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Toward Sustainable Land Management in Morocco: Environmental Governance and the Role of Digital Tools

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ABSTRACT

Sustainable land management is a pressing challenge in Morocco, where environmental pressures, rapid urbanization, and informal land practices undermine legal frameworks and planning efforts. Despite progress in service digitization, land governance remains weakened by inefficiency, overlapping claims, limited environmental oversight, and poor integration between cadastral data and ecological regulations. This paper examines the environmental and institutional shortcomings of Morocco's land management system and advocates for a shift toward digitally enabled environmental governance. Current weaknesses in administration contribute to urban sprawl, land degradation, and climate vulnerability, particularly in peri-urban and rural zones. A review of legal frameworks and planning instruments reveals gaps in enforcing environmental regulations, protecting sensitive ecosystems, and securing tenure in high-risk areas. To address these challenges, we propose a governance-centered strategy that leverages digital tools—not as technical ends, but as enablers of sustainability. Innovations such as automated verification, spatial planning systems, and simplified registration workflows can enhance the enforcement of zoning laws, prevent unauthorized construction, and facilitate climate-resilient planning. We also assess Morocco's commitments to environmental goals, including Nationally Determined Contributions and SDGs 11, 13, and 15, demonstrating the central role of sustainable land governance in achieving them. The study concludes with a roadmap for institutional reform that balances tenure security, ecological resilience, and equitable land access. Findings aim to guide

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policymakers, land managers, and planners in Morocco and across the MENA region, offering an integrated and adaptable model that bridges land administration with environmental protection.

Keywords: Blockchain; Smart Contracts; Self-Sovereign Identity; Environmental Governance; Sustainable Land Management; Digital Identity; Decentralized Land Governance

1. Introduction

The land tenure system and property rights are vital for supporting economic development and social stability, while also having significance for urban planning[1]. Land governance systems in several developing countries, Morocco included, continue to contend with severe land governance challenges, which often lead to ineffective land management and practice, lack of transparency and accountability, identity theft, and inefficiency[2,3]. Informal land ownership processes and title disputes are common in rural and peri-urban areas of Morocco, and some of these land governance challenges can lead to environmental degradation, mismanagement of land, and make it difficult for local authorities, and for example, under Moroccan laws, may set conditions for sustainable land use and development[4,5]. In Morocco, the Agence Nationale de la Conservation Fonciere, du Cadastre et de la Cartographie (ANCFCC) is charged with overall responsibility for the property registration system[6]. Local authorities, individuals, and developers may interact at different levels with ANCFCC for different services, which at least in part have been digitized; however, there remains a high degree of bureaucracy, several paper-based processes, at times frequent errors (i.e., misplaced documents), and often ineffective communication pathways for service delivery[7,8]. This bureaucratic and inefficient property registration, administration, and governance process is inefficient to property owners, but when taken from a land use and management perspective, may contribute to more difficulty monitoring environmental protection laws, enforcement of illicit land transactions, and facilitation of eco-friendly urban development[9,10].

Although many options have been considered, the adoption and implementation of new technologies such as blockchain, smart contracts, and Self-Sovereign Identity (SSI) systems provide valuable solutions to many of these systemic problems[11]. The benefits of blockchain can provide a blockchain-based record of land transactions that is secure, verifiable, immutable, and decentralized[12]. Smart contracts are automated digital agreements that can automate the land registration process, enable greater compliance with environmental and zoning laws, and alleviate administrative burden[13]. Self-Sovereign Identity systems allow individuals to manage their identity credentials in a secure fashion, which enables privacy-preserving methods for verifying ownership with a level of trust, especially in regions where public registries or land records have been compromised or disputed[14]. The research initiative presented in this paper provides a conceptual framework that combines blockchain-based digital registry systems, smart contracts, and SSI methods to improve the Moroccan cadastre system, which will enhance transparent and more efficient land governance overall. This new system not only ensures operational efficiency, but it also supports sustainable land management by protecting the public interest concerning compliance with existing legislation and/or the environment. The advantages of reducing inefficiencies and enabling transparency also manifest in the ability to jointly advance eco-friendly urban planning, land conservation, and environmental justice[15]. In addition to advancing digital governance, this study makes significant contributions to environmental and earth sciences by incorporating climate-resilient land use regulations, enforcing zoning laws through smart contracts, and facilitating spatially informed land planning. The model supports land degradation neutrality, SDG 13 (Climate Action), and SDG 15 (Life on Land), and serves as a digital policy tool to link land governance with broader environmental monitoring systems. This study advances eco-digital land governance for Morocco by embedding environmental constraints—protected areas, forest perimeters, Ramsar wetlands, and coastal setbacks—directly into cadastral workflows through smart-contract gates. To situate Morocco internationally, we draw on evidence from large-scale land-transfer and environmental regulation research (e.g., China's urban agglomerations and land-transfer dynamics) to show how socio-economic heterogeneity and institutional design shape environmental

outcomes. We evaluate a blockchain/SSI model that automates pre-transfer compliance checks, reduces fraud, and supports SDGs 11, 13, and 15, while acknowledging legal and institutional constraints.

2. Literature Review

2.1. Land Tenure Systems and Governance Challenges in Morocco

Land tenure in Morocco is shaped by a complex legal mosaic, comprising private land (melk), collective tribal land (sulaliyat), religious endowments (habous), and state-owned land (domaine public). This plural system, while historically rooted, has led to overlapping property rights, legal ambiguity, and institutional fragmentation. Studies such as Moujahid et al.[16] and the World Bank Group[17] emphasize that this lack of harmonization hinders cadastral reform and formalization, particularly in rural and peri-urban regions. Without a unified and transparent tenure system, land governance institutions struggle to coordinate planning, taxation, and environmental monitoring. The consequences are especially severe for environmental protection, where insecure tenure contributes to land misuse, speculative occupation, and uncontrolled development.

Socio-economic and cultural determinants. Differences in regional development, rural–urban income gaps, and the persistence of customary practices (e.g., collective *sulaliyat* land) influence both the adoption of digital registries and the social acceptance of environmental restrictions. Trust in public records, transaction informality in peri-urban belts, and culturally embedded dispute resolution mechanisms condition the effectiveness of automated compliance. Recognizing these factors is essential when aligning digital tools with sustainable land-use enforcement.

Beyond technical inefficiencies, land governance in Morocco is shaped by socio-economic and cultural dynamics. Rural–urban disparities create unequal access to land markets, while traditional tenure systems such as *sulaliyat* and *habous* limit the applicability of formal cadastral rules. Informal peri-urban settlements often expand without ecological consideration, weakening zoning enforcement. Moreover, trust in public registries is historically low, and dispute resolution is frequently conducted through customary or community-based mechanisms rather than formal courts. These cultural and economic realities condition the adoption of digital platforms and must be addressed to ensure the effectiveness and acceptance of eco-digital cadastres.

2.2. Informality and Urban Expansion in the Global South

In the Global South, informal land markets and unauthorized urban development are major challenges to sustainable land management. Morocco is no exception. Informal settlements often arise due to unmet demand for affordable housing and the slow pace of administrative procedures. As noted by Benchekroun et al.[18], this expansion undermines formal planning instruments and leads to the conversion of arable land and natural habitats into urbanized zones. The associated environmental impacts include deforestation, loss of biodiversity corridors, pollution, and hydrological imbalance. Moreover, informal settlements are rarely aligned with zoning laws or risk maps, exposing inhabitants to natural hazards such as floods and landslides. The literature increasingly calls for governance models that bridge formal and informal systems while protecting environmental integrity.

Comparative insights from international contexts demonstrate the value of integrating socio-economic considerations into land governance reforms. In China, for example, studies show that land resource misallocation has significant spillover effects on environmental pollution and that land transfers are strongly linked to patterns of urbanization in the Yangtze River basin. Moreover, socio-economic heterogeneity across 287 Chinese cities influences the scale and direction of land transfers, with direct environmental consequences. These findings underline the importance of incorporating environmental criteria into land markets. By drawing on such international experiences, Morocco's eco-digital cadastre can avoid similar pitfalls and strengthen alignment with sustainable development goals.

2.3. Environmental Governance and Land-Use Regulation

Effective environmental governance in land management requires institutional coordination, reliable data, and enforceable regulations. In Morocco, despite the existence of planning tools such as *schémas directeurs d'aménagement urbain* (SDAU) and *schémas d'aménagement régionaux*

(SAR), the integration of environmental criteria into land administration remains limited. According to Das et al.[19] and Der Sarkissian et al.[20], zoning laws and environmental protection zones are often poorly enforced or excluded from digital cadastral systems, which hampers the prevention of land degradation, habitat encroachment, and illegal development. To address this gap, Morocco relies on national environmental designations such as *Sites d'Intérêt Biologique et Écologique (SIBE)*, Ramsar wetlands, forest perimeters, and coastal setbacks. Together with municipal zoning and hazard maps (flood and erosion risk), these categories provide the official reference layers that should be enforced by compliance logic in any eco-digital cadastre. Comparative studies in China further demonstrate how land-resource misallocation and land-transfer regimes can shape pollution outcomes and urban morphology, underscoring the importance of preventive, rules-first approaches that embed ecological constraints directly into land transactions.

2.4. National Strategies for Sustainable Land Use and Climate Action

Morocco's environmental and territorial strategies recognize the crucial role of land governance in achieving sustainable development. The Sustainable Development Strategy (SNDD) promotes integration between environmental concerns and public policies, while the country's Nationally Determined Contributions (NDCs) under the Paris Agreement outline land-based mitigation and adaptation targets. The ONEDD platform provides environmental indicators linked to land degradation, urbanization, and resource use. However, implementation challenges persist due to institutional silos and limited interoperability of cadastral and environmental data. Scholars argue that aligning land tenure reform with Morocco's climate and biodiversity goals is essential to fulfill SDG targets 11, 13, and 15. A territorial governance model that incorporates environmental performance indicators into land policies is increasingly seen as a necessity.

2.5. Digital Tools for Land Management and Environmental Compliance

Digital innovation is increasingly recognized as a facilitator of land governance reform. Tools such as geographic information systems (GIS), participatory mapping, cadastral digitization, and remote sensing support spatially-informed decision-making. Blockchain technologies, although still in their early stages, are being studied for their potential to enhance transparency and accountability in land transactions. However, recent literature by Saetra and Selinger[21] and Mills and Saetra[22], cautions against techno-solutionism. The value of digital tools lies not in their complexity, but in their alignment with local needs and environmental priorities. Systems that automate zoning compliance, monitor land-use changes in real-time, and link cadastral platforms with environmental databases offer a pathway to enforce regulations efficiently and equitably. As such, the environmental governance function of digital tools should be prioritized over their technical novelty.

2.6. Cadastre Systems and Environmental Governance

Cadastre systems are key components of land management and governance, providing the legal framework to document and record land ownership, usage, and transactions related to ownership and usage[23]. In many developing countries, including Morocco, cadastre systems have evolved as paper-based and focused on the institution's goal of establishing a centralized record system[24]. The processes for land measurement and title recording result in inefficiencies and can allow for fraud and issues of transparency. This inefficiency makes it challenging to regulate land uses sustainably, creates unsustainable land practices that result in deforestation and urbanization, and disregards these inefficiencies in property transactions, which substantially impact the enforcement of environmental laws, zoning, and policies that support sustainable land use[25].

In Morocco, the Agence Nationale de la Conservation Foncière, du Cadastre et de la Cartographie (ANCFCC) is the organization that is responsible for land administration. While there has been some exploration of digitizing some aspects of land governance, there are still challenges with formal and informal ownership in rural regions and competition over land parcels that complicate sustainable land practices and governance, making land governance a major hurdle for sustainable environmental planning and implementation of environmental protection policies, and inclusive, equitable land distribution to encourage sustainability[26].

2.7. Blockchain in Land Registry and Environmental Protection

Blockchain technology has proven to be a disruptive tool for improving land registry systems by improving transparency, minimizing fraud, and speeding up property transactions [27]. The technology's inherent immutability and decentralization make it particularly useful for solving land governance challenges in numerous developing countries, including Morocco. It also has the potential to promote environmental governance by employing blockchain in land registries to ensure land transactions are consistent with sustainable land policies and zoning rules. Several international case studies have highlighted blockchain's capacity to improve land registry systems, especially with issues concerning fraud, corruption, and conflicts over land ownership [28]. Applications of blockchain have enhanced land registries in Sweden, Georgia, Ghana, and India through greater transparency, reduced time for transaction completion, and increased trust in ownership records. These initiatives, while not directly correlated with environmentally conscious practices, nevertheless offer good insights for the introduction of blockchain to land governance systems that also incorporate eco-friendly urban planning and sustainable land management approaches [29].

Table 1 summarizes key international blockchain-based land registry projects, highlighting their successes and challenges, and draws connections to Morocco's land governance context. These examples provide a foundation for understanding how blockchain can not only improve the efficiency and transparency of land transactions but also support environmental protection by reducing the potential for unsustainable land use and ensuring compliance with environmental laws.

Table 1. Summary of international blockchain land registry initiatives and their relevance to Morocco.

Country	Use Case	Technology Used	Key Outcomes	Relevance to Moroccan Context	Source
Sweden	Real estate transactions with digital contracts	Private blockchain + Smart Contracts	Reduced transaction time by ~75%; increased trust in property data	High — Morocco seeks similar process efficiency via ANCFCC	Syah et al. [30]
Georgia	National land title registry	Bitcoin blockchain	Immutable proof of ownership; reduced corruption	High — demonstrates use of public blockchain under state oversight	Lazuashvili et al. [31]
Ghana	Land records digitization in rural areas	Bitland platform	Improved access and trust in informal zones	Very High — similar rural challenges in Morocco	Kavaarpuo et al. [32]
India	Smart contract-based land deals in Andhra Pradesh	Ethereum (pilot)	Legal process automation and transparency	Medium — highlights regulatory flexibility needs	Aayog [33]
Brazil	Real estate taxation and ownership registry	Public blockchain	Automated tax compliance and ownership tracking	Medium — shows financial integration potential	De Filippi and Hassan [34]
Rwanda	Blockchain for land certificate issuance	National blockchain initiative	Digitized over 10 million land records	High — shows feasibility in African policy and land contexts	Hughes [35]

2.8. Smart Contracts in Land Transactions and Sustainable Development

Smart contracts allow for the automatic execution of agreements and become self-executing once certain conditions have been met. When applied to land governance, smart contracts can greatly reduce the required steps and eliminate the need for intermediaries and the time required for property transfer [36]. A smart contract could automate the process of transferring property when identity and ownership conditions have been met. Therefore, Smart contracts add speed and reduce cost while increasing efficiency and reliability [37]. From a sustainability perspective, of course, smart contracts can ensure that land transactions meet relevant environmental regulations and land use guidelines, which is a significant advantage for sustainable urban planning [38]. For example, smart contracts could be used to better enforce local building regulations in protected regions or ensure the transfer of land-use according to established zoning regula-

tions or to facilitate the pursuit of sustainable development goals (SDGs). In addition, due to the limitations of requiring intermediaries and the ability to automate continuous verification, Smart contracts enhance transparency and limit the potential for corruption, which are significant barriers to environmental governance, particularly in land governance. While the adoption of smart contracts in land transactions has gained traction in countries like India and Brazil, where they are used for property tax compliance and automated land deals, the integration of blockchain and smart contracts with SSI remains an emerging area of research, particularly in the Global South.

2.9. Self-Sovereign Identity (SSI) and Environmental Governance

Self-Sovereign Identity (SSI) offers a decentralized approach to identity management, where individuals have control over all their personal data and identity credentials. SSI approaches identity management differently from conventional identity systems that depend on a central authority to authenticate the user. SSI uses cryptographic proofs to create a system of peer-to-peer identity veracity among users [39]. This decentralized process of identity verification is helpful to the land governance sector, since landowners can safely provide proof of land ownership without the risk of central authorities who may be corrupt. SSI will be especially useful in regions that have faced challenges with land ownership disputes and identity fraud, such as Morocco. SSI can help landowners in Morocco who have legitimate land ownership start to trust the land registry by providing SSI credentialing when interacting with a blockchain-based land registry. In addition, SSI would enable participants to develop transactions using SSI verifiable credentials (VC), enabling them to complete land transactions that are securely conveyed via the land registry. SSI is also pertinent to the environmental governance context, particularly if using blockchain-based land registries enabled people to engage with the land with a VC. SSI would allow only persons who are verified to extract data and collaborate in engaging in land transactions that exceed the basic environmental impact, such as urbanization, extracting natural resources [40]. Collaboration between SSI, blockchain, and smart contracts would strengthen trust regarding the land registration system and speed up processes, confirming the legality of transactions while recognizing the environmental sustainability of transactions that may impact land. Despite the potential benefits, the practical implementation of SSI in land governance systems, particularly in developing countries, remains underexplored and warrants further investigation [41].

2.10. Land Management and Environmental Governance in Morocco

Morocco faces multiple land governance challenges that affect both urban development and environmental sustainability. The country's land tenure system is characterized by overlapping legal regimes (melk, guich, collective land, habous), which often lead to disputes and hinder integrated territorial planning. In rural and peri-urban areas, informal land transactions, limited cadastral coverage, and uncoordinated land conversion contribute to uncontrolled urban sprawl, habitat loss, and degradation of agricultural and forest lands.

Environmental governance is further constrained by fragmented institutional responsibilities and limited enforcement of environmental impact assessments (EIA), especially in land use and real estate development. The absence of systematic integration between land registries and zoning or conservation data makes it difficult to monitor compliance with land use plans or environmental protection zones (e.g., SIBE, forest perimeters, coastal setbacks).

Several policy instruments, such as the National Strategy for Sustainable Development (SNDD), Morocco's Nationally Determined Contributions (NDCs), and the ONEDD framework, emphasize the importance of linking land management with climate adaptation, biodiversity protection, and sustainable resource use. However, these initiatives remain poorly operationalized on the ground due to a lack of data interoperability and weak institutional coordination.

Strengthening environmental land governance thus requires not only legal and administrative reform, but also spatially informed tools that enable real-time monitoring, transparency, and accountability across agencies. In this context, digital innovation can serve as a catalyst, provided it is directed toward solving systemic land and environmental governance failures.

2.11. Eco-Digital Framework for Sustainable Land Use

The proposed digital governance model integrates cadastral data, land use regulations, and environmental constraints into a unified, transparent, and automated land management platform. Rather than focusing on the underlying blockchain code, the model emphasizes the practical ability to verify legal ownership, zoning compliance, and ecological restrictions in real time.

When a land transaction is initiated, the system cross-references the parcel with digital layers containing zoning regulations, protected areas, and risk zones (e.g., erosion-prone zones, floodplains). If the transaction does not comply with environmental or planning constraints, it is automatically blocked or flagged for review by planning authorities.

The goal is not to replace governance but to support decision-making and compliance enforcement by reducing institutional bottlenecks and increasing traceability. This framework also fosters citizen trust and legal certainty by ensuring that environmental criteria are integrated into every land transaction.

2.12. Research Gaps and Contribution

While there has been some discussion of blockchain, smart contracts, and SSI in certain settings, there is still a considerable lack of research examining specific applications related to the deployment of these digital technologies as solutions for environmental governance and sustainable land management, particularly in a developing country context, like Morocco. Specifically, examples of applied models that combine the use of these frameworks in a meaningful way to inform land governance related to the environment are limited. This paper will explore and fill this niche by proposing a blockchain-based cadastre system that incorporates smart contracts and SSI for land governance, while also accounting for environmental considerations in Morocco. The study addresses a significant gap in the literature on digital transformation in land governance while also offering a model that can be replicated in similar contexts in the Global South, where sustainable land management is key to both economic and environmental stability.

3. Methodology

This section presents the methodological approach adopted for developing and evaluating the proposed blockchain- and Self-Sovereign Identity (SSI)-based cadastre system tailored to the institutional framework of Morocco's ANCFCC. It outlines the research design, data collection techniques, simulation processes, tools employed, and the criteria used to assess the proposed solution.

3.1. Research Design

This research follows the Design Science Research (DSR) methodology, which is particularly suitable for designing and evaluating information systems aimed at tackling real-world problems. DSR enables the design of technological artifacts, the blockchain-based cadastre, to address specific human challenges in land governance. The challenge is the slow-moving and opaque land registration system in Morocco, which complicates our ability to manage land sustainably and environmental governance. The starting point for this DSR approach is an iterative review of relevant literature to identify the respective technology, legal, and environmental barriers present in the current cadastre. A conceptual framework is designed to pull together the broad categories of blockchain technology, Self-Sovereign Identity (SSI), and smart contracts to provide a product that is more transparent, less vulnerable to fraud, and faster in land transactions. The goal of the conceptual framework is to save time in the operational process of land transactions, resulting in compliance with a sustainable land use policy and fewer environmental permit/land use breaches. The next step in the research progression will be to test and validate the implications of simulating land transactions within the conceptual framework, including measuring the level of functionality and overall effectiveness, while identifying specific eco-friendly urban planning principles for sustainable land management.

3.2. Data Collection

The study uses two main sources of data to assess the potential of the proposed system: a simulated land transaction and qualitative data from expert interviews. The simulation

allows the interactions of the stakeholders of a land transaction: citizens, notaries, the land registry, and government agencies. The simulation is based on an assumption of the integration of SSI (self-sovereign identity) for identity verification, smart contracts for automating land transactions, and blockchain for transaction transparency. It should be noted that this simulation included aspects of environmental governance by embedding zoning laws, sustainable development laws, and regulations in the transaction workflow. The use case demonstrates the efficiency of a blockchain-based cadastre system while ensuring environmental compliance. The second source of data consists of qualitative expert interviews with experts in land governance, urban planning, and environmental policy. The interviews were conducted to elicit the perceptions of professionals on the challenges of the existing system and the potential for a future system based on blockchain. More specifically, the experts were to score and analyse the extent to which the existing system aligned with Morocco's environmental goals and its potential capacity to support sustainable land management.

To complement the simulation, we conducted an anonymized expert consultation with three professionals directly involved in Moroccan land governance: a cadastral officer from ANCFCC, a licensed notary, and a digital governance consultant. Participants were purposively selected for their domain expertise, each with more than five years of professional experience. The interviews were conducted virtually using a semi-structured format focused on fraud risks, transaction inefficiencies, and environmental compliance gaps. No personal or sensitive data were collected, and all responses were anonymized to protect participant identities. This approach ensured confidentiality and compliance with general ethical standards for social science research, while providing valuable insights that validate the conceptual framework. Although the sample size is limited, the consultation strengthens the study by grounding the proposed eco-digital cadastre model in practical expertise and highlighting institutional realities that cannot be captured through simulation alone.

For reproducibility, all smart contract functions were executed in a controlled local environment (Remix IDE on a localhost test blockchain). This setup ensured repeatability of the experiments without reliance on external networks. The pseudocode provided in **Algorithms 1** and **2** allows independent researchers to redeploy and validate the workflow on any Ethereum-compatible test network (e.g., Sepolia) if desired. The complete pseudocode implementations are provided in **Appendix A**.

Algorithm 1. registerProperty(parcelId, ownerDID, docsHash).

```
require VC.verify(ownerDID) && VC.verify(notaryDID)
envStatus ← ECM.check(parcelId)
if envStatus.compliant == false then
   emit ComplianceFailed(parcelId, envStatus.reason)
   revert("ENV_NON_COMPLIANT")
end if
propHash ← hash(parcelId, ownerDID, docsHash, envStatus.snapshotHash)
ledger.add(parcelId, propHash, ownerDID)
emit PropertyRegistered(parcelId, ownerDID, envStatus.snapshotHash)
return true
```

Algorithm 2. transferOwnership(parcelId, sellerDID, buyerDID, deedHash).

```
require VC.verify(sellerDID) && VC.verify(buyerDID) && VC.verify(notaryDID)
require ledger.owner(parcelId) == sellerDID
envStatus ← ECM.check(parcelId)
if envStatus.compliant == false then
   emit ComplianceFailed(parcelId, envStatus.reason)
   revert("ENV_NON_COMPLIANT")
end if
ledger.transfer(parcelId, sellerDID → buyerDID, deedHash, envStatus.snapshotHash)
emit OwnershipTransferred(parcelId, sellerDID, buyerDID, envStatus.snapshotHash)
return true
```

3.3. Tools and Technologies

The proposed and simulated system uses several leading technologies. The Ethereum test network, Sepolia testnet, is the blockchain platform selected for the development and testing of the smart contract elements that create the rules for the workflows that will govern all land transactions. Ethereum is selected as a blockchain platform because it has well-established support for developing smart contracts and blockchain-based applications. Ethereum is a well-supported option to test against. There is consideration of other options, such as Polygon and Hyperledger Fabric, as acceptable alternatives that may allow for national scale-up and to facilitate regulatory accommodations. Solidity is the programming language used to write smart contracts, featuring key methods such as registerProperty() and transferOwnership(), which automate the registration of land properties and transfer of land ownership. In defining the Self-Sovereign Identity management requirements, the Sovrin and uPort frameworks are explored as examples of allowing an individual to manage their identity credentials and credentials to retain control over their identity when using Decentralized Identifiers (DIDs) and Verifiable Credentials (VCs). The framework will facilitate secure and privacy-preserving identity verification, which will ensure that land transactions are only initiated by an authorized party when appropriate. The model and simulation of the artefacts of the system as architecture and workflow will be informed using tools such as the Business Process Model and Notation (BPMN) and Unified Modeling Language (UML). These tools enable detailed visualization of system processes and actor interactions, ensuring that the proposed solution meets both technical and environmental governance requirements.

Simulation set-up. For demonstration, smart contracts were deployed to a contemporary Ethereum test network (updated from Sepolia testnet) and exercised via Remix and a scripted client. We modeled two core functions, registerProperty() and transferOwnership(), each calling an Environmental Compliance Module (ECM) that queries parcel-level constraints (SIBE, Ramsar, forest perimeter, coastal setback, municipal zoning; hazard layers for flood/erosion). Inputs: parcelId, DID/VCs for seller/buyer/notary, and document hashes. Events emitted: PropertyRegistered, OwnershipTransferred, ComplianceFailed. Gas/latency were recorded at the call level; human bottlenecks (notary validation) were varied parametrically.

3.4. Evaluation Criteria

The evaluation criteria adopted to evaluate the proposed system are efficiency, transparency, environmental compatibility, identity integrity, legal compatibility, and feasibility. Efficiency is based on the fixed operational time of the processing of the systems compared to traditional, paper systems. The evaluation will primarily assess the extent to which the blockchain-based system lowers administrative delays and transaction costs. Transparency addresses whether the system provides an immutable, auditable record of land transactions to detect fraud and to assure compliance with sustainable land use policies. Environmental Compatibility measures whether the system helps people meet policy and legislation requirements, such as zoning laws and land conservation policies, to ensure that land transactions do not violate pro-environment urban design and planning goals. The integrity of identity refers to the trustworthiness of Self-Sovereign Identity (SSI) systems in identifying the parties involved in land transactions. Legal Compatibility refers to the system's compliance with Moroccan property laws and whether the latter is legally recognized as a method to represent a transfer of ownership capacity of land. Finally, the feasibility criterion accounts for all the technical infrastructure required to support the system while considering, among others, users' level of digital literacy, accessibility, and institutional readiness for adoption in urban and rural conditions. The performance of the system is validated through both simulated scenarios and feedback from expert interviews, providing a holistic assessment of its potential to improve sustainable land management in Morocco.

To ensure transparency of the simulation logic, we formalized the main smart contract functions into pseudocode representations. **Algorithm 1** illustrates the registerProperty() function, which validates the identity of stakeholders through Verifiable Credentials (VCs) and calls the Environmental Compliance Module (ECM) to verify parcel eligibility against zoning regulations, SIBE, Ramsar wetlands, forest perimeters, and coastal setbacks. If compliance fails, the transaction is automatically rejected, and an audit log is generated. **Algorithm 2** details the transferOwnership() function, which automates the transfer of property once all legal and environmental conditions are met. These algo-

rithms highlight how environmental rules are embedded into the transaction workflow, shifting compliance from post-hoc verification to preventive enforcement.

4. System Design and Framework

The proposed blockchain-based approach to land governance in Morocco will address the inefficiencies of the cadastre system while providing transparency and ensuring environmental compliance in land transactions. The system architecture comprises four intersecting layers: the Blockchain layer, the Smart Contract layer, the Self-Sovereign Identity (SSI) layer, and application layer. Each layer has a respective role to ensure the accountability, automation, and sustainability of land transactions, while reducing the elements of risk associated with fraud, inefficiency, and environmentally irresponsible practices. **Figure 1** presents a diagram that outlines the complete system architecture.

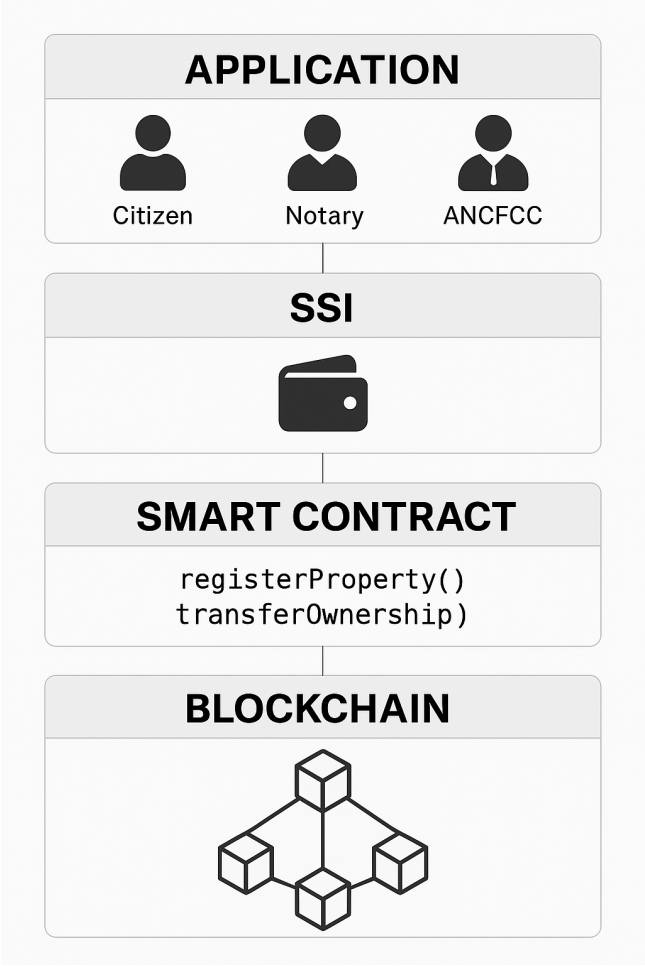

Figure 1. System architecture of the proposed eco-digital cadastre. The model integrates blockchain, self-sovereign identity (SSI), and smart contracts, with an Environmental Compliance Module (ECM) that verifies zoning regulations, SIBE, Ramsar wetlands, forest perimeters, and coastal setbacks before approving transactions.

4.1. Stakeholders

To be successful, the proposed system must engage multiple key stakeholders, each connected to the system via secure digital connections. In addition to citizens (landowners, buyers, and sellers), there are notaries, municipal authorities, and government agencies (the Agence Nationale de la Conservation Foncière, du Cadastre et de la Cartographie, ANCFCC). Each stakeholder will need their roles and responsibilities defined within the system, and these roles and responsibilities will be validated using appropriate Self-Sovereign Identity (SSI) mechanisms.

- Citizens start the land transaction process by first verify-

ing identity using digital wallets and managing the claim to their land securely and privately through Verifiable Credentials (VCs). This allows all land transactions to be limited to authenticated citizen landowners, thereby limiting the opportunities for fraudulent misuse of the identities of individuals who can legally transact land and manage secure land ownership.

- Notaries serve a vital role in legally verifying transaction legitimacy. They are responsible for ensuring land transfers comply with environmental laws, including zoning, sustainable urban development guidelines, and public land conservation policy.
- ANCFCC is the governing body responsible for certifying and maintaining cadastral records and the land registry. They also certify changes of ownership of land. The ANCFCC interacts with citizens and notaries to help land transactions comply with legal requirements in a sustainable manner.
- Municipal authorities are responsible for providing additional contextual information about zoning, land use, and environmental protection policies. They oversee that land transactions comply with urban planning regulations and sustainability objectives.

4.2. System Architecture

The system architecture is structured as a decentralized, blockchain-based structure for conducting transparent, secure, and efficient land transactions. The architecture has 4 layers, and each will be discussed in relation to the land transaction system:

- Blockchain Layer: At the bottom of the architecture is the blockchain layer. This is essentially the 'database' of the system, where the blockchain acts as the immutable ledger of all land transactions. The use of decentralized blockchain guarantees that once the actual data is entered into a block and the block is recorded on the chain, it cannot be tampered with. This guarantees an auditable history of land ownership, property transfers, and transaction history from the first recorded transaction. The Ethereum network has been selected for its flexibility, smart contracts exist; however, alternative networks like Polygon or Hyperledger Fabric were considered for government and / or nation scaling; the higher the intercapitalization between projects, the more efficiency it affords. This layer is shown schematically in **Figure 1**.
- Smart Contract Layer: The smart contract layer automates the processes involved in land transactions, such as property registration, ownership transfer, and compliance with zoning regulations. Smart contracts like registerProperty() and transferOwnership() are executed automatically once predefined conditions are met, reducing manual intervention and the risk of human error. These contracts ensure that all transactions comply with environmental standards, ensuring that land use aligns with the Sustainable Development Goals (SDGs). The functionality of this layer is also depicted in **Figure 2**, which shows the ownership transfer workflow through smart contracts.

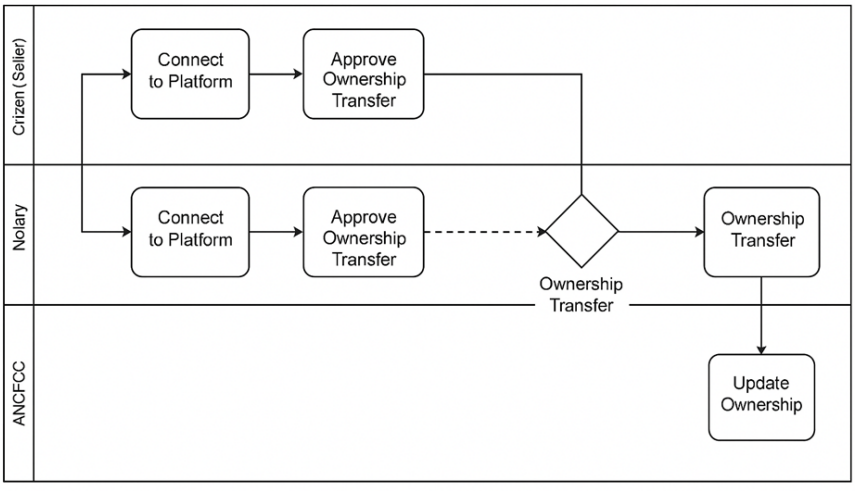

Figure 2. BPMN diagram — ownership transfer workflow.

- SSI Layer: The Self-Sovereign Identity (SSI) layer is crucial in this framework, as it enables individuals to maintain control over their identity credentials. Using technologies such as Decentralized Identifiers (DIDs) and Verifiable Credentials (VCs), this layer ensures that only verified stakeholders can initiate land transactions. SSI not only improves security and privacy but also empowers citizens by giving them ownership of their identity, preventing fraud, and ensuring the authenticity of land ownership claims. **Figure 3** illustrates the SSI credential exchange flow between stakeholders during a transaction.

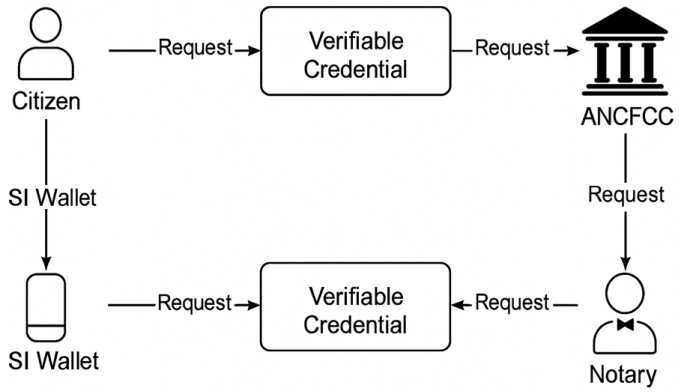

Figure 3. SSI credential exchange diagram.

- Application Layer: The application layer provides a user-friendly interface for all stakeholders. This layer includes web and mobile applications that enable citizens, notaries, and government agencies to interact with the system. The interface allows citizens to initiate transactions, upload supporting documents, and verify their identity, while notaries can validate the legal compliance of transactions. Municipal authorities and ANCFCC officials can access and validate land records, ensuring that all transactions align with legal and environmental regulations. The application layer is the final step in the system architecture, and its role is depicted through process diagrams in **Figure 2**.

4.3. Process Workflows

The design of the proposed system includes three core workflows that represent typical land governance processes: property registration, ownership transfer, and inheritance or dispute resolution. Each process is enhanced by the integration of blockchain, smart contracts, and SSI to improve efficiency, transparency, and environmental compliance.

- Property Registration Workflow: The property registration process begins when a citizen initiates the transaction through the application interface. The citizen's identity is verified using their SSI wallet containing a Verifiable Credential issued by an authorized authority. The notary then reviews the property documents and confirms that the land is free from encumbrances or legal issues. Once the verification process is complete, the smart contract is triggered, recording the property's cryptographic hash on the blockchain, ensuring immutability and auditability of the record. At the same time, a Verifiable Credential representing the citizen's legal ownership is issued to their SSI wallet. This process eliminates the need for paper-based documents and speeds up the registration process, ensuring compliance with environmental laws and land use policies.
- Ownership Transfer Workflow: In the ownership transfer process, the seller initiates the transaction through the digital platform, using their SSI wallet. The buyer also logs in to the system, and the transaction details are securely exchanged between the two parties. A notary then verifies the legal prerequisites of the transaction, such as property tax clearance and mortgage status. Once the necessary conditions are met, the smart contract for transferOwnership() is executed, and the ownership record is updated on the blockchain. A Verifi-

able Credential confirming the new ownership is issued to the buyer's SSI wallet, ensuring a secure and tamper-proof record of the transaction. The workflow of the ownership transfer process is shown in **Figure 2**.

- Inheritance and Dispute Resolution Workflow: For inheritance cases or disputes over property ownership, the relevant legal documentation, such as a notarized will or court-issued certificate, is submitted by the claimant. SSI credentials are used to authenticate the identity of the claimant, ensuring that the rightful heirs or claimants can access and transfer property ownership. The smart contract automates the distribution of the property based on the legal conditions or escalates the case for judicial review if necessary. The blockchain ledger is updated accordingly, reflecting the final ownership status.

4.4. System Evaluation

The system is evaluated based on five key criteria: efficiency, transparency, environmental compliance, legal compatibility, and feasibility. Each criterion is assessed through both simulated transactions and expert feedback. The efficiency of the system is measured by comparing transaction times and administrative costs with traditional paper-based methods. Transparency is evaluated based on the ability to audit land transactions in real-time, ensuring that the system enhances public trust and reduces fraud. Environmental compliance is assessed by examining how well the system ensures that land transactions comply with zoning regulations, land conservation laws, and eco-friendly urban planning guidelines. The legal compatibility criterion assesses whether the system aligns with Moroccan property laws and global digital identity standards. Finally, the feasibility criterion evaluates the system's scalability, user accessibility, and institutional readiness to adopt and implement the framework at both the national and local levels.

To operationalize these criteria, the roles of key stakeholders—including citizens, notaries, and government officials—and their interactions within the platform are summarized in **Table 2**, which highlights the specific verifiable credentials (VCs) used and the corresponding platform actions.

The overall design of the eco-digital cadastre integrates blockchain, self-sovereign identity (SSI), and smart contracts, with an embedded Environmental Compliance Module (ECM) to verify zoning and conservation rules (**Figure 1**). The privacy and access-control model relies on role-based permissions and verifiable credentials exchanged between citizens, notaries, and ANCFCC officials (**Figure 3**).

Table 2. Stakeholder roles and interactions.

Stakeholder	Role	SSI Credential Used	Platform Action
Citizen (Buyer)	Initiates transaction	Property Owner VC	Submit/approve purchase request
Citizen (Seller)	Approves transaction	Property Title VC	Approve ownership transfer
Notary	Legal validation & compliance check	Notary License VC	Verify documents, approve contracts
ANCFCC Official	Final validation	Government Agent VC	Record transaction, update registry

Privacy and Access-Control Model. Citizen SSI wallets hold DIDs/VCs for identity and property claims. Notaries hold Notary License VCs with scoped permissions to read necessary parcel attributes and attest to compliance. ANCFCC officials hold Government Agent VCs with write authority to finalize the registry state. Access is role-based with least privilege; credential revocation lists are checked in every call; all reads/writes are audited with event logs; incident response includes credential revocation, key rotation, and replayable audit over tamper-evident logs. The end-to-end ownership transfer process is modeled as a BPMN workflow to capture validation, approvals, and registry updates (**Figure 2**). Moreover, Core smart contract functions, including property registration and ownership transfer, are summarized in **Table 3**. Finally, the technological environment supporting the simulation—including blockchain platforms, SSI frameworks, and modeling tools—is detailed in **Table 4**.

Table 3. Smart contract function descriptions.

Function Name	Purpose	Inputs	Output
registerProperty()	Adds new property to registry	Owner DID, Property details	Property hash stored
transferOwnership()	Transfers ownership post-validation	Buyer/Seller DIDs, signature consent	Ownership update on chain

Table 4. Technology stack used in simulation.

Component	Technology / Tool	Purpose / Role
Blockchain Platform	Ethereum (Sepolia test network) / Hyperledger Fabric (permissioned pilot) – for evaluation only	Public testnet used to simulate and deploy smart contract logic
Alternative Blockchain	Polygon, Hyperledger Fabric (conceptual)	Options considered for permissioned or scalable national implementations
Smart Contract Language	Solidity	Used to define land transaction logic (e.g., registration, ownership transfer)
SSI Framework	W3C DID/VC (e.g., Aries/Indy or Veramo) – standards-conformant; final selection to align with national e-ID	Provides decentralized identity management using DIDs and Verifiable Credentials
SSI Wallet	uPort Mobile Wallet / Generic SSI Wallet	Used for holding and presenting credentials by citizens and notaries
Modeling Tools	BPMN, UML (Visual Paradigm, Lucidchart)	Used to model workflows and system architecture
Simulation Environment	Localhost / Remix IDE	Development and testing of smart contracts and interaction scenarios
Credential Standards	W3C DID & VC	Standards for decentralized identifiers and verifiable claims

5. Use Case Simulation

To demonstrate the practicality and potential impact of the proposed blockchain-based cadastre system, a use-case simulation was conducted. The primary goal of the simulation is to model a typical land transaction in Morocco, leveraging Self-Sovereign Identity (SSI) for secure identity verification, smart contracts for automating the land transfer process, and blockchain for providing an immutable and transparent record of the transaction. Importantly, the simulation also integrates environmental governance principles, ensuring compliance with zoning laws, eco-friendly urban planning, and land conservation regulations. The simulation focuses on the transfer of property ownership between two citizens, a seller and a buyer. This scenario was chosen because it closely reflects the most common land transaction in Morocco. By simulating this process, we aim to showcase how the proposed system can reduce administrative delays, enhance trust among stakeholders, and ensure legal compliance with environmental and sustainability standards.

5.1. Scenario Description

The scenario involves a land ownership transfer between two private citizens. The seller, a landowner, decides to transfer the ownership of a piece of land to the buyer, who has agreed to purchase the property. Both parties are registered in the system through Self-Sovereign Identity (SSI) wallets, which store their Verifiable Credentials (VCs). These credentials authenticate their identity and verify their legal rights to engage in the transaction.

The buyer's VC includes information regarding their identity and the financial transaction needed to purchase the land, while the seller's VC includes the seller's ownership details of the property. The notary involved in the transaction has a separate VC, which validates their legal authority to oversee the transaction. The ANCFCC (the Moroccan government agency) also plays a role in verifying the legitimacy of the property title and ensuring that the land complies with relevant environmental laws.

Once both parties agree to the terms, the transaction is executed through the use of a smart contract embedded with environmental regulations. The contract ensures that the land transfer complies with local zoning laws and eco-friendly urban planning guidelines, which are vital for sustainable land management.

5.2. Step-by-Step Workflow

The following describes the sequence of actions taken during the simulation.

5.2.1. Seller Initiates Transaction

The seller accesses the system via the application interface and logs into their SSI wallet. They select the property they intend to transfer and input the transaction details. The system prompts the seller to confirm their identity through their Verifiable Credential (VC).

5.2.2. Buyer Receives Transfer Offer

The buyer logs into the system, receiving a notification of the seller's land transfer offer. The buyer reviews the transaction details, including the property specifications and price, and confirms their identity through their own VC. The buyer also agrees to the terms of the transaction.

5.2.3. Notary Verifies Legal Compliance

A licensed notary accesses the system to authenticate the identities of both parties and verify the legal prerequisites of the land transfer, including checking for any mortgages, encumbrances, or legal disputes. The notary also ensures that the property adheres to zoning regulations and sustainability standards. This step is crucial for ensuring that the land is being used according to eco-friendly urban planning and environmental protection laws.

5.2.4. Smart Contract Execution

Once the notary validates the legal conditions, the smart contract is triggered. This contract automates the transaction, ensuring that ownership is transferred securely and that all conditions are met, including compliance with environmental regulations. The transferOwnership() function of the contract is executed, updating the ownership status on the blockchain. The Ethereum blockchain records the new owner's Verifiable Credential, making the transaction tamper-proof and transparent.

5.2.5. Ownership Credential Issued

Upon successful execution of the smart contract, a new Verifiable Credential is issued to the buyer's SSI wallet, confirming their legal ownership of the property. This credential is stored securely and provides the buyer with proof of ownership, accessible to relevant authorities and stakeholders.

5.2.6. Blockchain Update and Transparency

All actions, including the property registration, identity verification, and transaction details, are permanently recorded on the blockchain. This immutable record provides a transparent, auditable trail of the transaction, accessible by authorized parties such as government agencies and notaries. The transparency of the blockchain ensures that any environmental regulations are met and that the land is transferred in a compliant and sustainable manner.

5.3. Process Analysis

The simulation highlights several significant advantages over traditional, paper-based land transfer methods:

5.3.1. Speed and Efficiency

Traditional land transfer processes often involve lengthy administrative procedures, including manual paperwork, in-person visits to notaries, and waiting for government verification. The blockchain-based system automates many of these processes, reducing the total processing time from several days or weeks to under one hour, depending on the responsiveness of the notary and other stakeholders.

5.3.2. Transparency and Trust

The blockchain's immutable ledger provides an auditable record of the entire transaction, ensuring transparency and trust among all parties. In contrast to paper-based systems, which can be prone to corruption and fraud, the blockchain ensures that the property ownership history is secure and transparent. This fosters confidence in the land transaction process and provides a reliable public record.

5.3.3. Environmental Compliance

One of the key benefits of the proposed system is its integration with environmental regulations. The system ensures that all land transactions comply with zoning laws and eco-friendly urban planning principles. This feature is crucial for promoting sustainable land use and ensuring that land transactions contribute to the development of eco-conscious urban areas.

5.3.4. Reduction of Fraud and Errors

The integration of Self-Sovereign Identity (SSI) ensures that only verified individuals can engage in land transactions. This minimizes the risk of fraud, such as impersonation or identity theft, which is prevalent in traditional land governance systems. The use of smart contracts also reduces the risk of errors that can occur with manual data entry, ensuring that the transaction is legally binding and accurately recorded.

5.4. Diagrammatic Illustration

To further clarify the ownership transfer process, **Figure 4** illustrates the Business Process Model and Notation

(BPMN) of the entire transaction flow, from initiation to completion. This diagram visualizes the interaction between the seller, buyer, notary, and ANCFCC within the digital environment. The diagram shows the sequential steps taken to complete the transaction, ensuring that environmental compliance is met at each stage of the process.

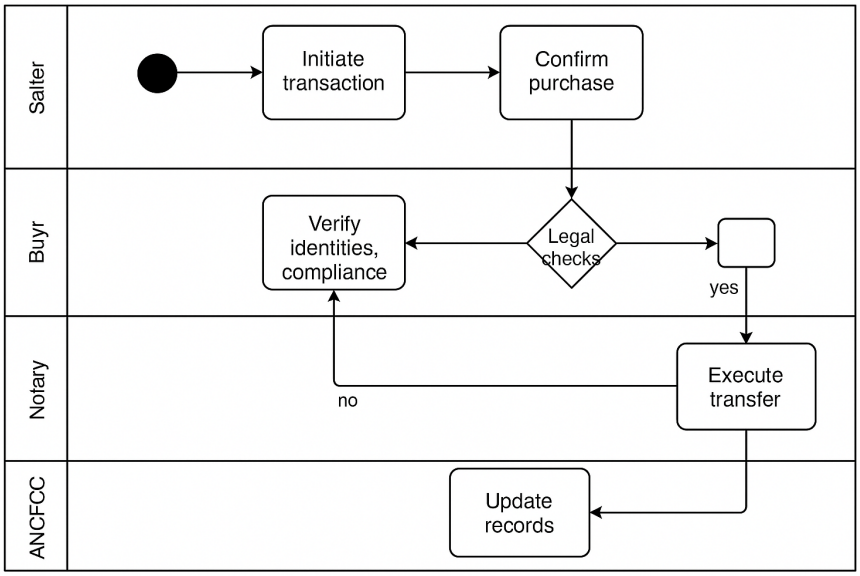

Figure 4. BPMN diagram—ownership transfer workflow.

6. Results and Evaluation

The results of the simulation and expert interviews provide valuable insights into the performance, efficiency, and environmental compatibility of the proposed blockchain-based cadastre system. The evaluation is based on five key criteria: efficiency, transparency, environmental compliance, legal compatibility, and feasibility. These criteria were assessed through a combination of quantitative simulations, expert feedback, and comparative analysis against traditional land governance methods.

6.1. Expert Interview Highlights

A series of expert interviews was conducted with three professionals in the fields of land governance, urban planning, and digital transformation. The purpose of these interviews was to gather qualitative insights into the practical challenges of implementing the proposed system, as well as to assess its potential benefits from an environmental governance perspective.

All responses were anonymized, and no personal data was collected, ensuring confidentiality and ethical compliance.

The key insights from the expert interviews are summarized in **Table 5**, which captures the experts' feedback on various aspects of the proposed system.

These insights confirm that the proposed system could improve land governance by enhancing efficiency and transparency, while also helping to reduce fraud and administrative bottlenecks. From an environmental perspective, the experts emphasized the system's potential to ensure compliance with sustainable land use policies and zoning regulations, which are crucial for eco-friendly urban planning.

6.2. Performance Metrics

Timing protocol. Reported times reflect a 10-run scenario analysis: we mapped the baseline paper workflow (document intake, identity checks, notary review, ANCFCC registry update) and timed each step using conservative medians from administrative guidance and expert estimates; we then executed scripted calls to contracts on a test network and simulated notary response times at {5, 15, 30} minutes. The "< 1 hour / ~90% faster" figure corresponds to the median response time under a 15-minute notary response; variance bands are shown in **Table 6**, with the human bottleneck isolated. When steps were not empirically timed, we mark them assumption-based and keep them in the scenario column.

Table 5. Summary of expert interview insights.

Expert Code	Role / Affiliation	Key Insight	Implications
Expert A	ANCFCC Cadastral Officer	"Delays are often caused by lack of real-time validation between agencies."	Justifies the need for an integrated blockchain system for faster validation.
Expert B	Licensed Notary	"Identity fraud and disputes over inheritance are our biggest challenges."	Highlights the need for SSI-based verification to reduce fraud.
Expert C	Digital Governance Advisor	"Blockchain is promising, but legal alignment and pilot programs are essential."	Supports phased implementation and legal review to ensure system adoption.

Table 6. Scenario medians; human-in-the-loop times parameterized; on-chain gas/latency recorded at call level.

Metric	Traditional Process	Proposed System	Improvement	N / Dispersion
Average processing time	5–15 business days	< 1 hour	~90% faster	N = 10; Median = 0.9 h; IQR = 0.8–1.2 h
Identity verification method	Paper ID, manual signatures	SSI + Verifiable Credentials	Stronger and faster	N = 10; consistent across runs
Risk of fraud (inheritance, forgery)	Medium to high	Low	Strong reduction	Expert score; N = 3 interviews
Transparency and auditability	Low (paper trails)	High (on-chain logs)	Significant improvement	N = 10 runs; consistent
Required in-person visits	Multiple	Optional (digital onboarding)	Substantially reduced	N = 10; SD = 0 (all digital)

The simulation included N = 10 runs; variance was reported with median and interquartile range (IQR). Human-in-the-loop parameters, such as notary validation times, were varied at {5, 15, 30} minutes. Indeed, the simulation results reveal that the blockchain system can reduce the average processing time by approximately 90%, significantly enhancing transaction speed and reducing administrative burdens. Additionally, the blockchain system enhances transparency, as on-chain logs provide a permanent record of each transaction, making it easier to verify property ownership and land use compliance. This is a key feature for environmental governance, as it ensures that all transactions are auditable and compliant with zoning and environmental laws.

6.3. Environmental Compliance

A major benefit of the system proposed is its ability to add environmental governance to the land transaction process. The system ensures land transactions are compliant with zoning regulations, land conservation laws, and environmentally considerate urban planning policies. This benefit was evaluated through stakeholder feedback and simulation scenarios. Stakeholders and expert assessors indicated that the system could actually facilitate sustainable land use in the context of Morocco. By creating contractual obligations through smart contract logic, the system guarantees that any land transaction must also comply with environmental criteria. For example, the system may automatically restrict land transactions involving land in protected areas or land designated for conservation. This capability could be a significant benefit to areas in Morocco where illegal land development or unsustainable land use practices have caused significant environmental degradation.

6.4. SWOT Analysis

A SWOT analysis was performed to identify the strengths, weaknesses, opportunities, and threats associated with the proposed system. The analysis, summarized in **Table 7**, provides a strategic perspective on the viability and scalability of the blockchain-based land governance system.

The SWOT analysis reveals a strong potential for the system to transform land governance, especially in terms of transparency and efficiency. However, it also highlights challenges such as the need for digital literacy and legal alignment, which could affect the system's broader adoption. From an environmental governance perspective, the system's ability to integrate with sustainable land use policies and promote eco-friendly urban planning offers significant opportunities for improving land conservation and zoning regulations.

Table 7. SWOT analysis of blockchain-SSI cadastre system.

Strengths	**Weaknesses**
High transparency and tamper-proof ownership logs	Requires high digital literacy among users
Reduction in identity fraud and human error	Smart contract enforceability still untested in court
Real-time auditability and stakeholder trust	Infrastructure limitations in rural regions
Role-based credentialing ensures access control	Initial setup costs and integration complexity
Opportunities	**Threats**
Scalable to other North African countries	Legal ambiguity around blockchain and digital IDs
Synergy with national digital ID programs	Institutional resistance to decentralization
Improved land governance for informal zones	Cybersecurity vulnerabilities if not properly secured
Pilot programs can inform broader eGov reforms	Potential digital divide in access and adoption

6.5. Legal and Policy Considerations

The promotion of blockchain, smart contracts, and Self-Sovereign Identity (SSI), in land governance, presents distinct areas of legal uncertainty, such as whether blockchain records constitute legal records and whether proofs of digital ownership are recognized by law. As a notable legal area of focus in the expert interviews and outcome assessments pointed out, the legal status of the system (in terms of its legality in Morocco) is still underway, as Moroccan property law to date does not recognize blockchain records or smart contracts as legal documents. However, Morocco's promotion of digital services and the Maroc Digital 2020 Strategy has invoked a collective push towards digitalization in the governance framework, presenting an avenue for regulatory modernization. This presents opportunities for the potential legal recognition of blockchain systems in land governance and an environment conducive to technology enablement for environmental governance.

Legal blockers and alignment path. Presently, there is no explicit recognition of blockchain records or smart-contract state changes as probative instruments for property transfer in Morocco; notarial law and land-book statutes still presume paper or certified electronic records anchored to the ANCFCC register. To enable eco-digital enforcement, (i) a decree or legislative amendment should recognize digitally signed, qualified notary acts and digitally archived cadastral updates as legally binding; (ii) ANCFCC workflows should incorporate MA-LADM-conformant feature classes and versioned environmental overlays, so the environmental snapshot hash recorded on-chain references a state-controlled canonical dataset; (iii) a regulatory sandbox should authorize pilots in selected communes, with audit procedures and fallback to paper records. This path links your smart-contract events to ANCFCC validation checkpoints and MA-LADM entities already cited in Section 2.6.

6.6. Data Protection and Access Control

The proposed eco-digital cadastre uses self-sovereign identity (SSI) wallets for citizens, notaries, and government officials. Citizens control their property credentials, while notaries hold licensed Verifiable Credentials authorizing them to validate transactions. ANCFCC officials maintain write access to finalize registry states. All interactions follow a role-based access control model with least-privilege permissions. Credential revocation and event logging ensure that every action is auditable. In case of key loss or misuse, recovery protocols and incident response procedures are triggered. This model guarantees compliance with both digital security and data protection requirements.

7. Discussion

7.1. Reframing Digital Innovation Through the Lens of Environmental Governance

This study demonstrates that digital innovation—when aligned with local governance needs—can support environmental objectives in land management. Rather than focusing on technological novelty, platforms should be designed to enforce zoning regulations, protect sensitive ecological areas, and promote sustainable land allocation. Embedding spatial and legal compliance into digital workflows transforms cadastral operations into environmental governance instruments. In Morocco, where environmental and cadastral data remain fragmented and poorly integrated, the unification of spatial layers (e.g., zoning plans, conservation maps, and cadastral parcels) within a digital framework could drastically enhance monitoring and enforcement capabilities.

Digital systems should prioritize the protection of ecologically sensitive zones such as wetlands, forest perimeters, and floodplains. This eco-digital perspective promotes proactive governance that aligns land administration practices with long-term environmental and climate resilience goals.

7.2. Governance Implications: From Reactive Control to Preventive Regulation

Current land governance practices in Morocco often rely on ex-post validation and fragmented institutional controls, leading to delays in enforcement and missed opportunities for environmental protection. The proposed framework introduces a preventive approach where land transactions are automatically checked against environmental, zoning, and hazard constraints prior to legal registration. This shift to anticipatory regulation strengthens the ability of institutions to prevent environmental degradation and promotes a more transparent and accountable planning process. For instance, the platform can flag attempted sales of land within a protected coastal buffer zone or within a flood-prone area, preventing illegal development. The automation of such checks ensures uniform enforcement of regulations, limits human discretion and corruption, and enhances transparency for all stakeholders.

7.3. Strengthening Institutional Capacity for Sustainable Land Use

While technology provides essential tools, institutional coordination and reform remain the foundation for effective implementation. The successful deployment of eco-digital governance platforms requires a clear legal mandate, updated regulatory frameworks, and interoperable databases shared among planning, cadastral, and environmental agencies. Strengthening local institutional capacity is also vital—particularly in municipalities and regional councils that often lack the technical expertise to engage with spatial data systems. Training programs, stakeholder consultations, and legal reforms that formally recognize environmental zoning constraints in cadastral procedures are crucial. Moreover, participatory governance—including involvement from civil society, notaries, surveyors, and land users—can enhance legitimacy and ensure that the platform serves the public good rather than reinforcing bureaucratic inertia.

7.4. Opportunities for Replication Across the Global South

Many countries in the Global South experience similar challenges, including fragmented tenure systems, rapid urbanization, weak enforcement of environmental regulations, and limited technological infrastructure. The Moroccan case presents a scalable and adaptable model for integrating environmental governance into land administration. By emphasizing functionality over technological complexity, this framework can be adapted to various national contexts. Potential applications include real-time alerts for deforestation in protected areas, automated denial of land transactions in ecologically fragile zones, and improved planning in disaster-prone regions. As climate change accelerates land pressure and socio-ecological vulnerabilities, such integrated systems offer a timely, policy-relevant response for achieving both tenure security and environmental sustainability.

7.5. Benefits for ANCFCC and Citizens

The Agence Nationale de la Conservation Foncière, du Cadastre et de la Cartographie (ANCFCC) can utilize an innovative blockchain-based system that materially enhances efficiency. By reducing the number of manual processes involved in land registration, the blockchain system reduces delay, speeds up processing, and allows for more easily auditable and tamper-proof records. Improving efficiency in this manner not only promises cost savings for the government but also restores public confidence in the overall land governance process. For citizens, the system offers a verified method of securely establishing and maintaining land ownership through the use of Self-Sovereign Identity (SSI) that independently authenticates ownership without the requirements of prior governmental documents or processes, thereby contributing to the reduction of identity fraud and empowerment over their right to maintain prevailing privacy considerations and norms. Privacy-preserving technologies are currently the subject of interest on a global scale, protecting the privacy of individuals while fostering the growth of digital sovereignty, also known as the "sovereignty of the information." The system also supports environmental governance by ensuring comprehensive applications of sustainable land use practices within land transaction processes. It does this by ensuring land transactions are preceded and supported

by complying with zonal determinations, adherence to eco-friendly procedures in urban planning, and maintaining land conservation and climate initiatives. There is no doubt this sustainability proposal presents a substantial opportunity for Morocco to revamp its, as I have analyzed, unguided urban development and governance towards a more eco-friendly urban planning focus, while reinforcing environmental justice indicators.

7.6. Implementation Challenges

Although the system described is promising, there would be barriers to implementing it. One of the most significant barriers is the legal status of blockchain records and smart contracts within Moroccan property law. Based on interviews with experts and performance measures, it is uncertain whether the system can be legally sound, as Moroccan property law does not currently recognise blockchain land registries or digital proof of ownership. This legal issue could impede acceptance of the system, especially given that ownership and transaction rights are structured around a historical paper-based service. What would Morocco have to do to make this happen? Rahimi's recommendation entails a review of Moroccan property laws, as by necessity it would require a totally new 'process of access' to formal land governance and therefore the creation of a legal framework for digital land governance. This framework could then be initiated with existing digital identity and e-government initiatives, such as Morocco Digital 2020, which includes the intention of bringing digital governance to its public services.

If legal reform were enacted in relation to blockchain and smart contracts, you would theoretically create an independent avenue for blockchain technologies and smart contracts to be legitimate; land transactions in Morocco would need to be recognised and embraced via legal status. Additionally, there will be institutional resistance against the adoption of new technologies. In Morocco, since land governance remains heavily reliant on traditional bureaucratic processes, government agencies and land administrators may be hesitant to adopt the new system. Effective change management, training, and multi-phase implementation, integrating the new system into the current system of which it is part, will be required to address the resistance. The digital divide, especially in rural areas, is another challenge. While urban areas in Morocco have been proactive in embracing digital technologies, some rural areas may lack internet technologies and cannot engage in a blockchain-based cadastre system. Some work will be required to establish equitable access to the system, with additional funding needed to advance digital infrastructure and digital literacy in rural and peri-urban areas.

7.7. Scalability and Replicability

One of the most valuable features of the proposed system is its scalability and replicability. While the system is tailored to Morocco, its blockchain-based underlying architecture, combined with Self-Sovereign Identity (SSI) and smart contracts, makes it flexible enough to apply to other countries with similar land governance challenges. North African and Sub-Saharan African countries would certainly benefit from adapting a model that accounts for their own land governance challenges, including land disputes, informal land ownership, and delayed and inefficient land registration systems. In addition to the conditions found in these areas with respect to land governance, the country context also makes the system's focus on environmental governance highly relevant in regions that are quite dependent on land and experiencing land degradation and poor development. The proposed system will also be able to incorporate eco-friendly urban planning and environmental protection laws into land transactions, providing a significant opportunity to coordinate the practice of digital land governance with sustainable development goals (SDGs) opportunities, especially in regions and countries vulnerable to climate change and urban sprawl. The system is scalable in terms of its integration with national e-government platforms and digital identity programs, which may enable constituency interactions with multiple public services. This potential for interoperability would make the system more efficient and relevant, while also serving a larger public good in the public service field, contributing to the broader enterprise of digital transformation.

7.8. Risk Considerations

The incorporation of blockchain technology into land governance introduces new ethical and operational risks that must be carefully considered and effectively managed. One of the most significant concerns is data privacy. While Self-

Sovereign Identity (SSI) creates value by ensuring privacy and security, inadequate implementation or security measures that fail to adhere to industry standards could result in the exploitation of people's sensitive land ownership data. To manage this risk, strong cryptographic protocols must be implemented and data must be securely stored. The other major concern refers to the technological dependence on a completely digital system. Although blockchain has many benefits, it can also be connected to new vulnerabilities, especially if the digital system were to experience a leading system failure or cybersecurity attack. There should also be backup procedures and human oversight to ensure the integrity of the system. In conclusion, regulatory ambiguity around the governance of smart contracts and blockchain can open up opportunities for legal disputes and potentially hinder the ground implementation of land governance systems. Without a regulated legal framework around the legal status of blockchain records or digital ownership proofs, disputes over property rights may lead to a reduction in the credibility of the system itself. To plan for blockchain use in land governance, legal scholars, policymakers, and blockchain experts must come together to set forth a legal framework that acknowledges blockchain and SSI as legitimate tools for land governance.

7.9. Broader Implications for Digital Land Governance

The proposed blockchain-based cadastre system has the potential to transform the way we approach land governance in Morocco and globally. By utilizing blockchain and Self-Sovereign Identity (SSI), our proposed cadastre system is a single source of truth for land governance that preserves everyone's privacy while providing a record that is trustworthy, transparent, and accountable to each. Moreover, the cadastre system described in this paper can incorporate environmental regulations directly into land transactions, which is a unique feature that establishes the cadastre as a viable model for sustainable use of land that can be transferred to other countries with similar land governance challenges. As many governments continue along their journey towards digital transformation, integrating blockchain and SSI in land governance could be the beginning of the ability to integrate eco-friendly urban planning and sustainable development policies. In particular, regions simply undergoing the urbanization process can take advantage of this dynamic system to ensure the sustainability of land by sustaining land resources while providing policies to address environmental degradation and social equity in the decision processes.

7.10. Environmental and Earth Science Implications

The proposed blockchain- and SSI-fueled systemic land governance system in Morocco is not merely an administrative innovation – it carries ramifications for environmental sciences, natural resource management, impacts of climate change, and sustainable development. This section will investigate whether the combination of decentralized technologies with environmental data and regulations can promote more eco-responsible governance and help realize environmental justice, conservation, and resilience.

7.10.1. Enforcing Environmental Laws Through Smart Contracts

One of the most novel features of the proposed system is its integration of environmental compliance into the digital workflow of land transactions. Environmental compliance is achieved through adherence to applicable land use regulations, including zoning and environmental protection laws, as well as restrictions on land use, which are defined within smart contracts as part of the system's operational capabilities. The system acts in real-time to protect environmental areas. Any transaction that fails to comply with protected area designation or is not in compliance with forest conservation legislation and with respect to urban planning laws would be automatically flagged, rejected, or, depending on the condition of the smart contract, would require special permission prior to transaction execution.

This process fundamentally changes environmental law from a rule structure to an active enforcement model. The process eliminates bureaucratic loopholes and discretion. Sustainability criteria cannot simply be criteria but rather become prerequisites to enforce compliance and achieve a legitimate transaction. Over time, the active enforcement of environmental regulations will create a cumulative effect of regulation to push land markets towards ecologically sustainable practices.

7.10.2. Climate Change Adaptation and Risk-Sensitive Land Planning

While Morocco is becoming increasingly vulnerable to the dramatic consequences of climate change, such as prolonged droughts, desertification, flash floods, and coastal erosion, the proposed system will increase both national and local capacity for risk-informed urban development and territorial resilience.

The proposed system will allow an integration of environmental parameters (e.g., flood zones, erosion-prone slopes, seismic risk zones, and climate-sensitive ecosystems) into the blockchain-based land registry, which will provide local authorities and land-use planners with legally enforceable spatial data to inform climate-resilient infrastructure development, managed retreat options, and climate adaptation funds that prioritize identified vulnerable communities.

The proposed blockchain system may also enable climate-sensitive zoning that could allow building permits or changes in land-use in high-risk places to automatically have more stringent reviews or be denied altogether if that land use permission was incompatible with resiliency plans. This approach will advance SDG 13 (Climate Action) and link with existing national climate strategies presented under Morocco's NDC (Nationally Determined Contribution).

7.10.3. Monitoring Land Use Change and Environmental Degradation

Land use and land cover changes (LULCC) drive mainly deforestation, habitat loss, soil erosion, and greenhouse gas emissions. Land cadastre systems based on paper systems are unable to assess changes over time or link owners to land impacts. Blockchain tools can replace paper systems, affording clear, immutable, and time-stamped records of ownership and land-use history.

In combination with the use of remote sensing and Earth observation methodologies (for example, Sentinel-2, Landsat, and radar interferometry), the digital cadastre system could enable advanced spatio-temporal monitoring of land use systems. These new tools can be used in early warning systems anticipating illegal conversions of land to other uses, urban encroachments on agricultural farmland, or degradation of wetlands.

Exemplary projects can be deployed by government agencies to initiate legal alerts, environmental remediation, or compensation mechanisms under Payment for Ecosystem Services (PES) frameworks. Further, such systems can support Morocco in its commitments under UNCCD's objectives of land degradation neutrality.

7.10.4. Soil, Water, and Ecosystem Services Management

By adding environmental metadata to the land registry, such as the soil, slope, groundwater depth, or the classification of land capability, the cadastre becomes a capacity for governing natural resources. In Morocco, fragile soils are being overexploited, with aquifers becoming increasingly threatened from unsustainable land practices. Integrating smart contract rules in particular could limit a transaction of land to certain uses (i.e., rain-fed agriculture to reduce the water table depth versus crops that use much more irrigation and water), depending on the parcel's environmental sensitivities. Other examples include authorities identifying overuse zones, as well as illegal drilling, maintaining compliance with environmental codes, and better protecting hydrological resources. The result of these mechanisms will provide more opportunities for SDG 6 (Clean Water and Sanitation) and SDG 15 (Life on Land) as well as complement local strategies around watershed management, reforestation, and agroecological transitions.

7.10.5. Supporting Sustainable Urban Development and Eco-Cities

Morocco's fast-paced urbanization has often occurred in an informal manner with little planning or consideration of environmental constraints. A key component of the proposed digital cadastre system is the introduction of a digital mechanism to control land extrusion, construction permits, and urban growth boundaries.

For example, environmental regulations may involve the verification of various urban planning codes, green infrastructure requirements, and environmental impact assessments (EIAs) through smart contract verification. Smart contracts provide for the development of green urban zones and also enrich cities' understanding of urban heat island impacts, access to green spaces, and access and mobility patterns regarding clean transportation corridors.

The combined elements of the proposed study and the digital cadastre system comply with the SDG 11 Objectives (Sustainable Cities and Communities) and provide mecha-

nisms to achieve inclusion, resilience, and low GHG intensity urban development strategies in the context of Sustainable Cities (Villes Durables), which is a significant policy program of Morocco.

7.10.6. Environmental Justice and Community Empowerment

Environmental governance is not only technical—it is fundamentally about equity, inclusion, and justice. The proposed system will empower individuals and marginalized communities through a Self-Sovereign Identity (SSI) framework, allowing them to assert and safeguard their land rights securely and transparently to better manage their formal and customary land rights. This process is most important in areas with informal settlements, land grabbing, and inequity over environmental resources. With guaranteed land tenure and digital ownership verification, the proposed system strengthens the ability of communities to engage in conservation programs, REDD+ initiatives, and land restoration programs, while providing better access to remuneration for ecosystem services, protection against land dispossession, and recognition under statutory law for customary land rights. Digital empowerment can promote environmental democracy, relate to SDG 16 (Peace, Justice and Strong Institutions), and repair the trust between communities and the institutions that manage their natural resources.

7.10.7. A Platform for Cross-Sectoral Environmental Policy Integration

Finally, the system has the potential to serve as an integrated digital policy infrastructure that links land administration with broader environmental governance domains. For instance, through APIs and interoperability standards, it could be connected to:

- National environmental monitoring systems (e.g., ONEDD in Morocco);
- Climate information platforms;
- EIA registries;
- Land taxation and subsidy platforms;
- Environmental education and public transparency portals.

Such integration facilitates whole-of-government approaches to sustainable development, encourages transparency in public decision-making, and reduces fragmentation between land, water, forestry, and urban policies.

7.11. Theoretical and Practical Implications for Environmental Governance

The blockchain cadastre system represents an innovative and transdisciplinary method for environmental governance by transforming land cadastres into self-enforcing ecological instruments. The traditional mechanism for land governance separates administrative records from environmental oversight; they assume that matters of environmental enforcement are secondary to matters of administrative record keeping. The proposed model includes sustainability criteria through programmable smart contracts in the transaction workflow.

This is a radical rethinking of the approach to environmental governance. Inserting conditions of compliance (zoning requirements, conservation area limitations, and ecologically-sustainable urban planning) into legally binding smart contracts allows land transactions to be self-governing in compliance with a wide range of environmental standards. Essentially, compliance is shifted to legal ownership transfer rather than a post hoc administrative burden.

From a theoretical point of view, this framework represents a contribution towards the emerging body of literature on “eco-digital governance” by combining property law, climate adaptation planning, and decentralised technologies. The framework challenges conventional styles of regulation, positioning technology as an enforcer rather than as a mechanism to support environmental policies.

On a practical level, this eco-cadastre framework proposes a dynamic “eco-digital” path to transition environmental regulatory policies into local and national urban planning instruments. Local governments and agencies can use the framework to monitor land-use in real-time, restrict development in protected areas, and support the development of green infrastructure. The automated features for legal-environmental obligations reduce bottlenecks in governance, increase transparency for citizens and notaries, and engender citizen trust in planning authorities.

Overall, this presents a replicable framework for developing countries to enhance environmental governance without having to layer additional bureaucracy, instead, relying on digital processes that are secure, transparent, and auditable, supporting sustainability and justice.

7.12. Environmental and Policy Implications

The integration of environmental constraints into land transaction systems contributes to sustainable land governance by ensuring that ecological risks, conservation zones, and urban planning regulations are automatically considered before legal validation. This shift from post-transactional enforcement to pre-emptive digital compliance could significantly improve Morocco's capacity to protect ecosystems and reduce urban pressure on vulnerable lands.

From a policy perspective, the system offers a concrete mechanism to support national environmental strategies and international climate commitments. It operationalizes SDG targets related to sustainable cities (SDG 11), climate action (SDG 13), and land degradation neutrality (SDG 15) through local land governance tools. It also provides a replicable model for other countries in the MENA region facing similar challenges.

By reorienting digital transformation toward environmental objectives, Morocco can simultaneously modernize its land administration, close governance gaps, and promote inclusive, ecologically sound development.

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7.13. Future Environmental Applications

Potential future enhancements of the proposed system could include integrations with satellite-based Land Use and Land Cover Change (LULCC) monitoring systems, and AI-based, early warning systems to detect illegal encroachment and land conversion. The infusion of real-time Earth observation data, along with blockchain registries, would permit authorities to respond more nimbly to illegal land uses causing environmental degradation, such as deforestation or water resource incursions.

These extensions are likely to contribute to and enhance Morocco's climate change adaptation initiatives, and can further assist in proactive environmental planning actions in high-risk vulnerable contexts. In addition, these and other enhancements provide potential pathways for building/discursive connections between land tenure systems, Payment for Ecosystem Services (PES), REDD+ arrangements, and developments in global biodiversity monitoring frameworks.

8. Conclusion

Morocco's land governance system must evolve to address growing pressures from urbanization, informal development, and environmental degradation. This study highlights the opportunity to merge administrative reform with environmental protection through a digitally enabled governance framework. Rather than focusing solely on technical innovation, the proposed approach prioritizes environmental compliance, enforcement of spatial planning, and transparent, integrated decision-making. The use of digital platforms to automate legal and ecological checks in land transactions can help enforce zoning laws, protect natural ecosystems, and build resilience to climate risks. While the underlying technology can vary, the essential value lies in reconfiguring land governance around sustainability, legitimacy, and environmental accountability. Future research should explore the implementation of pilot platforms in Moroccan regions most exposed to land-use conflicts and environmental risks, particularly in peri-urban and arid zones. With proper institutional alignment, the model can support Morocco's transition toward a greener, more just, and climate-resilient land governance system.

Author Contributions

Conceptualization, L.B. and A.B.; methodology, L.B.; software, A.B.; validation, L.B. and A.B.; formal analysis, L.B.; resources, A.B.; data curation, L.B.; writing—original draft preparation, L.B.; writing—review and editing, A.B.; visualization, L.B.; supervision, A.B.; project administration, L.B.; funding acquisition, A.B. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Ethical review and approval were waived for this study as it did not involve human subjects requiring formal institutional review. Expert interviews were conducted on an anonymized basis, without the collection of personal or sensitive data.

Informed Consent Statement

Informed consent to participate was obtained verbally from all experts involved in the study.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

Appendix A

As this study was conducted as a proof-of-concept simulation, the smart contracts were not deployed permanently on a public blockchain. Instead, reproducibility is supported through the detailed pseudocode and workflow descriptions. Researchers wishing to replicate the experiment may redeploy the same contract functions (registerProperty() and transferOwnership()) on a public Ethereum testnet (e.g., Sepolia).

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