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High-Performance Decentralized Land Administration on Solana

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Abstract: ***Land administration is a critical function for ensuring ownership rights, resolving disputes, and enabling economic development. Conventional systems for managing land records often suffer from inefficiencies, centralization-related vulnerabilities, and recurring fraudulent practices like multiple property sales, falsified documents, and illegal changes in ownership. These issues are further exacerbated in developing countries, where digital infrastructure is limited, and manual processes dominate. While blockchain technologies like Ethereum have attempted to address these challenges through decentralization and smart contracts, their practical implementation is often hindered by high transaction (gas) fees, limited scalability, and network congestion. This paper presents a novel, decentralized land administration framework built on the Solana blockchain, which offers significant performance advantages due to its Proof of History (PoH) consensus mechanism and Sealevel parallel processing engine. Utilizing Solana's rapid transaction processing and low- latency architecture, the platform delivers a reliable, efficient, and tamper-resistant solution for land record management. In addition to its blockchain-based core, the system leverages a modern technology stack comprising for an intuitive and responsive user interface, for executing backend logic and managing smart contract interactions, and Supabase for off-chain data storage with real-time database capabilities. This combination ensures efficient integration between components, delivering a seamless user experience while maintaining high system performance and reliability. The proposed system automates critical functions like property register, ownership confirmation, and document validation using smart contracts, thereby greatly decreasing reliance on intermediaries and reducing the risks linked to centralized data storage.. Experimental outcomes and practical validation confirm the platform's effectiveness in significantly improving transparency, security, and operational efficiency over conventional land systems and previous blockchain-based solutions. This makes the solution highly suitable for integration into contemporary land governance models, particularly in regions that demand scalable and trustworthy digital infrastructure.***
Keywords: Blockchain, Land Administration, land records, Solana, Smart contract, Proof of History.

I. INTRODUCTION

Traditional land administration systems are predominantly managed by centralized authorities and rely heavily on physical or semi-digital records. These legacy systems are vulnerable to numerous issues such as data tampering, unauthorized alterations, and the loss of information due to natural disasters or human error. Additionally, such systems often involve manual verification procedures and a reliance on intermediaries—such as notaries, revenue officers, and clerks—which introduces inefficiencies, delays, and opportunities for corruption and mismanagement [18], [21]. Centralized databases also pose a single point of failure; a cyberattack or internal compromise can jeopardize the entire land registry infrastructure. These problems are particularly severe in developing countries, where the lack of digitization further impedes the establishment of transparent and trustworthy land governance frameworks [3], [18].

Blockchain technology emerges as a powerful solution to these challenges by offering a decentralized, transparent, and tamper-proof ledger system. Transactions recorded on a blockchain are immutable, time- stamped, and cryptographically secure, significantly reducing the potential for fraudulent manipulation and human error [1], [2]. Furthermore, blockchain enables the automation of processes through smart contracts— self-executing scripts that run when predetermined conditions are met—thereby eliminating the need for intermediaries in property transactions [4], [7]. This automation not only reduces operational costs but also accelerates transaction timelines and enhances auditability.

Despite its potential, the widespread application of blockchain in land administration has been limited by the technical and economic constraints of mainstream platforms such as Ethereum. High gas fees and limited transaction throughput have raised concerns about scalability, especially for countries with high transaction volumes and complex land records [2], [3], [6]. These limitations undermine blockchain's promise as a universally applicable solution for land governance.

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To overcome these bottlenecks, this study introduces a decentralized land registry system built on the Solana blockchain, which is specifically engineered for speed and efficiency. Solana integrates a unique Proof of History (PoH) consensus algorithm with its Sealevel parallel execution engine, enabling the platform to process up to 60,000 transactions per second with negligible fees [12], [14]. This architecture significantly enhances the scalability and cost-effectiveness of blockchain-based land record systems, making it suitable for both urban and rural deployments at scale.

The proposed Decentralized Application (DApp) leverages Solana's performance advantages to streamline land registration, ownership transfer, and digital document authentication. All essential transaction metadata is stored on-chain to ensure immutability, while larger documents are stored off-chain using decentralized storage mechanisms. The system ensures transparency by allowing public verification of records while maintaining data privacy through cryptographic techniques [5], [20].

By replacing manual, error-prone, and opaque systems with an auditable and secure digital framework, this work aims to address the core issues of trust, data integrity, and accessibility in land governance. This approach is particularly relevant for regions facing challenges of corruption, legal ambiguity, and infrastructural inefficiencies [17], [19], [22]. Furthermore, it lays the groundwork for broader adoption of blockchain-enabled e-governance systems, where secure, scalable, and tamper-resistant infrastructure is essential [8], [16], [23].

II. RELATED WORK

Numerous research efforts have investigated the use of blockchain technology in land administration, with the goal of enhancing transparency, security, and the overall efficiency of property management processes. Blockchain's decentralized and unalterable structure has gained widespread attention for its potential to resolve long-standing challenges, including manipulation of land records, illegal ownership transfers, and administrative delays caused by bureaucratic processes [1], [2], [3].

Stefanovic et al. [11] implemented Ethereum-based smart contracts integrated with ERC-721 tokens to facilitate digital property transfers. Their system effectively mitigated concerns like fraud, forged documents, and complex ownership disputes through tokenized land titles. However, the high transaction fees (gas costs) and limited scalability of the Ethereum network posed significant barriers to broader adoption, particularly in high- volume or resource-constrained environments.

Alharby and van Moorsel [13] conducted a comprehensive study on the limitations of smart contracts, highlighting vulnerabilities in contract logic, performance bottlenecks, and the irreversible execution of flawed contracts. Their findings underscored the importance of rigorous testing and formal verification before deploying smart contracts in critical applications like land registration.

Yakovenko [12] introduced Solana's high-performance blockchain framework built on the Proof of History (PoH) consensus mechanism. His work emphasized Solana's unique ability to achieve high throughput (up to 60,000 TPS) with minimal latency and reduced transaction fees, making it a promising alternative to traditional blockchain platforms for applications requiring speed and scale, such as land administration systems.

Ullah and Al-Turjman [17] designed a layered smart contract framework specifically for real estate applications within smart city environments, aiming to improve efficiency and stakeholder trust. To address transparency challenges on the Solana blockchain, Pierro and Amoordon [15] introduced a verification tool for confirming property ownership, helping to ensure public access to immutable records and reduce dependence on centralized entities.

In the Indian context, Singh [18] proposed a peer-to-peer blockchain-based approach for land record management aimed at overhauling the fragmented and corruption-prone land registry framework. While the model addressed key concerns such as ownership verification and data reliability, it lacked the scalability and real-time processing capabilities needed to handle high transaction volumes efficiently.

Pierro and Amoordon's [15] work also advanced the discussion on transparency and accountability by focusing on property record validation through blockchain-based proof of ownership systems on Solana. Their solution fostered trust among stakeholders by minimizing the need for central authorities. Additionally, Zhai et al. (as cited in [3]) explored the integration of Internet of Things (IoT) and Geographic Information Systems (GIS) with blockchain to enhance land surveillance and spatial data accuracy. These interdisciplinary advancements further illustrate the growing synergy between emerging technologies and smart land governance.

Expanding upon these previous works, this study leverages Solana's high-performance blockchain architecture to develop a decentralized application (DApp) specifically designed for land registration, property transfer, and document verification. Unlike earlier solutions hindered by scalability limitations, high operational costs, or complex deployment challenges, the system proposed in this study is optimized for reliability, transparency, and cost-effectiveness. Its architecture is particularly suited for deployment in developing countries, where infrastructure limitations call for an efficient and lightweight land administration solution [2], [14], [19].

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III. METHODOLOGY

The proposed decentralized land administration system is built using a combination of modern web technologies and blockchain infrastructure to streamline land registration, document verification, and ownership transfer. The system architecture includes a React-based frontend, Node.js backend, smart contracts deployed on the Solana Devnet blockchain, and Supabase for secure off-chain storage. The methodology focuses on automation, tamper-proof data integrity, cost efficiency, and user accessibility..

A. System Workflow Overview

The entire system follows a sequential and verifiable process, depicted in Figure 1 and Figure 2, which visualize the user flow and technology stack:

This flowchart outlines the basic sequence:

1) User Input – The landowner enters property ID, ownership details, and documents via the frontend.
2) Validation – The data is validated for completeness and integrity at both client and server ends.
3) Smart Contract Execution – A Solana smart contract receives and stores the hash of the core land record on-chain, ensuring tamper-resistance.
4) Supabase Storage – Additional documents (PDFs, images) are stored in Supabase, and their identifiers are linked to the blockchain.
5) Confirmation – A block hash and UUID are generated, confirming the successful transaction to the user.

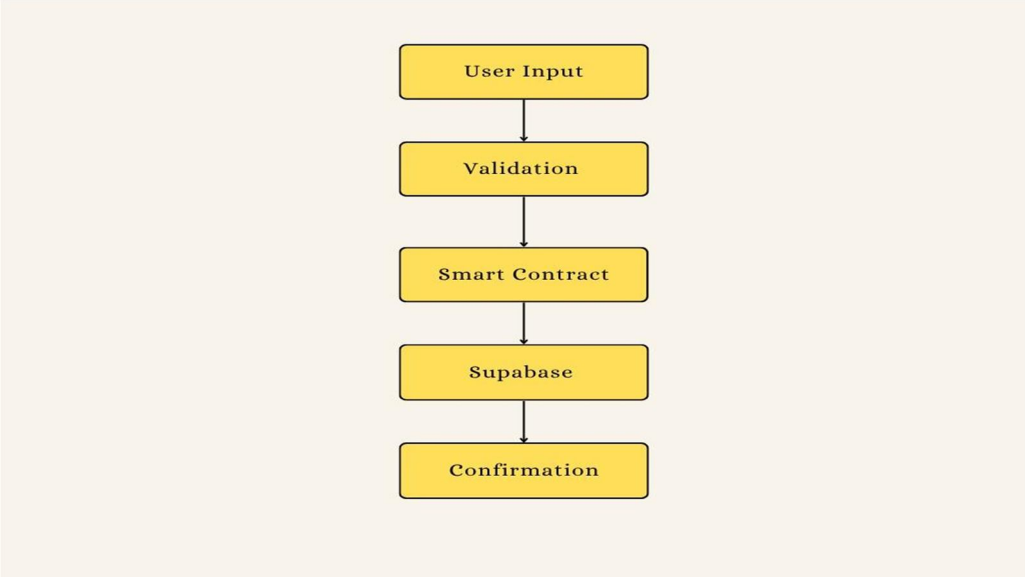


Figure 1: Process Flow

This diagram maps each phase of the process to its corresponding tool:

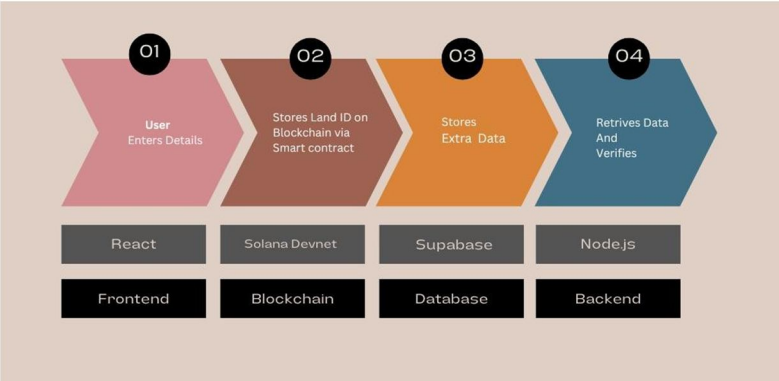


Figure 2: Workflow with Technology Stack This diagram maps each phase of the process to its corresponding tool:

1) Step 1: (React / Frontend): The user interface captures data inputs.
2) Step 2: (Solana / Blockchain): The smart contract stores hashed land IDs securely on the blockchain.
3) Step 3: (Supabase / Database): Additional land documents are stored off-chain in a scalable database.
4) Step 4: (Node.js / Backend): Handles verification and retrieval requests, connecting to both Supabase and the blockchain.

This modular design enables high-speed processing and ensures each component functions independently but in sync with the rest of the system.

B. *Key Algorithms and Processes*

1) Validation: Inputs are validated using client-side JavaScript and backend logic before being passed to the smart contract. Incorrect or duplicate IDs are rejected.
2) Smart Contract Logic: Written in Rust, the smart contract checks for data integrity and duplicates, hashes the input, and stores it on-chain.
3) Blockchain Storage: Solana's Proof of History (PoH) enables fast, immutable transaction ordering. Transactions are confirmed by validator nodes using Tower BFT.
4) Off-Chain Storage: Documents are uploaded to Supabase, and a unique identifier (UUID) is returned and stored on-chain as reference.
5) Retrieval & Verification: Users can retrieve the record using the land ID. The hash stored on-chain is compared with a hash of the fetched document to confirm authenticity.

C. *Platform Comparison and Performance*

The system is benchmarked against Ethereum and Hyperledger platforms to highlight its efficiency in terms of speed, cost, and finality.

Platform	TPS	Avg. Cost (USD)	Finality Time (sec)
Ethereum	25	15.00	12.00
Hyperledger	1,500	0.01	3.50
Solana (Proposed)	60,000	0.00025	0.45

Solana clearly outperforms its counterparts by providing:

- 2400x lower cost than Ethereum
- Significantly faster confirmation times
- Unmatched scalability, supporting real-time property transactions

D. *Advantages of This Architecture*

1) Low Latency & High Throughput: Ideal for national-scale property systems.
2) Cost Efficiency: Affordable even in resource-constrained economies.
3) Tamper-Proof Records: Blockchain ensures immutable history.
4) Modular and Scalable: Can integrate with mapping, IoT, or AI in the future.
5) User Friendly: A seamless web interface masks backend complexity.

IV. RESULTS AND DISCUSSION

The implementation of the proposed decentralized land administration system was successfully tested on the Solana Devnet, and the end-to-end process—from data entry to smart contract execution and verification—was fully validated. Upon submitting land registration details through the front-end React application, the transaction was processed and confirmed on the Solana blockchain. A unique transaction signature was generated and returned as proof of successful submission. This transaction hash acts as a verifiable reference for the recorded entry, demonstrating that the data was immutably stored on-chain. The actual output of this successful operation is illustrated in Figure 3, confirming the DApp's capability to interact with Solana's decentralized infrastructure and submit valid smart contract-based transactions.

To complement the backend processing confirmation, the DApp also features a clean user interface that allows users to add land details and verify them using the Land ID and its associated blockchain hash. As shown in Figure 4, users can enter parameters such as Land Name, Location, and Size, and the system automatically generates a Land ID and Block Hash. These identifiers can be retrieved and verified against the blockchain to confirm data integrity. This visualization validates the real-time linking of on-chain records with user-entered data, emphasizing both usability and functional robustness.The recorded transaction signature serves as cryptographic proof that the land data has been logged into the blockchain in a tamper-proof and verifiable manner. This ensures not only trust among users but also enables independent validation by any stakeholder using the publicly viewable Solana block explorer.

To evaluate the effectiveness of the Solana blockchain in this domain, the proposed system was compared against two widely referenced blockchain platforms: Ethereum and Hyperledger. The comparison was based on three key performance metrics: transactions per second (TPS), average transaction cost, and finality time. Solana demonstrated superior performance with 60,000 TPS, an average cost of $0.00025, and a finality time of 0.45 seconds, compared to Ethereum's 25 TPS and $15.00 cost per transaction with 12 seconds finality, and Hyperledger's 1,500 TPS with $0.01 cost and 3.5 seconds finality. These results validate Solana as an ideal choice for applications involving frequent and scalable interactions such as land registration systems.

Moreover, the system was stress-tested for fraud detection capabilities by attempting duplicate land ID submissions. The smart contract was able to detect and reject duplicate entries efficiently, thereby preventing unauthorized double registration or forgery attempts. Additionally, the off-chain documents stored in Supabase were accurately linked with their corresponding blockchain hashes, and integrity checks through hash verification proved successful in ensuring the authenticity of retrieved data. These mechanisms collectively enhance trust and minimize human error.

User experience was also prioritized during implementation. The frontend interface built using React.js facilitated intuitive data entry, while the backend using Node.js and Supabase ensured reliable and scalable document management. The separation of on-chain and off-chain data allowed the system to scale effectively without overloading the blockchain, maintaining performance while preserving decentralization.

In summary, the results clearly demonstrate the system's robustness in handling real-time land data processing and validation. The proposed solution not only ensures high throughput and low latency but also enhances security, transparency, and auditability. The integration of a decentralized, cost-effective architecture highlights the system's potential for nationwide deployment in land governance, particularly in developing countries where corruption, manual errors, and inefficiencies are prevalent.

V. CONCLUSION

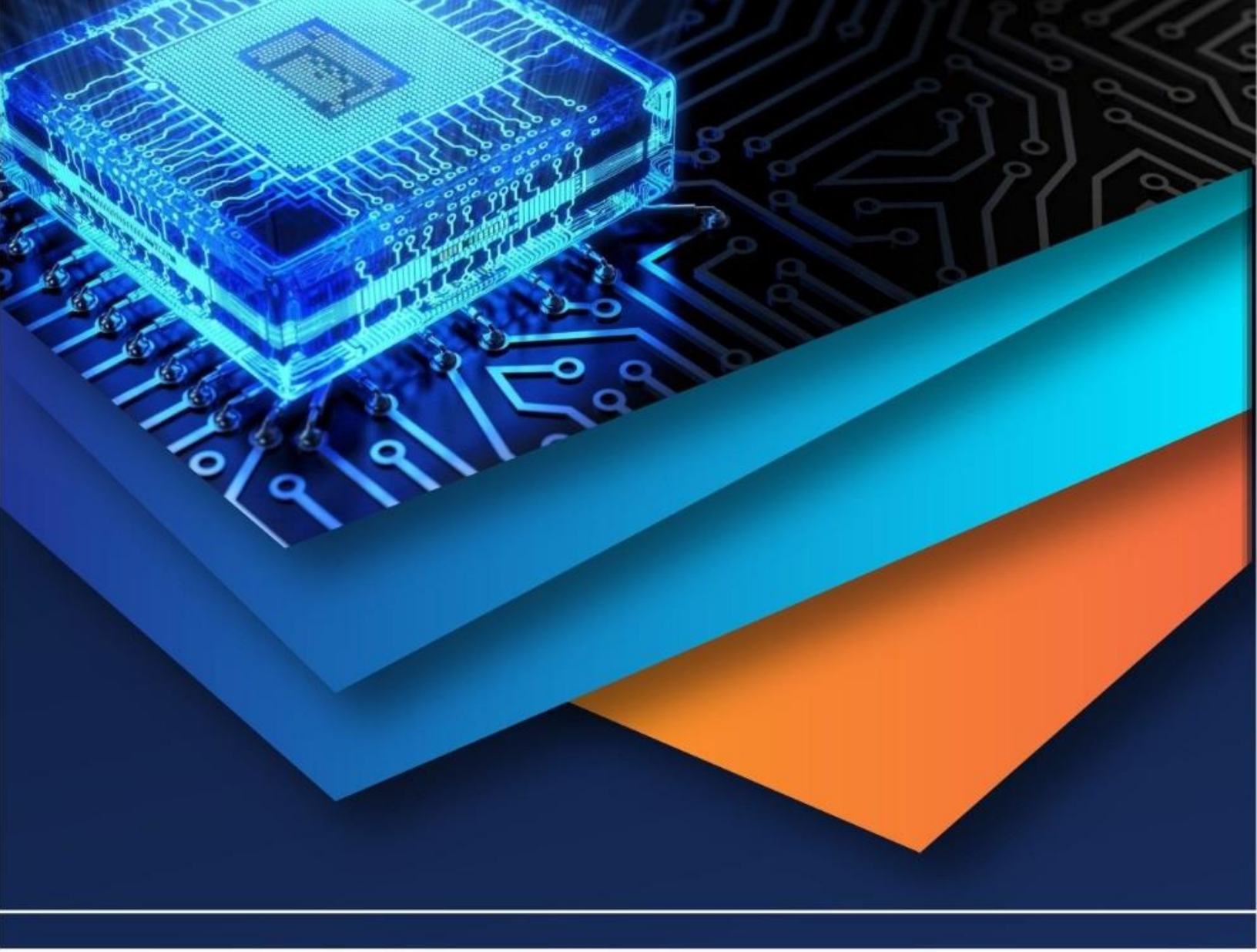
The proposed land administration system built on Solana's blockchain effectively tackles the limitations found in both conventional methods and earlier blockchain-based approaches. By leveraging Solana's Proof of History (PoH) and Tower BFT consensus mechanisms, the system ensures high efficiency, scalability, and low transaction costs.The system delivers high transaction throughput with minimal costs—key advantages for large-scale real estate implementations. Additionally, smart contracts automate property registrations, minimizing the need for intermediaries and significantly reducing the potential for fraud.The hybrid on-chain/off-chain architecture ensures tamper-proof records without overwhelming blockchain storage.Future improvements will focus on incorporating geospatial mapping for real-time monitoring of land assets and enhancing the system to accommodate multi-party approval processes, allowing for more complex and collaborative transaction workflows.The system sets a precedent for applying blockchain beyond cryptocurrency and opens pathways for secure, decentralized digital governance in land administration.

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