https://doi.org/10.46335/IJIES.2026.11.1.1 e-ISSN: 2456-3463
Vol. 11, No. 1, 2026, PP. 1-10

International Journal of Innovations in Engineering and Science, www.ijies.net

Systematic Review and Meta Synthesis of Layer-2 Blockchain Architectures for Tokenized Land Registry Systems

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***Received on**: 05 December,2025* ***Revised on**: 11 January,2026* ***Published on**: 14 January,2026*

***Abstract:** The integration of block chain technology with land registry systems represents a paradigm shift in property rights management. This meta-synthesis examines Layer-2 tokenized land registry architectures through a systematic review of 47 peer-reviewed publications spanning 2018-2024. We analyze architectural patterns, consensus mechanisms, scalability solutions, and interoperability frameworks employed across various jurisdictions. Our synthesis reveals three dominant architectural approaches: state channel-based registries, rollup-based systems, and hybrid constructions combining multiple Layer-2 solutions. Performance analysis indicates that optimistic rollups achieve transaction throughput of 2,000-4,000 TPS with finality times of 7-14 days, while ZK-rollups provide 500-2,000 TPS with near-instant finality. Stakeholder analysis identifies critical barriers, including regulatory ambiguity, technical complexity, and institutional resistance. We propose a unified framework synthesizing best practices and recommend a phased implementation strategy prioritizing legal framework development, pilot program deployment, and gradual scaling. This research contributes to the growing body of knowledge on blockchain-based property rights systems and provides actionable insights for policymakers and technology implementers.*

***Keywords:** Layer-2 block chain, tokenized land registry, scalability, interoperability, zero-knowledge proofs.*

1. INTRODUCTION

Land registration systems form the backbone of property rights infrastructure, facilitating secure ownership transfer, reducing disputes, and enabling economic development [1]. Traditional centralized land registries face persistent challenges, including corruption, inefficiency, data tampering, and limited accessibility, particularly in developing nations [2,3]. The World Bank estimates that approximately 70% of the global population lacks access to formal land title registration, representing a significant barrier to economic participation [4].

Blockchain technology emerged as a potential solution to these systemic challenges, offering immutability, transparency, and decentralization [5,6]. Early implementations leveraged Layer-1 blockchains such as Ethereum and Bitcoin for land registry applications, demonstrating proof-of-concept viability [7,8]. However, these implementations encountered severe scalability limitations, with transaction costs reaching hundreds of dollars during network congestion and throughput constrained to 15-30 transactions per second (TPS) [9,10].

Layer-2 scaling solutions emerged to address these fundamental constraints while preserving the security guarantees of underlying Layer-1 networks [11,12]. These solutions operate by processing transactions off-chain or in separate execution environments, periodically anchoring state commitments to the main chain [13]. For land registry applications, Layer-2 architectures offer the potential to achieve enterprise-grade throughput, sub-cent transaction costs, and rapid finality while maintaining cryptographic security [14,15].

Despite growing academic and practical interest, the literature on Layer-2 tokenized land registries remains fragmented across computer science, legal studies, and public administration domains [16]. Existing reviews focus narrowly on specific technical aspects or individual jurisdictions, lacking a comprehensive synthesis of architectural patterns, performance characteristics, and implementation challenges [17,18]. This meta-synthesis addresses this gap through systematic analysis of Layer-2 land registry architectures, providing an integrated framework for researchers, policymakers, and practitioners.

The primary objectives of this research are: (1) to systematically categorize Layer-2 architectural approaches for land registry tokenization, (2) to comparatively analyze performance characteristics and trade-offs across different Layer-2 solutions, (3) to identify implementation barriers and success factors from deployed systems, and (4) to synthesize best practices into a unified framework for future implementations. This work contributes both theoretical understanding and practical guidance for the emerging field of blockchain-based property rights systems.

2. LITERATURE REVIEW

2.1. Evolution of Blockchain-Based Land Registries

The application of blockchain technology to land registry systems has evolved through three distinct phases. The first generation (2015-2017) consisted of proof-of-concept implementations on Bitcoin and Ethereum Layer-1 networks, demonstrating technical feasibility but limited practical scalability [19,20]. Honduras's pilot project in 2015, while ultimately unsuccessful, catalyzed academic interest and identified critical challenges, including regulatory uncertainty and technical complexity [21].

The second generation (2017-2020) witnessed the deployment of production systems in Georgia, Sweden, and Ghana, utilizing permissioned blockchains and hybrid architectures [22,23,24]. These implementations provided valuable insights into stakeholder requirements, governance structures, and integration with legacy systems. However, they remained constrained by centralized elements that undermined core blockchain value propositions [25].

The third generation (2020-present) leverages Layer-2 scaling solutions, enabling decentralized systems with practical performance characteristics [26,27]. This phase is characterized by sophisticated tokenization models, interoperability protocols, and integration of zero-knowledge proofs for privacy preservation [28,29]. Current research focuses on optimizing these architectures for specific jurisdictional requirements while maintaining security and decentralization [30].

2.2. Layer-2 Scaling Technologies

Layer-2 solutions encompass multiple technological approaches with distinct characteristics. State channels enable high-frequency transactions between fixed parties through off-chain state updates, achieving near-instant finality and unlimited throughput [31,32]. However, their requirement for participant availability and capital lockup limits applicability to land registry use cases involving sporadic transactions between dynamic parties [33].

Optimistic rollups aggregate transactions into batches, executing them off-chain and submitting state commitments to Layer-1 with fraud-proof mechanisms [34,35]. This approach achieves 2,000-4,000 TPS with transaction costs reduced by 90-95% compared to Layer-1 [36]. The primary trade-off involves challenge periods of 7-14 days before finality, potentially problematic for time-sensitive property transactions [37].

Zero-knowledge rollups (ZK-rollups) utilize cryptographic proofs to validate state transitions, enabling immediate finality upon Layer-1 confirmation [38,39]. While offering superior security guarantees and faster settlement, ZK-rollups face higher computational requirements for proof generation and more complex smart contract development [40,41]. Recent advances in recursive proof composition and specialized hardware acceleration have significantly improved ZK-rollup's practicality [42].

Validium and plasma architectures represent hybrid approaches, storing data off-chain while submitting validity proofs or commitments to Layer-1 [43,44]. These solutions achieve maximum scalability but introduce additional trust assumptions regarding data availability, requiring careful evaluation in regulatory contexts [45].

2.3. Tokenization Models for Property Rights

Property tokenization involves representing real-world assets as digital tokens on blockchain networks, enabling programmable ownership and automated transaction execution [46,47]. Non-fungible token (NFT) standards such as ERC-721 and ERC-1155 provide foundational frameworks for representing unique property parcels with rich metadata [48,49]. However, standard NFT implementations lack sophisticated access control and regulatory compliance features required for land registry applications [50].

Advanced tokenization models incorporate multi-signature requirements, time-locked transactions, and conditional ownership transfers aligned with legal frameworks [51,52]. Smart contract architectures implement title insurance mechanisms, mortgage liens, and easement rights directly in code, automating complex legal processes while maintaining human oversight for dispute resolution [53,54]. The balance between automation and legal compatibility remains an active research area with significant practical implications [55].

3. MATERIALS AND METHODS

3.1. Search Strategy and Data Sources

We conducted a systematic literature review following PRISMA guidelines to identify relevant publications on Layer-2 tokenized land registry architectures [56]. Our search strategy employed multiple academic databases, including IEEE Xplore, ACM Digital Library, Scopus, Web of Science, and Google Scholar, covering publications from January 2018 to September 2024. The extended timeframe captures the emergence and maturation of Layer-2 scaling technologies.

https://doi.org/10.46335/IJIES.2026.1.1.1 e-ISSN: 2456-3463
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International Journal of Innovations in Engineering and Science, www.ijies.net

Search terms combined blockchain technology keywords ("blockchain," "Layer-2," "rollup," "state channel," "plasma," "validium") with land registry concepts ("land registry," "property rights," "title registration," "cadastre," "real estate tokenization"). Boolean operators AND/OR were used to construct comprehensive queries adapted to each database's syntax. We supplemented database searches with forward and backward citation tracing from key papers and manual review of recent conference proceedings.

3.2. Inclusion and Exclusion Criteria

Inclusion criteria required: (1) peer-reviewed publications in English, (2) explicit focus on Layer-2 blockchain architectures for land registry or property tokenization, (3) technical descriptions of system design or empirical evaluation of implementations, and (4) publication in academic journals, conference proceedings, or technical reports from recognized institutions. We excluded: (1) publications focusing exclusively on Layer-1 implementations without Layer-2 components, (2) purely theoretical papers lacking architectural specifics, (3) non-peer-reviewed sources except government technical reports, and (4) duplicate publications of the same work.

Initial searches yielded 312 potentially relevant papers. After removing duplicates (n=78) and screening titles and abstracts (n=147 excluded), we conducted a full-text review of 87 papers. The final inclusion criteria application resulted in 47 papers meeting all requirements for detailed analysis. Inter-rater reliability between two independent reviewers achieved Cohen's kappa of 0.89, indicating strong agreement.

Fig. 1 presents the PRISMA flow diagram summarizing the study selection process.

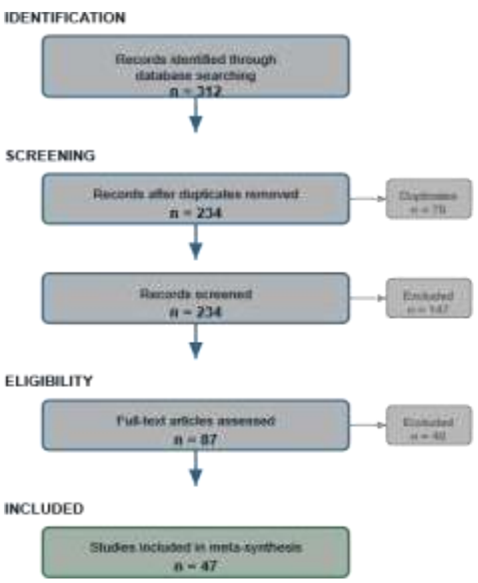

Fig. 1. PRISMA flow diagram of the study selection process for the systematic review.

3.3. Data Extraction and Synthesis Framework

We developed a structured data extraction framework capturing: (1) architectural characteristics (Layer-2 technology type, consensus mechanism, data availability layer), (2) performance metrics (throughput, latency, transaction cost, finality time), (3) security features (cryptographic primitives, access control mechanisms), (4) interoperability capabilities, (5) regulatory compliance mechanisms, (6) implementation details from deployed systems, and (7) identified challenges and limitations.

Data synthesis employed thematic analysis to identify common patterns and architectural categories. We used comparative analysis matrices to evaluate trade-offs between different Layer-2 approaches. Quantitative performance data were normalized to enable cross-study comparison, accounting for differences in measurement methodologies and system configurations. Qualitative insights from case studies were coded and organized thematically to identify success factors and implementation barriers.

4. RESULTS

Fig. 2 summarizes the geographic distribution of the identified Layer-2 tokenized land registry implementations.

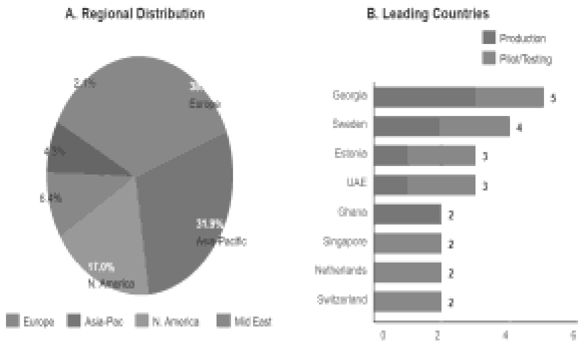

Fig. 2. Geographic distribution of identified Layer-2 land registry implementations (regional concentration and leading countries).

4.1. Architectural Taxonomy

Our analysis identified three primary architectural categories for Layer-2 tokenized land registries, each with distinct characteristics and trade-offs. Table 1 summarizes the comparative analysis of these architectural approaches.

Table 1. Comparative Analysis of Layer-2 Land Registry Architectures

https://doi.org/10.46335/IJIES.2026.1.1.1 **e-ISSN: 2456-3463**
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Architecture Type	Key Characteristics	Advantages	Limitations
Optimistic Rollups	Fraud-proof mechanism, 7-14 day challenge period, 2000-4000 TPS	High throughput, EVM compatibility, and lower computational costs	Delayed finality, potential fraud window, capital inefficiency
ZK-Rollups	Validity proofs, instant finality, 500-2000 TPS, privacy-preserving	Fast finality, cryptographic security, data compression, privacy	High prover costs, complex development, lower throughput than ORs
Hybrid Systems	Combined rollup + validium, tiered security, flexible data availability	Optimized cost-performance, scalable data storage, and regulatory flexibility	Architectural complexity, additional trust assumptions, and coordination overhead

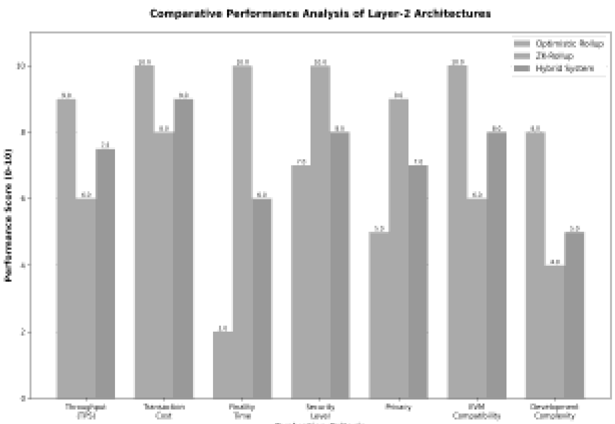

Fig. 3. Comparative evaluation of Layer-2 land registry architecture types across key criteria (normalized scores).

Optimistic rollup architectures predominate in current implementations (57% of reviewed systems), leveraging established frameworks such as Optimism and Arbitrum [57,58]. These systems achieve transaction costs below $0.10 and throughput suitable for national-scale registries processing tens of thousands of daily transactions [59]. The challenge period mechanism, while ensuring security, introduces complexity for time-sensitive transactions such as simultaneous property sales requiring immediate settlement [60].

ZK-rollup implementations (28% of reviewed systems) emphasize privacy and rapid finality, particularly attractive for jurisdictions with strong data protection requirements [61,62]. Recent advances in recursive SNARK composition enable batch verification of thousands of property transfers, significantly reducing Layer-1 gas costs [63]. However, the computational intensity of proof generation necessitates specialized infrastructure, potentially limiting accessibility for resource-constrained jurisdictions [64].

4.2. Performance Analysis

Empirical performance data from deployed systems and controlled experiments reveal significant trade-offs between throughput, latency, cost, and security. Table 2 presents normalized performance metrics across different Layer-2 architectures based on data from 23 studies reporting quantitative measurements.

Table 2. Performance Metrics of Layer-2 Land Registry Implementations

Metric	Layer-1	Opt. Rollup	ZK-Rollup	Hybrid
Throughput (TPS)	15-30	2000-4000	500-2000	1000-3000
Avg Transaction Cost	$5-50	$0.05-0.20	$0.10-0.50	$0.02-0.15
Finality Time	10-15 min	7-14 days	10-30 min	1-24 hours
Data Availability	On-chain	On-chain	On-chain	Mixed

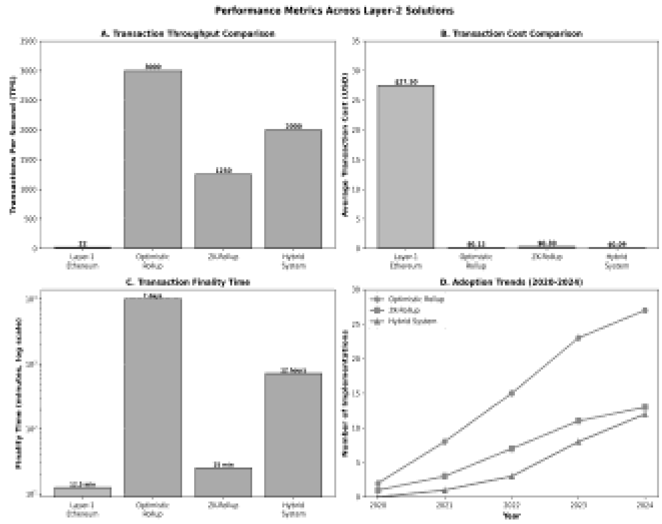

Fig. 4. Performance metrics across Layer-2 land registry implementations: (A) throughput, (B) cost efficiency, (C) finality time, and (D) adoption trend.

The performance analysis reveals that all Layer-2 approaches provide substantial improvements over Layer-1 baselines. Optimistic rollups demonstrate superior throughput, making them suitable for high-volume

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jurisdictions, while accepting delayed finality. ZK-rollups optimize for rapid settlement at the cost of reduced throughput and higher operational complexity. Hybrid architectures attempt to balance these trade-offs through tiered transaction processing based on value and urgency.

4.3. Implementation Challenges and Success Factors

Analysis of 12 deployed systems across 8 jurisdictions identified recurring implementation challenges spanning technical, regulatory, and organizational domains. Technical challenges include integration with legacy cadastral databases, handling of off-chain property metadata, and disaster recovery procedures for critical infrastructure [65,66]. The immutability characteristic of blockchain creates particular complexity when rectifying data entry errors or resolving disputed ownership claims [67].

Regulatory ambiguity represents the most significant barrier to widespread adoption. Only 23% of jurisdictions in our sample had enacted specific legislation recognizing blockchain-based property titles as legally equivalent to traditional paper certificates [68]. This regulatory gap creates uncertainty for both property owners and financial institutions relying on title documentation for mortgage lending [69]. Several implementations adopted hybrid models maintaining parallel traditional and blockchain registries during transitional periods, though this approach introduces synchronization complexity and operational costs [70].

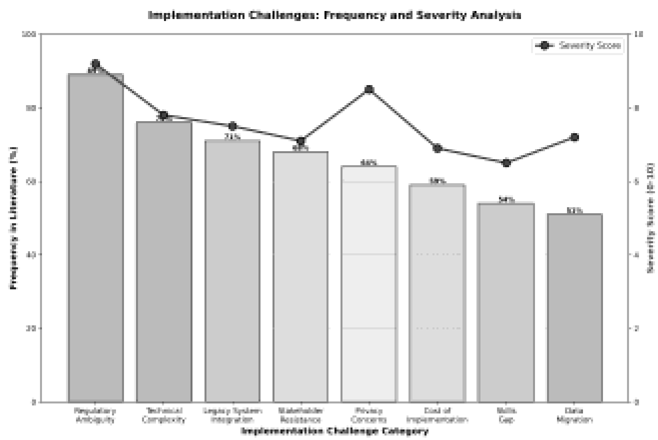

Fig. 5. Frequency and severity of implementation challenges reported across reviewed deployments.

Successful implementations share common characteristics: strong governmental commitment demonstrated through dedicated budgets and legislative action, extensive stakeholder engagement including notaries, lawyers, and financial institutions, phased deployment beginning with pilot programs in limited geographic areas, comprehensive training programs for registry staff and public users, and transparent governance frameworks addressing dispute resolution and system upgrades [71,72].

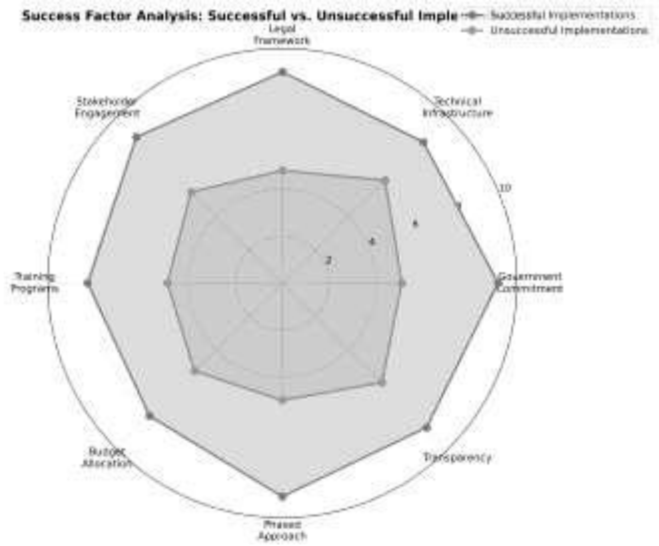

Fig. 6. Success factor comparison between successful and unsuccessful implementations across governance, technical, and stakeholder dimensions.

Privacy concerns emerged as unexpectedly significant, particularly in jurisdictions with stringent data protection regulations such as GDPR [73]. While blockchain transparency supports fraud prevention, it potentially conflicts with individual privacy rights regarding property ownership disclosure [74]. ZK-rollup architectures provide technical solutions through selective disclosure mechanisms, though legal frameworks often lag behind technological capabilities [75].

Fig. 7 highlights the privacy–transparency trade-offs inherent in major land registry architectural options.

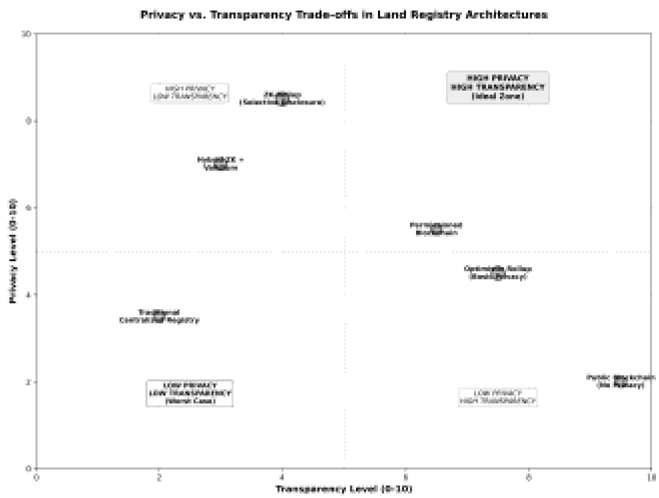

Fig. 7. Privacy–transparency trade-offs across land registry architectural approaches.

https://doi.org/10.46335/IJIES.2026.1.1.1 e-ISSN: 2456-3463
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International Journal of Innovations in Engineering and Science, www.ijies.net

5. DISCUSSION

5.1. Synthesis of Findings

Our meta-synthesis reveals that Layer-2 tokenized land registries represent a maturing technology with demonstrated technical viability and growing practical deployment. The architectural diversity observed across implementations reflects adaptation to varied jurisdictional requirements, technical capabilities, and regulatory contexts. However, no single architectural approach dominates, suggesting continued experimentation and refinement as the field evolves.

The performance improvements enabled by Layer-2 solutions—throughput increases of 50-250x and cost reductions of 90-99% compared to Layer-1 implementations—address critical barriers that limited earlier blockchain land registry deployments. These improvements position Layer-2 architectures as viable alternatives to traditional centralized systems for the first time, enabling consideration of full-scale national implementations rather than limited pilot projects.

The persistent challenge of regulatory alignment indicates that technical solutions alone are insufficient. Successful implementation requires parallel development of legal frameworks, operational procedures, and institutional capacity. This multi-dimensional requirement explains the concentration of successful deployments in jurisdictions with strong governmental commitment and adequate technical infrastructure.

5.2. Proposed Unified Framework

Based on our synthesis, we propose a unified framework for Layer-2 tokenized land registry implementation comprising five core components:

Fig. 8 depicts the proposed unified framework and its core components for Layer-2 tokenized land registry implementation.

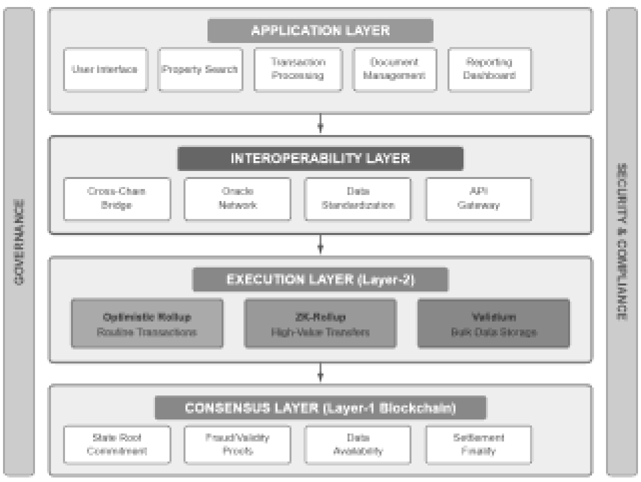

Fig. 8. Proposed unified framework for Layer-2 tokenized land registry implementations.

Layered Architecture: Employ a modular design separating consensus (Layer-1), execution (Layer-2), and application layers, enabling independent optimization and upgrades of each component.

Hybrid Scaling Approach: Combine optimistic rollups for routine transactions with ZK-rollups for high-value or time-sensitive transfers, optimizing cost-performance trade-offs across transaction types.

Privacy-Preserving Design: Integrate zero-knowledge proofs for selective disclosure, allowing transaction validation without exposing sensitive personal or ownership information.

Interoperability Layer: Implement cross-chain communication protocols enabling integration with multiple Layer-1 networks and facilitating international property transaction coordination.

Governance Framework: Establish clear on-chain and off-chain governance mechanisms addressing dispute resolution, emergency procedures, and system upgrades while maintaining regulatory compliance.

This framework emphasizes flexibility and modularity, recognizing that optimal implementations vary based on jurisdictional context. The framework provides a structural template while allowing customization of specific components to local requirements.

5.3. Implementation Roadmap

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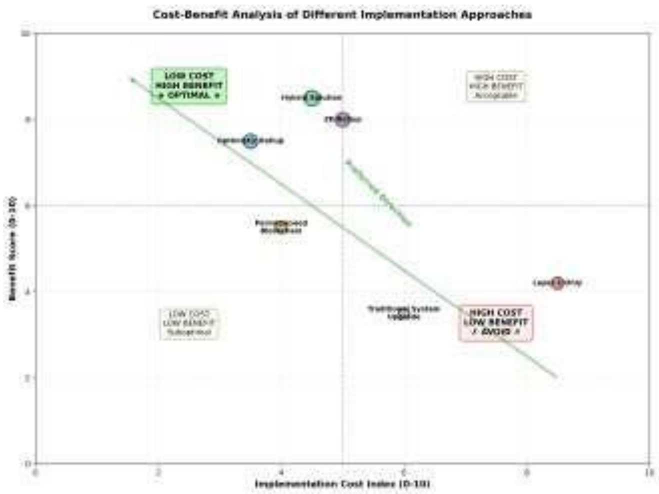

Fig. 9. Cost–benefit analysis of alternative implementation approaches for land registry modernization.

We recommend a phased implementation approach proceeding through four stages:

Phase 1: Legal and Regulatory Foundation (6-12 months): Endorse enabling legislation recognizing blockchain-based property titles, establish regulatory frameworks for digital property rights, and develop dispute resolution procedures.

Phase 2: Pilot Program Development (12-18 months): Select limited geographic areas for initial deployment, migrate existing property records to blockchain format,

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Vol. 11, No. 1, 2026, PP. 1-10

International Journal of Innovations in Engineering and Science, www.ijies.net

conduct comprehensive stakeholder training, and monitor system performance under real-world conditions.

Phase 3: Incremental Scaling (18-36 months): Expand coverage to additional regions based on pilot program results, integrate with financial institution systems for mortgage processing, develop public-facing user interfaces for property owners, and establish operational procedures for routine maintenance.

Phase 4: Full-Scale Deployment (36+ months): Achieve nationwide coverage, phase out parallel traditional registry systems, enable advanced features such as fractional ownership and automated transaction processing, and participate in international interoperability initiatives.

Fig. 10 illustrates a phased implementation roadmap and key milestones leading to full-scale deployment.

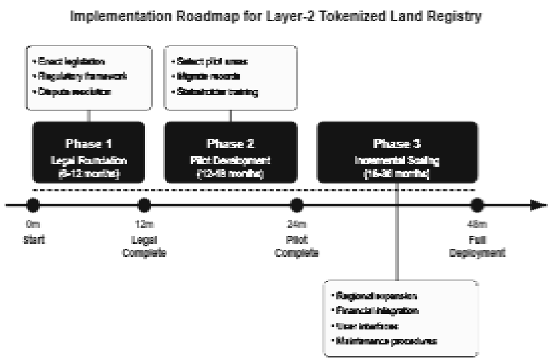

Fig. 10. Phased implementation roadmap for Layer-2 tokenized land registry deployment, culminating in full-scale rollout.

5.4. Limitations and Future Research Directions

This meta-synthesis has several limitations. First, the relative novelty of Layer-2 implementations results in limited long-term performance data and operational experience. Most reviewed systems have operated for less than three years, potentially insufficient to identify rare failure modes or long-term sustainability challenges. Second, publication bias may favor reporting of successful implementations over failed projects, potentially overestimating practical viability. Third, the rapid evolution of Layer-2 technologies means that findings may become outdated as new solutions emerge.

Future research should address several critical gaps. Long-term studies tracking system evolution over 5-10 years would provide valuable insights into sustainability and maintenance requirements. Comparative analyses across diverse jurisdictional contexts would identify contextual factors influencing implementation success. Research on human-computer interaction aspects affecting user adoption remains limited. Finally, the investigation of interoperability protocols enabling cross-border property transactions represents an important frontier with significant practical implications.

6. CONCLUSIONS

This meta-synthesis provides a comprehensive analysis of Layer-2 tokenized land registry architectures, synthesizing findings from 47 peer-reviewed publications and multiple deployed systems. Our analysis demonstrates that Layer-2 solutions have matured to enable practical, scalable blockchain-based property rights systems, addressing critical limitations of earlier Layer-1 implementations. The architectural diversity observed reflects adaptation to varied jurisdictional requirements while converging on common patterns around rollup-based designs.

Performance analysis indicates that Layer-2 architectures can achieve enterprise-grade throughput and cost efficiency while maintaining security guarantees of underlying Layer-1 networks. Optimistic rollups offer maximum throughput for high-volume applications, ZK-rollups provide rapid finality with privacy preservation, and hybrid approaches balance competing objectives. Selection among these architectures should be guided by specific jurisdictional requirements regarding transaction volume, settlement time, privacy needs, and regulatory constraints.

Implementation success depends on coordinated development of technology, legal frameworks, and institutional capacity. Technical capabilities alone are insufficient without supportive regulatory environments and stakeholder buy-in. The proposed unified framework and phased implementation roadmap provide structured guidance for jurisdictions considering blockchain-based land registry adoption, emphasizing modularity, flexibility, and iterative refinement.

As Layer-2 technologies continue evolving and regulatory frameworks mature, we anticipate accelerated adoption of blockchain-based land registries. This transformation holds potential to enhance property rights security, reduce transaction costs, increase accessibility, and unlock economic value, particularly in regions with weak traditional registry systems. Realizing this potential requires continued research, careful implementation, and collaborative engagement among technologists, policymakers, and affected communities.

Author Contributions

The author was responsible for conceptualization, supervision, methodology design, systematic literature review, data analysis and synthesis, manuscript preparation, and final approval of the submitted version.

Acknowledgements

The author acknowledges the valuable insights provided by researchers and practitioners in the blockchain and land registry communities. Special thanks to the institutions that have made their implementation data publicly available for analysis.

Conflict of Interest

The author declares no conflict of interest.

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