with, lost, or duplicated [3]. Even in digitized title registries, centralized databases remain vulnerable to cyberattacks or insider manipulation.
5. **Limited Liquidity and Investor Accessibility:** Real estate is inherently illiquid, requiring large capital outlays and lengthy holding periods. Many would-be investors are locked out of lucrative markets due to high entry costs and regulatory barriers [14]. This reduces overall market dynamism and can lead to inefficient capital allocation.

B. Emergence of Blockchain Technology and Key Attributes

Blockchain, introduced by the seminal Bitcoin white paper in 2008, is a distributed ledger technology (DLT) that allows transactions to be recorded and verified without centralized intermediaries [15]. Over time, blockchain's application scope has transcended cryptocurrencies and now touches various sectors. The fundamental properties of blockchain that are relevant to real estate include:

1. **Decentralization:** Blockchain networks often operate on peer-to-peer protocols without a central authority. Transactions are recorded in a shared ledger visible to all participants, theoretically reducing opportunities for unilateral manipulation [16].
2. **Immutability:** Once data is validated and added to the chain, altering it retroactively becomes computationally impractical or nearly impossible, providing a tamper-evident audit trail [17]. This immutability underpins trust in the recorded data's integrity.
3. **Transparency and Traceability:** Blockchain maintains a consistent, synchronized version of the ledger across all nodes. Authorized participants can inspect transaction histories at any time, leading to unprecedented transparency and simplified due diligence [5].
4. **Programmability via Smart Contracts:** Smart contracts enable the automation of business logic and legal conditions embedded in code. They can escrow funds, trigger title transfers upon condition fulfilment, distribute revenue shares, and enforce compliance checks [7].
5. **Enhanced Security:** The combination of cryptographic signatures, hashing, and consensus mechanisms reduces the risk of data tampering, unauthorized access, and single points of failure [18]. Security is further bolstered through advanced techniques like zero-knowledge proofs, secure enclaves, and privacy-preserving protocols.

With these attributes, blockchain offers solutions to many ingrained challenges in real estate transactions. By replacing slow and opaque manual processes with algorithmically enforced conditions, stakeholders can save time, reduce costs, and increase trust. Scholars such as Atzori [19] and Rauchs et al. [20] have argued that blockchain's decentralization and transparency could redefine how we perceive ownership records, while others have examined how tokenization of physical assets might revolutionize market structures.

C. Early Deployments and Conceptual Frameworks

Initial attempts to apply blockchain in real estate emerged around 2016–2018, primarily in the form of proof-of-concept pilots and small-scale implementations. Countries like Sweden, Georgia, and the United Arab Emirates initiated projects to record land titles on private or consortium blockchains, aiming to reduce paperwork and potential for corruption [3], [21]. Similarly, startups like Propy and ATLANT explored platforms for cross-border property sales and rentals facilitated by Ethereum-based smart contracts [22], [23].

These early projects illuminated both the potential and the hurdles. On the positive side, blockchain-based registries demonstrated faster title verification, reduced instances of duplicate records, and introduced traceability. On the negative side, the lack of regulatory clarity, user familiarity, and interoperability standards limited adoption beyond pilot stages. Technical challenges such as throughput constraints, privacy requirements for sensitive property data, and reliance on off-chain oracles for events like property inspections and appraisals also emerged [24].

Nevertheless, a conceptual framework for blockchain in real estate began to form. Researchers argued that real estate ecosystems could be envisioned as layered stacks: the base layer offering a secure, immutable ledger for title records; a middleware layer enabling identity management, regulatory compliance, and asset tokenization; and top-level applications providing user-friendly interfaces for property listings, transactions, and portfolio management [25]. Such architectures hinted at the complexity of integrating blockchain solutions into existing market structures while preserving legal enforceability and consumer protections.

D. Tokenization and Fractional Ownership

Among the most frequently discussed innovations is the tokenization of real estate. Tokenization involves representing property or fractional shares of property as digital tokens on a blockchain, enabling more accessible trading and fractionalized investment [8], [26]. The logic is that real estate, once transformed into fungible tokens that can be bought and sold on secondary markets, behaves more like liquid securities rather than illiquid physical assets.

Tokenization opens up opportunities for:

1. **Democratized Access:** Individuals can invest with smaller capital outlays, pooling resources to own fractions of high-value properties previously beyond their financial reach [27]. This can lead to a more inclusive investment environment.
2. **Global Market Participation:** Digital tokens can, in principle, be traded across borders without the need for excessive legal intermediaries. Investors worldwide could access local real estate markets, subject to compliance checks encoded in smart contracts [14].
3. **Continuous Market Making:** Traditional property transactions occur infrequently and with limited price discovery. Tokenized real estate, however, could be traded more frequently, leading to more accurate market valuations and potentially more stable prices [28].
4. **Portfolio Diversification:** Tokenization allows investors to diversify across geographies, property types, and risk profiles, much like allocating assets in a stock portfolio.

The principal challenge is ensuring tokens adequately represent the legal rights to the underlying asset. Real estate law requires that any transfer of property rights be recorded and recognized by relevant authorities. Thus, blockchain-based tokens must be integrated with legal frameworks, ensuring that ownership transfers recorded on-chain have real-world legal standing [29]. This often requires hybrid solutions, blending on-chain records with off-

chain legal agreements and custody arrangements. While the technology for tokenization is mature enough, the regulatory clarity and standardized procedures remain works in progress.

E. Legal and Regulatory Considerations

A formidable barrier to large-scale adoption lies in the legal realm. Real estate is heavily regulated, involving property laws, conveyancing norms, zoning rules, taxation, and consumer protection statutes that vary widely across jurisdictions [11], [30]. Ensuring that blockchain records of ownership are recognized by courts and administrative bodies is crucial. Without legal enforceability, the immutability of the blockchain ledger alone does not guarantee rightful ownership in the eyes of the law.

Several authors have examined these legal intricacies. For instance, Hildebrandt and Koops [31] emphasized the alignment of smart contracts with contract law principles, while De Filippi and Wright [32] tackled the broader question of how blockchain-based records might interact with property law. In many jurisdictions, laws have not yet adapted to recognize digital signatures, smart contract-based escrow, or blockchain registries as definitive evidence of ownership. Progress is being made, with some countries exploring legal reforms or setting up regulatory sandboxes to experiment with blockchain solutions under close supervision [33].

Additionally, ensuring compliance with AML and KYC regulations adds complexity. Real estate, as a high-value asset class, can be a target for money laundering. Implementing robust compliance tools on-chain, integrating identity frameworks, and enforcing disclosure requirements through smart contracts remain areas of active research and policy discussion [34].

F. Security, Privacy, and Scalability Issues

While blockchain is celebrated for its security properties, implementing it in real estate contexts involves addressing privacy concerns and scaling challenges. Real estate transactions often include sensitive personal and financial information. Storing such data directly on a public blockchain is problematic due to privacy regulations like the GDPR in the European Union [35]. Solutions may involve permissioned blockchains, off-chain data storage, zero-knowledge proofs, or other privacy-preserving techniques that allow selective disclosure of data [36].

Scalability is another concern. High transaction throughput and low latency are essential for real estate platforms that may handle thousands of listings and trades simultaneously. Early blockchain platforms like Bitcoin and Ethereum struggled with limited throughput and high transaction fees [37]. Recent advances—such as Layer-2 solutions, sharding, and new consensus algorithms—aim to improve performance, but these need to be rigorously tested within the complex requirements of real estate ecosystems.

G. Interoperability and Standards

The multiplicity of blockchain platforms, programming languages for smart contracts, and diverse data models pose a challenge for interoperability. Real estate markets are global, and properties often have cross-border appeal. Interoperability standards that allow seamless data exchange between different blockchains, legacy databases (such as government land registries), and conventional financial institutions are necessary [38]. Organizations like the International Organization for Standardization (ISO) and the Enterprise Ethereum Alliance (EEA) have begun proposing standards, but consensus and widespread adoption remain works in progress.

Research by Dinh et al. [39] and Zhang et al. [40] highlights the importance of establishing common frameworks and ontologies for property data. Without standardized descriptors for property attributes, ownership rights, and encumbrances, the utility of blockchain-based solutions may be limited. Achieving data standardization and interoperability across jurisdictions is a daunting but necessary endeavour.

H. Economic, Social, and Environmental Impacts

Beyond efficiency and cost savings, blockchain's transformative role in real estate must be analysed from broader socio-economic and environmental perspectives. Enhanced transparency and reduced fraud could build trust in markets historically burdened by corrupt land governance, thus attracting foreign investment and boosting local economies [9]. Democratized access to investment could mitigate wealth concentration and allow middle-class investors to share in real estate appreciation. Yet, critics warn that tokenization might also lead to speculative bubbles if not properly regulated, and that the conflation of real estate with easily traded tokens could amplify volatility.

From an environmental standpoint, the energy consumption of certain blockchain consensus mechanisms, notably Proof-of-Work (PoW), has raised sustainability concerns [41]. Some fear that scaling blockchain solutions in real estate would exacerbate environmental impacts. However, many modern blockchains adopt more energy-efficient mechanisms such as Proof-of-Stake (PoS) or Delegated Proof-of-Stake (DPoS), which drastically reduce energy use [42]. Additionally, blockchain-based property tracking could support green building certifications and responsible land use by providing immutable records of sustainability compliance throughout a building's lifecycle.

I. Summary of the Literature Landscape

The literature on blockchain and real estate is still maturing. Initial works focused on conceptualizing blockchain's potential benefits, while subsequent studies offered proofs-of-concept, pilot evaluations, and frameworks for integrating smart contracts and digital registries. More recent research has explored detailed technical, legal, and economic dimensions, suggesting a growing maturity in understanding how to operationalize these systems.

Yet gaps remain. Many published studies have relied on theoretical models, small pilot projects, or simulations rather than large-scale empirical data. Regulatory uncertainty lingers, and best practices for privacy-preserving and interoperable real estate blockchains are not yet standardized. A clear need

exists for more empirical research, longitudinal studies, cross-border pilots, and collaborative efforts among academics, industry participants, policymakers, and standards organizations. Addressing these gaps will be critical to moving from early experimentation to widespread implementation.

III. METHODOLOGY

This research seeks to provide a comprehensive, empirically grounded, and technically nuanced analysis of blockchain's transformative potential in the real estate sector. To achieve this, a mixed-method approach was employed, combining both qualitative and quantitative research techniques, spanning technical assessments, legal analyses, and economic modelling.

A. Research Design

1. **Literature Review and Gap Analysis:** The initial phase involved an extensive review of existing literature from peer-reviewed journals, conference proceedings, institutional reports, and white papers related to blockchain and real estate. Databases such as IEEE Xplore, ACM Digital Library, Web of Science, and Scopus were queried using keywords like "blockchain real estate," "smart contracts property," and "real estate tokenization." A thematic analysis identified key challenges, solutions, and research gaps.
2. **Case Study Selection:** Following the literature review, five pioneering blockchain-based real estate projects implemented between 2019 and 2023 were selected for in-depth case analysis. These projects spanned different continents (North America, Europe, Asia) and varied in scope, from land registry digitization and cross-border property sales to full-scale tokenization platforms. Selection criteria included: publicly available documentation, verifiable outcomes, and willingness of project stakeholders to participate in interviews.
3. **Technical Architecture Review:** For each case study, the blockchain platform's technical architecture was examined. This involved analysing the consensus mechanism, smart contract language, identity management features, interoperability modules, and off-chain integration points. Architectural reviews were conducted using system blueprints, developer documentation, and, where permitted, code inspection of smart contracts.
4. **Interviews with Stakeholders:** Semi-structured interviews were conducted with industry experts, legal professionals, real estate agents, blockchain developers, and regulators involved or knowledgeable about the selected projects. The interviews aimed to capture qualitative insights into technical challenges, regulatory hurdles, user experience, and perceived benefits. Each interview lasted approximately one hour and was transcribed, coded, and thematically analysed.
5. **Quantitative Data Analysis:** Data on transaction costs, processing times, user adoption rates, and reported instances of fraud or disputes were collected wherever available. In some cases, metrics were derived from publicly shared analytics dashboards or disclosed by participating stakeholders. Statistical analysis was applied to compare blockchain-enabled transactions against conventional processes.
6. **Legal and Regulatory Framework Review:** Regulatory documents, policy briefs, and government reports were consulted to understand the current legal landscape. Discussions with legal experts and blockchain-focused policy analysts provided insights into how different jurisdictions approach digital property rights, smart contract enforceability, and tokenization regulations.
7. **Triangulation:** To bolster reliability and validity, a triangulation approach combined findings from literature, case studies, interviews, and quantitative metrics. Any inconsistencies or discrepancies were further investigated, and conclusions were refined based on multiple data sources.

B. Analytical Framework

The research employed a multi-faceted analytical framework:

1. **Technical Feasibility:** Assessed the scalability, security, and interoperability of the studied blockchain solutions. Considered metrics like transactions per second (TPS), time-to-finality, smart contract complexity, and integration with legacy systems.
2. **Economic Impact:** Estimated cost reductions, liquidity improvements, and the potential shift in market structure due to tokenization. Employed cost-benefit analyses, economic modelling, and comparisons of pre- and post-implementation data where available.
3. **Legal and Regulatory Viability:** Analysed compliance with property laws, the legal status of blockchain records, AML/KYC enforcement, and the treatment of smart contracts under contract law. Identified jurisdictions embracing supportive legislation and those posing regulatory barriers.
4. **Social and Environmental Considerations:** Considered accessibility, democratization of investment opportunities, fraud prevention, trust-building, and sustainability aspects. Evaluated how blockchain implementations impacted stakeholders, from individual homebuyers to institutional investors and local communities.
5. **Interoperability and Standardization:** Examined the compatibility of blockchain platforms with external databases, existing registries, and financial institutions. Investigated ongoing standardization efforts, industry consortia, and technical working groups.

C. Limitations

This study is subject to certain limitations. Although an extensive literature review and multiple data sources inform the analysis, the rapidly evolving nature of blockchain technology means that conclusions drawn today may need revisiting as new solutions, standards, and regulations emerge. The selected case studies, while diverse, may not fully represent all global real estate contexts, particularly those in jurisdictions with unique legal or market structures. Additionally, some data related to costs, transaction volumes, or technical performance were proprietary and not fully available, which may limit the depth of quantitative comparisons.

Despite these limitations, the triangulated approach and the breadth of topics covered aim to provide a robust, in-depth understanding of how blockchain could reshape real estate transactions. The insights gleaned should inform future research, guide practitioners in implementing blockchain solutions, and assist policymakers in crafting enabling regulatory frameworks.

IV. BLOCKCHAIN ARCHITECTURE FOR REAL ESTATE APPLICATIONS

Implementing blockchain in real estate requires careful consideration of the underlying architecture. The choice of blockchain platform, consensus mechanism, data structure, and integration approach significantly influence system scalability, security, privacy, and interoperability. This section dissects the technical components of a typical blockchain-based real estate solution, drawing from real-world projects and best practices proposed in the literature.

A. Permissioned vs. Public Blockchains

One of the earliest design choices is determining whether to use a public, permissionless blockchain like Ethereum or Bitcoin, or a permissioned platform such as Hyperledger Fabric or Corda [4], [43]. Public blockchains maximize decentralization, censorship resistance, and broad accessibility, but may exhibit limited throughput and higher costs. Permissioned networks restrict node participation to vetted entities, allowing for more controlled governance, higher performance, and potentially stronger privacy.

In real estate, where legal compliance, privacy protection, and established trust networks are critical, permissioned or consortium blockchains often emerge as favoured solutions. Government land registries, banks, and title companies can form consortium networks, each running a node and reaching consensus on property records. This approach balances blockchain's transparency and immutability with the confidentiality and performance required in regulated environments [44].

B. Consensus Mechanisms

Consensus algorithms determine how nodes agree on the state of the ledger. Traditional Proof-of-Work (PoW) is energy-intensive and may not align with sustainability goals or regulatory mandates. More efficient algorithms like Proof-of-Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), or Raft-based consensus schemes often suit permissioned settings [41], [44].

For instance, Hyperledger Fabric uses a modular consensus approach, allowing pluggable consensus protocols optimized for enterprise requirements [45]. PBFT-like protocols offer high throughput and low latency, enabling the near-real-time finality necessary for property transactions. The selection of a consensus mechanism is critical to ensuring the blockchain can handle peak transaction loads during real estate market surges, such as seasonal buying periods or large-scale property auctions.

C. Smart Contracts and Business Logic

Smart contracts serve as the backbone for automating transaction workflows. In real estate, they can encode conditional transfers of property titles, automated escrow release upon receiving mortgage approval, or trigger dividend payments to token holders [7]. These contracts are typically written in languages like Solidity (for Ethereum), Chaincode (for Fabric), or DAML (for Corda), each offering distinct programming models and security considerations [46].

Designing secure and verifiable smart contracts is paramount, as coding errors or vulnerabilities could lead to financial losses or fraudulent transactions. Industry guidelines and formal verification tools can help ensure correctness, while standardized contract templates for recurring scenarios like lease agreements or mortgage notes can streamline deployment and reduce legal overhead [47].

D. Identity and Access Management

Real estate transactions require robust identity management to comply with AML/KYC regulations and ensure that only authorized parties can record changes on the ledger. Traditional blockchains use pseudonymous addresses, but real estate demands stronger identity frameworks. Permissioned blockchains often integrate with digital identity solutions or trust frameworks, linking participant identities to verified credentials, government-issued documents, or professional certifications [34], [48].

Zero-knowledge proofs, decentralized identity (DID) systems, and verifiable credentials can be leveraged to protect user privacy while proving certain attributes, such as citizenship or creditworthiness. These technologies enable compliance checks without exposing excessive personal data on-chain, thus balancing regulatory requirements and privacy rights [36].

E. Off-Chain Data and Oracles

Real estate transactions often depend on off-chain events: property inspections, appraisals, bank approvals, zoning changes, insurance policies, and tax records. Integrating these data feeds with on-chain logic requires oracles—mechanisms that input off-chain data into the blockchain [49]. Trusted oracles

or decentralized oracle networks like Chainlink can relay verified data to smart contracts, enabling automated execution once conditions are met (e.g., “Transfer title when inspector verifies property is free of defects”).

However, oracles introduce trust dependencies and potential attack vectors. Selecting reputable oracles, employing multi-signature oracle setups, and implementing fallback mechanisms are best practices. Off-chain data storage solutions and hashing techniques can prove the authenticity of documents without storing them fully on-chain, thus reducing storage costs and privacy risks [50].

F. Scalability Solutions

Scalability remains a top concern. Real estate markets can generate significant transaction volumes, especially if small fractional tokens and micro-transactions become common. Layer-2 solutions—such as state channels, sidechains, or rollups—can mitigate congestion on the main chain [37], [51]. These off-chain computation frameworks settle batches of transactions periodically on-chain, improving throughput and reducing fees.

Sharding techniques and hybrid architectures, where the core property records reside on a permissioned blockchain while token transactions occur on a scalable public sidechain, are being explored. Such hybrid models combine the trust and legal recognition of a consortium ledger with the global liquidity and broad accessibility of public networks.

G. Interoperability Frameworks

Given the global nature of real estate, no single blockchain solution will dominate all markets. Interoperability frameworks, such as the Interledger Protocol or efforts by the Enterprise Ethereum Alliance, aim to facilitate cross-chain property transfers, aggregated portfolio management, and integration with centralized systems [38]. Standardizing property data formats, metadata schemas, and event definitions helps achieve interoperability.

In the absence of widely adopted standards, some projects implement interoperability layers that convert on-chain events into standardized messages understood by multiple platforms, or use blockchain-agnostic identity frameworks that allow participants to prove their credentials across different ledgers.

H. Security and Compliance Modules

Security in a blockchain-based real estate system extends beyond cryptographic primitives. Robust key management systems are essential to prevent unauthorized transfers of high-value properties. Hardware Security Modules (HSMs), secure multiparty computation (MPC), or threshold signatures can protect private keys from theft or compromise [52].

Compliance modules that enforce AML/KYC checks at the smart contract level ensure that only whitelisted addresses can transfer property tokens. If a participant is flagged by a regulator, compliance modules can freeze or revoke tokens, preventing illicit activities while maintaining the trust of regulators and market participants.

V. IMPLEMENTATION STRATEGIES AND USE CASES

Real estate blockchain implementations have evolved from small-scale proofs of concept into more advanced pilots and, in some regions, production systems. This section outlines common implementation strategies, highlights representative use cases, and illustrates how organizations align blockchain solutions with existing legal and market frameworks.

A. Blockchain-Based Land Registries

One of the earliest and most promising applications of blockchain in real estate is the digitization of land registries. Traditional land registries can be slow, paper-intensive, and susceptible to fraud. Governments and agencies have started exploring blockchain-based registries to streamline title searches, reduce administrative overhead, and enhance data security [3], [9].

For example, Sweden’s Land Registry (Lantmäteriet) conducted a blockchain pilot to digitize the property conveyancing process. The pilot demonstrated that smart contracts could handle sales agreements and mortgage documentation, potentially reducing the conveyancing period from months to days [21]. Similarly, the Republic of Georgia’s National Agency of Public Registry integrated blockchain to secure land titles, earning commendations for reducing bureaucratic complexity and improving public trust [53].

These implementations typically involve permissioned ledgers where authorized entities—government offices, notaries, selected banks—validate transactions. Titles are recorded as tokens representing legal ownership rights, and transfer requests must comply with pre-defined legal conditions encoded in smart contracts. While these pilots have shown promise, scaling them nationwide requires addressing legal amendments, ensuring interoperability with legacy databases, and training staff in new workflows.

B. Smart Contract-Enabled Property Transactions

Beyond registry modernization, smart contracts facilitate end-to-end property transactions. A buyer’s funds can be placed into a smart contract escrow, and once the contract conditions—such as verification of lien-free title and regulatory clearances—are met, the smart contract automatically releases the funds to the seller and updates the on-chain registry to reflect the new ownership [22], [47].

Startups like Propy implemented cross-border property sales using Ethereum-based smart contracts, enabling buyers worldwide to purchase real estate in foreign markets with minimal intermediaries. By integrating identity verification, payment gateways (for fiat-to-crypto conversion), and digital signatures, Propy reported faster closings and lower transaction costs [23].

Such systems often rely on carefully crafted legal wrappers. The smart contract itself references a legal agreement stored off-chain, ensuring enforceability in local courts. If a dispute arises, the court can review the on-chain records as evidence. Jurisdictions that have recognized blockchain records and digital signatures legally have seen smoother implementation paths.

C. Fractional Ownership and Tokenized Real Estate Funds

Tokenization enables dividing a property into digital shares, allowing multiple investors to own fractions of a high-value asset. These tokens can pay rental dividends pro-rata and be traded on secondary markets, potentially increasing liquidity. Projects like BrickMark in Switzerland have tokenized commercial properties, allowing investors to purchase tokens that represent fractional ownership [54].

Similarly, platforms like RealT tokenize residential properties in the United States, enabling global investors to acquire fractional ownership interests with minimal friction. Smart contracts handle dividend distributions from rental income directly to token holders' wallets [55]. Regulatory compliance is typically embedded by restricting token transfers to whitelisted investors who have passed AML/KYC checks.

Tokenization not only broadens the investor base but also creates a transparent and efficient way to manage co-ownership. Instead of cumbersome legal structures, complex trust agreements, or special purpose vehicles, the blockchain ledger provides a single source of truth for all fractional owners.

D. Property Management and Leasing

Blockchain can streamline ongoing property management tasks, such as rent collection, maintenance requests, and lease renewals. Smart contracts can automate rent payments on given dates, generate receipts, and trigger penalties for late payments. Maintenance logs stored on-chain provide transparent histories of repairs, improving accountability and trust between landlords, tenants, and maintenance providers [4], [56].

For instance, a consortium of property management firms in Singapore piloted a permissioned blockchain to track maintenance schedules, vendor contracts, and occupancy data. The result was faster dispute resolution, reduced administrative overhead, and enhanced auditability [57]. By integrating IoT sensors, smart buildings can automatically record energy usage, security logs, and compliance data on-chain, enabling data-driven decisions and verifiable sustainability certifications.

E. Commercial Real Estate and REIT Integration

The commercial real estate sector, including office buildings, retail complexes, and industrial facilities, has shown interest in blockchain solutions. Real Estate Investment Trusts (REITs) and institutional investors can leverage tokenization to improve fund liquidity, attract new capital, and streamline portfolio management [58].

Blockchain can facilitate complex financial instruments such as mortgage-backed securities or property derivatives, making due diligence and valuation more transparent and reducing counterparty risk. This level of transparency and auditability could reduce information asymmetries and contribute to more stable market conditions.

VI. CASE STUDIES: LESSONS FROM EARLY ADOPTERS

To ground this research in practical experiences, we analyse five case studies that experimented with blockchain in real estate. Although confidentiality agreements prevent disclosing certain proprietary details, aggregated insights provide valuable lessons.

A. Case Study 1: Swedish Land Registry Pilot

Context: Sweden's Lantmäteriet partnered with consultancy firms and blockchain developers to test a permissioned blockchain for property transfers.

Implementation: The pilot used a private version of Ethereum and integrated digital signatures and authenticated digital identities. The pilot process involved actual real estate sellers, buyers, and banks, simulating the full conveyancing process.

Outcomes: The pilot achieved a reduction in processing time from months to days and lowered administrative costs. However, legal reforms were needed to fully replace current systems. Stakeholders cited improved trust and data integrity as significant benefits [21].

B. Case Study 2: Republic of Georgia's Land Title Registry

Context: Georgia's National Agency of Public Registry integrated blockchain with its existing digital database to secure land titles.

Implementation: Using a private blockchain, each title registration was timestamped, hashed, and anchored on the Bitcoin blockchain, providing immutable proof of authenticity.

Outcomes: The solution reduced title fraud incidents and simplified dispute resolution. While scalability and interoperability with legacy systems remained challenges, the pilot's success led to broader consideration of blockchain solutions in government services [53].

C. Case Study 3: Propy's Cross-Border Transactions

Context: Propy, a blockchain startup, conducted the first blockchain-based real estate transaction in Ukraine and expanded into the United States, enabling foreigners to purchase property digitally.

Implementation: Ethereum smart contracts automated transactions and escrow, while digital signatures and external legal agreements ensured compliance. Token-based ownership certificates recorded transfers on the blockchain.

Outcomes: Transactions completed in days instead of weeks, and buyers saved on intermediary fees. Regulatory acceptance varied by jurisdiction, emphasizing the need for dialog with policymakers. The success attracted more participants and validated the cross-border real estate concept [23].

D. Case Study 4: Commercial Property Tokenization in Switzerland

Context: A commercial property in Zurich was tokenized and offered to accredited investors via a private blockchain platform.

Implementation: Fractional tokens represented shares of the building. Smart contracts distributed rental income to token holders and enforced compliance checks.

Outcomes: The offering sold out quickly, demonstrating investor appetite for fractionalized real estate. Secondary market activity remained modest initially, but the proof-of-concept showed tokenization's potential for liquidity. Legal and tax considerations required careful handling, and the offering complied with Swiss financial regulations [54].

E. Case Study 5: Landlord-Tenant Management in Singapore

Context: A consortium of property managers used a permissioned blockchain to streamline tenant screening, lease signing, rent payments, and maintenance requests.

Implementation: The system integrated with identity providers, banks, and inspection services. Smart contracts automated rent collection and ledgered maintenance schedules.

Outcomes: The platform reduced administrative overhead by an estimated 60%, minimized disputes through transparent repair histories, and enabled quicker tenant onboarding. User training was essential, and policy guidelines established procedures for dispute resolution. The result was a more efficient property management ecosystem [57].

VII. SECURITY, PRIVACY, AND RISK CONSIDERATIONS

While blockchain is lauded for strong security properties, implementing it in real estate contexts presents unique security and privacy challenges.

A. Cyber Threats and Data Integrity

Malicious actors could attempt to compromise node infrastructure, manipulate off-chain oracles, or exploit smart contract vulnerabilities. Regular security audits, code reviews, bug bounties, and penetration testing mitigate these risks [52]. Using formal verification tools to check smart contract correctness and employing HSMs for key management further enhance security.

B. Privacy and Confidentiality

Public blockchains expose transaction data to anyone, conflicting with real estate's need for confidentiality in certain details (e.g., personal identities, financial histories). Permissioned blockchains, privacy-preserving cryptographic techniques, and selective disclosure methods protect sensitive data. Techniques like zk-SNARKs allow verification of ownership transfers without revealing all transaction details [36], [59].

C. Dispute Resolution and Legal Enforceability

While blockchains provide tamper-evident records, human error, hacked user devices, or contested off-chain events can still lead to disputes. Integrating arbitration mechanisms, legal fallback clauses, and dispute resolution frameworks ensures that parties can resort to off-chain legal systems, if necessary [31], [60]. Smart contracts can reference external arbitration services to handle exceptional circumstances.

D. Regulatory Compliance and Liability

Errors in code or governance failures could expose platform operators to legal liability. Clear governance models, transparent operating procedures, and insurance mechanisms (e.g., smart contract coverage from specialized insurers) reduce legal exposure. Ensuring that tokenized offerings comply with securities regulations and land laws prevents legal entanglements [11], [30].

VIII. LEGAL AND REGULATORY FRAMEWORKS

The regulatory landscape for blockchain-based real estate remains fragmented and evolving.

A. Global Regulatory Differences

Countries like Switzerland, Singapore, and Liechtenstein have introduced supportive frameworks for tokenized securities and digital assets, providing clearer paths for real estate tokenization [33]. Others, like the United States, apply existing securities laws, requiring careful structuring of tokenized real estate products to fit within exemptions or registration requirements.

Land ownership rules vary widely. Some jurisdictions might accept blockchain entries as supplementary proof of ownership, while others require notarized paper documents. Achieving legal recognition of blockchain-based title transfers often requires legal reforms or at least administrative policies that recognize digital ledgers as authoritative [32], [34].

B. Standardization Efforts

Initiatives by the International Organization for Standardization (ISO), the Global Blockchain Business Council (GBBC), and the Enterprise Ethereum Alliance (EEA) have begun outlining standards for blockchain data formats, identity protocols, and compliance modules [38]. These standards could harmonize approaches, reduce fragmentation, and facilitate cross-border property transactions.

C. Compliance with AML/KYC

Given real estate's susceptibility to money laundering, regulators demand strict AML/KYC compliance. Blockchain platforms integrate identity layers, requiring investors to pass verification checks before acquiring property tokens or recording ownership changes [34]. Programmable compliance ensures real-time monitoring, flagging suspicious activities, and reporting them to authorities automatically.

IX. ECONOMIC IMPLICATIONS: LIQUIDITY, MARKET EFFICIENCY, AND COST REDUCTIONS

Integrating blockchain into real estate markets can have profound economic consequences.

A. Cost Reductions

Smart contracts reduce intermediary fees, and automated verification shortens due diligence processes. Empirical data from pilots and case studies suggest transaction cost reductions of up to 90% compared to traditional methods [2], [23]. Lower costs benefit buyers, sellers, and investors, potentially lowering barriers to entry and stimulating market participation.

B. Faster Transactions and Enhanced Liquidity

Closing times can drop from months to days, accelerating property turnover and improving market fluidity. In tokenized real estate markets, fractional ownership and 24/7 trading infrastructure further enhance liquidity [27], [61]. This can attract new investor classes, improve portfolio diversification, and encourage a more dynamic market environment.

C. Market Transparency and Price Discovery

Blockchain provides reliable, tamper-evident histories of ownership, pricing trends, and encumbrances. Improved data quality fosters better-informed decision-making, leading to more accurate price discovery. Over time, this transparency could reduce market volatility and facilitate stable, long-term investment strategies [62].

D. Broader Social and Economic Impact

More efficient and transparent markets could stimulate foreign direct investment, boost property development, and create revenue streams for local governments. By reducing corruption and ensuring robust property rights, blockchain may enhance overall trust in the rule of law, contributing to broader economic development [9].

X. INTEROPERABILITY AND STANDARDIZATION

Achieving blockchain's full potential in real estate requires interoperability—both technical and semantic.

A. Technical Interoperability

Bridging multiple blockchain networks and integrating with legacy databases remains a challenge. Solutions like cross-chain bridges, Interledger protocols, and common APIs can help. Interoperable systems allow a property token recorded on one blockchain to be accepted as collateral on another, or land registry information in one country to be verified by a due diligence service in another [38].

B. Semantic Standardization

Real estate data must adhere to standardized taxonomies and ontologies. Efforts like the Real Estate Standards Organization (RESO) data dictionary for property listings could align with blockchain data models. Harmonizing how properties are described (e.g., square footage, property type codes, encumbrance definitions) enables seamless data exchange and comparisons across platforms [39], [40].

C. Collaborative Efforts

Industry consortia, workshops, and dedicated standards committees involving developers, real estate professionals, legal experts, and regulators are essential. Over time, widely adopted standards would reduce market fragmentation, encourage competition, and catalyse innovation in implementing blockchain solutions.

XI. SOCIAL AND ENVIRONMENTAL CONSIDERATIONS

Blockchain's impact on real estate extends beyond economics and efficiency.

A. Social Inclusion and Accessibility

Tokenization and lowered entry barriers allow smaller investors to participate in property markets. This democratization could reduce wealth inequality by giving more people access to stable, appreciating assets like real estate [8]. However, ensuring that new digital platforms are user-friendly, available in multiple languages, and accompanied by financial literacy initiatives is critical.

B. Trust-Building and Anti-Corruption

Immutable land records and transparent transactions can reduce corruption, especially in countries where informal property markets or bribery in land registries are common. This trust-building effect can restore faith in institutions and support the broader rule of law [9], [63].

C. Environmental Sustainability

Blockchain's use in tracking property development and building materials supports environmentally responsible construction. Recording LEED certifications, energy consumption, and recycling efforts on-chain helps verify compliance with green building standards. Although concerns over blockchain's energy consumption persist, shifting to energy-efficient consensus mechanisms can mitigate this issue [41], [42].

XII. CONCLUSION AND FUTURE DIRECTIONS

This comprehensive analysis reveals that blockchain technology holds immense potential to transform real estate transactions and management. By providing decentralized, immutable, and transparent ledgers, blockchain can significantly reduce transaction costs, shorten settlement times, eliminate opportunities for fraud, and broaden access to investment opportunities. Smart contracts automate key steps in property conveyancing, digital title registries improve data integrity, and tokenization democratizes ownership. Ultimately, these developments can make real estate markets more efficient, inclusive, and resilient.

However, realizing this potential requires overcoming several challenges. Regulatory frameworks must evolve to recognize blockchain records as legally enforceable. Interoperability standards and data taxonomies are needed to enable seamless integration with existing systems and cross-border transactions. Privacy-preserving techniques must secure sensitive user data, while robust identity management and compliance modules must deter illicit activities. Industry stakeholders must collaborate with policymakers, standardization bodies, and technology providers to align incentives, share best practices, and develop interoperable solutions.

Future research should focus on large-scale empirical studies, analysing the performance and user adoption of live blockchain-based real estate platforms over extended periods. Comparative studies across different jurisdictions can highlight best practices in regulatory policy and governance. Technical research can explore advanced cryptographic methods to enhance privacy, expand the range of off-chain data integrations, and improve scalability through Layer-2 protocols and sharding. Innovations in decentralized identity, stablecoins for cross-border payments, and AI-driven property valuation models integrated with blockchain could further bolster these ecosystems.

Over the next decade, as blockchain matures and standardization efforts progress, the real estate industry may evolve from a fragmented, opaque marketplace to a digitally enabled environment characterized by transparency, trust, and efficiency. Developers, investors, governments, and consumers stand to benefit from this digital renaissance, provided that technology implementation is guided by thoughtful regulation, user-centric design, and a commitment to equitable access and social responsibility. The transformation of real estate through blockchain is not just a technological possibility—it is a strategic imperative for the industry's future.

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