Evaluating Performance and Security Trade-offs in Blockchain-Based REDD+ Projects

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Abstract

The credibility and efficiency of REDD+ projects rely heavily on the implementation of transparent monitoring, reporting, and verification (MRV) mechanisms. In this context, Blockchain technology has been increasingly explored as a means to enhance trust, traceability, and automation in carbon credit management. This paper presents a comparative analysis of three mature Blockchain-based REDD+ projects, namely Ambify, MCO_2, and TreeCycle, focusing on how different architectural and consensus design choices affect performance, scalability, and systemic security. The evaluation considers three key metrics: block-finalization traffic, block-finalization time, and systemic security. The first two metrics are obtained through computational simulations, while the latter is examined via a theoretical security analysis. The results indicate that the analyzed projects exhibit distinct performance and security profiles that are closely tied to their underlying Blockchain platforms and consensus mechanisms. In particular, architectures optimized for high throughput demonstrate lower communication overhead and latency under transaction-intensive scenarios, whereas more decentralized designs entail higher latency while offering alternative security and governance trade-offs. Overall, this study provides empirical and theoretical insights that support a context-dependent evaluation of Blockchain-based REDD+ platforms, highlighting that architectural suitability depends on specific operational requirements and governance constraints rather than on universally optimal design choices. General conclusions and recommendations for future research end this paper.

Keywords: Blockchain, REDD+, Carbon Credit, Management.

1 Introduction

This article presents a comparative analysis of three *Reducing Emissions from Deforestation and Forest Degradation* (REDD+) projects: Ambify [1], MCO_2 [2], and TreeCycle [3]. These projects have been selected for this research due to the completeness of their technical documentation, in addition to the maturity level already achieved in implementation [4].

The three projects above manage carbon credits by deploying Blockchain technology [5]. This distinguishing feature, compared to previous literature projects, enhances the effectiveness of the management process. This is because Blockchain enables the creation of a decentralized, immutable, and auditable database, thereby facilitating transparent and secure systems for carbon credit management. As a result, it allows

for decentralized validation of submitted data, which accelerates the carbon credit issuance process, reduces costs, and increases buyers' trust in the origin of the credits [6, 7].

In this study, we assess three performance metrics: *block-finalization time* (T_b), *block-finalization traffic* (C_b), and *systemic security* (S_s), which are defined in Table 1. The first two metrics are measured through computational simulations, while the third is assessed theoretically. See that they provide a comprehensive perception of efficiency, scalability, and security, respectively. The pivotal contributions of this work are therefore threefold:

1. A quantitative performance comparison of three well-matured REDD+ Blockchain projects using standardized simulation parameters;
2. A theoretical evaluation of systemic security across distinct Blockchain architectures; and
3. Practical and theoretical insights for guiding the development of future Blockchain-based REDD+ implementations.

Table 1: Performance metrics.

Metric	**Symbol**	**Unit**	**Definition**
Block-finalization time	T_b	sec	Average time to finalize a block in the Blockchain network. It is measured from the moment the block is proposed until it receives sufficient votes or confirmations to be immutable.
Block-finalization traffic	C_b	MB	Average network traffic generated during the block-finalization process. It results from transmitted data for confirmations, block propagation, and other related messages.
Systemic security	S_s	Concept	Adherence to confidentiality, integrity, and availability (CIA) principles besides the network's resistance to malicious attacks.

The remainder of this article is organized as follows. Section 2 presents the theoretical foundation of this research, covering the carbon market, REDD+ projects, and the Blockchain technology. Section 3 discusses related work. Section 4 briefly explains the three projects under analysis within this research. Section 5 details the experimental methodology and discusses the results. Finally, general conclusions and future research directions are presented in Section 6. Still, for the sake of easy reading, Table 2 presents several important acronyms used in this manuscript.

Table 2: Acronyms.

Acronym	**Meaning**
BFT	Byzantine Fault Tolerance
BSC	Binance Smart Chain
CIA	Confidentiality, Integrity, and Availability
DLT	Distributed Ledger Technologies
DOE	Designated Operational Entities
GHG	Greenhouse Gas
IS	International Standards
JABS	Just Another Blockchain Simulator
MCO_2	MOSS Carbon Credit
MRV	Measurement, Reporting, and Verification of emission reduction
PoS	Proof-of-Stake
PoSA	Proof of Staked Authority
PoW	Proof-of-Work
REDD+	Reducing Emissions from Deforestation and Forest Degradation
TPS	Transactions per Second
VCM	Voluntary Carbon Market
VER	Verified Emission Reduction

2 Theoretical Foundation

2.1 Carbon Market

Faced with worsening global climate crises, there is an increasing need for initiatives that accelerate the transition to more sustainable development models, including the adoption of greenhouse gas (GHG) emission reduction targets. However, many industrial sectors still face technological limitations in reducing GHG emissions at a commercial scale. This limitation highlights the importance of emission offset mechanisms, among which carbon markets stand out [8, 4, 5, 9].

The carbon market is a systematized environment for trading carbon credits, defined as intangible units representing one ton of CO_2 equivalent avoided or removed from the atmosphere. This environment operates as an offset system where entities that remove GHGs from the atmosphere sell credits to emitting companies. In jurisdictions with regulations imposing emission limits, many industrial sectors rely on carbon markets to meet emission quotas. Even where non-mandatory, many sustainability-focused companies participate in the Voluntary Carbon Market (VCM) for other corporate objectives, such as obtaining climate certifications, meeting stakeholder demands, and preparing for future regulations. These companies use the VCM to increase their market value through consumer recognition [10, 8, 7, 4].

To ensure the legitimacy of traded carbon credits, a series of norms and International Standards (IS) were established for Verified Emission Reduction (VER) projects. Each IS provides methodologies for measurement, reporting, and verification (MRV) of emission reductions, requiring independent audits for credit issuance. One of the most widely used standards in Brazil is the Verified Carbon Standard (VCS). Various actors develop VER projects, including private companies, cooperatives, local communities, non-governmental organizations, and national or sub-national governments. They are categorized by their mitigation activity type, known as sectoral scopes [10, 11].

VER projects face multiple operational challenges: high transaction costs, methodological complexity, and risks of information asymmetry. Currently, most MRV process validations are performed manually through documentation submitted to Designated Operational Entities (DOEs), leaving room for human error or fraud. Another risk is the double-counting of credits, where a project submits the same VER quantity in different documents to attempt to double their carbon credits and obtain more resources through duplicate sales [10, 9].

Figure 1 illustrates the carbon credit management process, from the view of a VER project by a private or governmental entity to the emission offset through traded credits. In the diagram, the DOE depends on the country implementing the projects and its environmental sector. For instance, Verra is the Brazilian DOE that validates and certifies projects in the Brazilian forestry sector [10, 11]. The steps highlighted in green refer to documentation stages, where the main obstacles for proper carbon credit control reside.

2.2 Understanding REDD+ Projects

REDD+ projects represent one of the most significant VER initiatives developed in the world. These projects focus on conserving and restoring tropical forests by creating financial incentives for preserving ecosystems critical to climate balance. This project type requires complex MRV systems to demonstrate the additionality and permanence of forest carbon stocks. Typically implemented by private landowners or subnational governments (states, provinces, or regions depending on the country), many such projects rely on carbon credit revenues to maintain long-term financial viability [6, 11].

The REDD+ MRV process begins with baseline establishment, involving reference scenario modeling, precise initial carbon stock calculations, and rigorous additionality analysis. This phase proves that emission reductions would not occur without the project. Continuous monitoring combines remote sensing technologies with on-site verification. Accredited organizations conduct verification to ensure CO_2 permanence, prevent leakage of polluting activities, and confirm compliance with technical protocols [10, 5, 11].

Beyond challenges common to all VER projects, REDD+ initiatives face unique difficulties. Methodological uncertainties in carbon stock estimates, combined with MRV operational costs, land tenure conflicts, and reversal risks, pose constant threats to project viability. These challenges undermine potential buyers' confidence in generated carbon credits, making it difficult to secure sustained funding for long-term project maintenance [6, 4, 9].

2.3 Blockchain Technology

Blockchain technology enables the creation of distributed databases where data is stored in physical replicas across interconnected processing nodes, forming a peer-to-peer network topology. A Blockchain-based system possesses the following key properties: distributed consensus, which eliminates the need for centralized validation; immutability, providing enhanced auditability and security; traceability and non-repudiation,

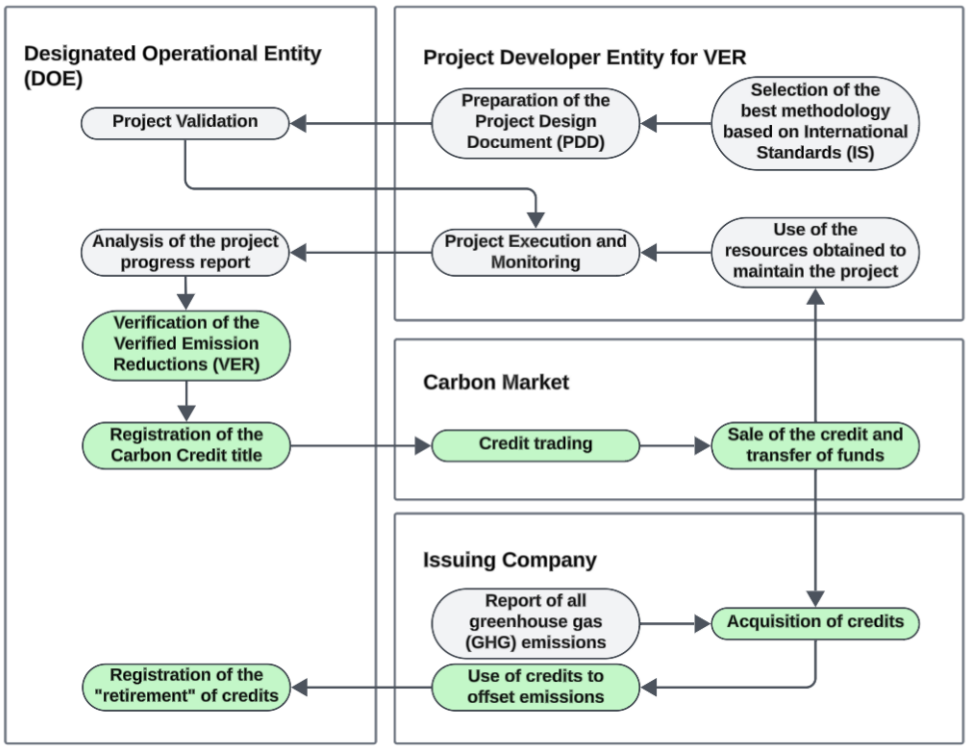


Figure 1: Carbon credit management diagram. Documentation stages of the process are highlighted in green.

through mandatory public signatures for all records; and control with transparency, allowing all network nodes (or some of them) to validate records [12, 5, 13].

In Blockchain systems, consensus algorithms serve as protocols that establish agreement among distributed nodes about the valid state of transactions. The choice of consensus algorithm directly impacts three system characteristics: scalability, security, and decentralization. The first consensus algorithm ever created, Proof of Work (PoW), requires miners to solve cryptographic challenges to validate blocks, with all other network nodes verifying the solution, offering high security at the cost of significant energy consumption. Another widely used algorithm is Proof of Stake (PoS), which selects validators based on the amount of resources (stake) nodes possess, demonstrating greater energy efficiency. To mitigate centralization risks in PoS, various adaptations have emerged, such as Proof of Staked Authority (PoSA), combining PoS elements with a reputation system for pre-approved validators, seeking a balance between decentralization and performance [14, 15, 13].

Another key feature of Blockchain technology is the presence of smart contracts, self-executing programs that implement agreements between parties without intermediaries. These programs emulate paper contracts, automatically executing when predefined conditions are met, enabling a wide range of applications. For carbon credit trading, smart contracts can accelerate credit circulation, reduce operational costs, and provide greater transparency and security for participants [6, 12, 5].

Finally, under the Blockchain technology, all data is stored in interconnected transaction blocks forming a linked chain, where each block cryptographically references the previous one through hashes. A Blockchain platform comprises the complete infrastructure enabling the development and execution of decentralized applications (DApps), smart contracts, and digital assets. These platforms vary in architecture, being either permissioned or permissionless, each with specific characteristics for different use cases [13, 15].

3 Related Work

The following discussion especially examines recent studies in the literature concerning REDD+ projects utilizing Blockchain technology. The goal is to provide readers with a comprehensive overview of the current state of the art in this field. These studies are synthesized in Table 3, which highlights the present work in its final row.

In [6], the authors focus on how Blockchain-based systems can address challenges in REDD+ projects. Specifically, they analyze: limited investment, lack of transparency, inadequate resource distribution, and difficulties in protecting traditional and indigenous community rights. The authors conclude that Blockchain's

Table 3: Synthesis of related works.

Ref	Primary theme	Study characterization
[6]	Benefits of Blockchain.	Theoretical aspects only
[7]	Local community rights.	Theoretical discussion.
[4]	Private REDD+ projects.	Theoretical discussion.
[5]	DLTs for carbon-market projects.	Business requirements and architecture proposal.
[16]	Review of Blockchain applications for forestry, including REDD+ projects.	Theoretical discussion.
[9]	Review of carbon-market projects, including REDD+ projects.	Theoretical discussion.
[11]	Evaluatiion of Blockchain-based REDD+ projects.	Theoretical discussion.
Ours	Blockchain-based REDD+ projects.	Theoretical discussion plus empirical analysis.

core features could potentially increase investor confidence, improve forest monitoring, and enable direct community participation in carbon markets, allowing them to benefit from carbon credit sales directly. However, the study lacks detailed technical implementations.

In [7], the authors explore key advantages of Blockchain applications in REDD+ projects, particularly those without government funding. The benefits align with those identified by [6]. However, the study primarily examines implementation challenges in safeguarding traditional and indigenous community rights. As a potential solution, they propose a risk assessment system to notify credit buyers about companies violating these rights. The authors conclude that this topic remains understudied and requires deeper analysis. Despite these insights, technical implementation details are lacking.

In [4], the authors evaluate Blockchain's positive impacts on REDD+ projects by examining 11 private initiatives at various development stages. Most projects utilize Blockchain to create tokens representing carbon credits or environmental assets. Notably, the TreeCycle project issues TREE tokens, each representing a eucalyptus tree planted in Paraguay. Investors funding tree planting and maintenance receive long-term profits. The authors find that despite growing private sector involvement, validating proper carbon credit certification remains challenging due to methodological transparency gaps. Like other studies, this analysis remains at the business rule level without technical project details.

In [5], the authors explain how Distributed Ledger Technologies (DLT) can enhance carbon-market management. Among the analyzed projects, they focus on MOSS.Earth initiative. Built on Ethereum, this project created the MCO_2 cryptocurrency, where each unit represents a carbon credit from Amazon rainforest projects. The authors conclude that DLT systems could revolutionize carbon credit generation and trading processes. Nevertheless, the study presents no practical experiments or theoretical DLT comparisons, focusing instead on business requirements and proposing a general system architecture.

In [16], the authors conduct a literature review of recent studies on Blockchain applications in forestry. Their analysis reveals that forest management - particularly REDD+ projects - represents the most explored application area. The study concludes that Blockchain technology holds significant potential for enhancing transparency and efficiency in REDD+ initiatives, especially when integrated with complementary technologies like Internet of Things (IoT) and Artificial Intelligence (AI). Furthermore, the research highlights the need for more in-depth research to understand risks and threats specific to REDD+ implementations. The study is tough, mainly conceptual, without technical implementation details.

In [9], the authors perform a comprehensive literature review examining Blockchain applications across various carbon-market sectors, including REDD+ projects. Their findings indicate that REDD+ initiatives indeed benefit from Blockchain's advantages, as they require particularly efficient and transparent management systems. The technology's decentralization and immutability features directly address REDD+'s persistent challenges with double-counting and double-selling of credits. The authors conclude by identifying critical research gaps, particularly regarding the quality assessment of emerging Blockchain-based projects.

In [11], the author conducts a bibliographic and documentary analysis to evaluate Blockchain's impact on REDD+ projects, using Acre State's Environmental Services Incentive System (SISA) as a reference framework. The study examines Ambify as a case study - a carbon offset platform converting certified Brazilian REDD+ credits into fungible tokens. The author concludes that Blockchain can enable more holistic and transparent carbon credit ecosystems when implemented adequately by developers who understand both REDD+ project requirements and carbon market dynamics.

From the above works, current research on Blockchain applications in REDD+ projects remains predominantly theoretical and business requirement-focused. Robust methodologies for evaluating the practical performance of existing implementations are notably absent. This research therefore settles its novelty by conducting a comparative performance assessment using realistic case studies of three promising projects: MCO_2, TreeCycle, and Ambify. Finally, while a review of more general technical studies on blockchain performance evaluation and comparative analyses of consensus mechanisms is beyond the scope of this paper, interested readers are referred to recent works such as [17, 18, 19] for detailed discussions.

4 REDD+ Projects under Analysis

The three projects to be analyzed herein utilize Blockchain technology to generate tokens representing resources from their respective REDD+ projects, whether carbon credits or physical assets. Each of them was developed atop existing Blockchain platforms, facilitating token exchanges with other cryptocurrencies native to those platforms.

The used platforms demonstrate resistance to Application-Specific Integrated Circuit (ASIC) mining, ensuring greater decentralization and accessibility in transaction validation. Another common feature is probabilistic block latency, i.e., blocks remain subject to modifications for a defined period after being added to the chain until network consensus confirms their final state. The following subsections detail each project's implementation, with particular emphasis on the conceptual framework and technical platform specifications.

4.1 MOSS Carbon Credit Project

The MOSS Carbon Credit (MCO_2) represents a pioneering initiative in the tokenized carbon credit market, launched in 2020 by MOSS.Earth. The project created the MCO_2 token, the first carbon credit-backed digital asset. Operating on the Ethereum Blockchain platform as an ERC-20 standard token, MCO_2 facilitates seamless exchanges with other compatible tokens and cryptocurrencies. Each MCO_2 token corresponds to one carbon credit, equivalent to one ton of neutralized carbon. Token holders can burn (retire) their MCO_2 to receive offset certificates through the company's official platform, thereby compensating for their greenhouse gas emissions [2].

Currently, MOSS.Earth purchases carbon credits from the VCM and converts them into MCO_2 tokens. However, the company plans to fully automate REDD+ project credit certification through its second product, MOSS Forest, which aims to digitize and automate significant portions of the MRV processes for REDD+ initiatives [2]. Figure 2 depicts the current carbon-credit management workflow.

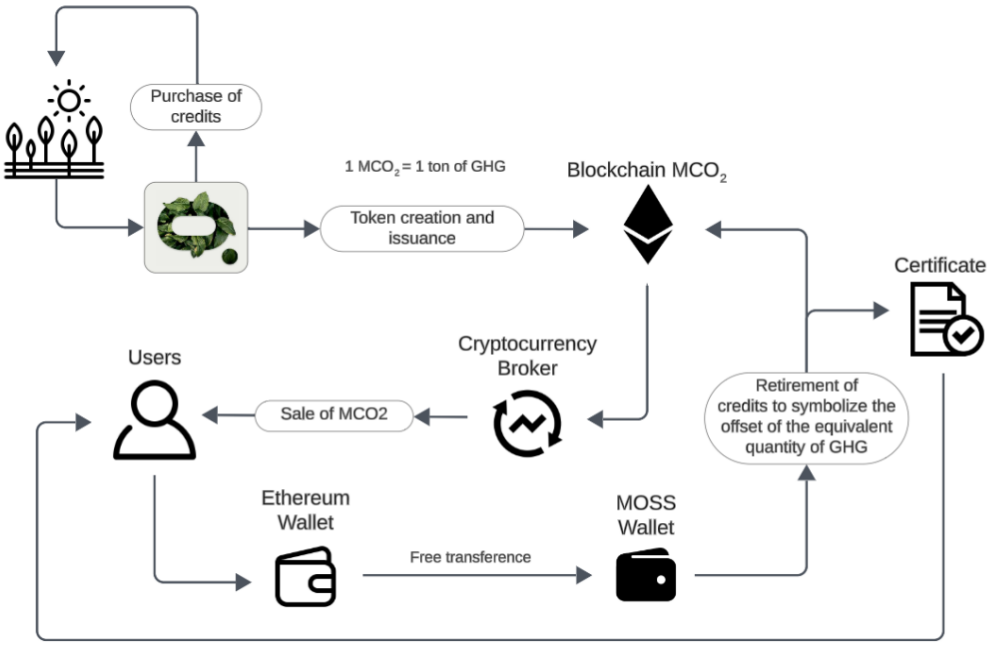


Figure 2: MCO_2 token creation and sales process.

Ethereum remains one of the most established platforms for tokens and smart contracts, offering a robust and secure ecosystem for decentralized applications. Before 2022, the platform utilized the PoW consensus,

supporting approximately 15 transactions per second with block creation times around 15 seconds. The upgraded version adopted the PoS consensus, significantly improving scalability and energy efficiency. While post-upgrade performance studies remain pending, the network has demonstrated a verified 99.5% reduction in energy consumption [14, 20].

4.2 TreeCycle Project

The TreeCycle project utilizes Blockchain technology to generate TREE tokens, each representing actual eucalyptus trees located in Paraguay. By purchasing a TREE token, investors provide the necessary funds to plant and maintain an eucalyptus tree as part of the company's reforestation initiative. All profits generated by the invested tree are shared with token holders annually, from the planting year through to the planned harvest year of the represented tree [3]. This process is detailed in Figure 3.

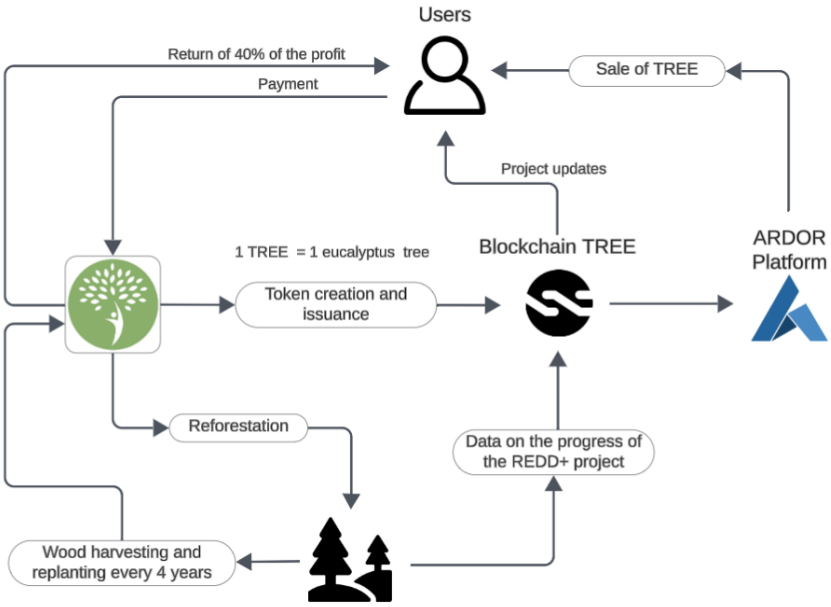


Figure 3: TREE token creation and sales process.

The project operates on the IGNIS Blockchain platform, a child-chain of the ARDOR Blockchain, which itself is built upon the NXT platform. ARDOR maintains most features of the original NXT platform, with its key innovation being the capacity to create subsidiary chains within its ecosystem. ARDOR's architecture comprises a main chain (parent-chain) handling security and processing. At the same time, child-chains like IGNIS allow customization for specific projects, ensuring business logic compliance while preserving the parent-chain's security. Among all child-chains, IGNIS uniquely retains full ARDOR parent-chain functionality, whereas others restrict access to specific ARDOR features according to their respective business requirements [21].

Launched in 2013, the NXT platform pioneered the PoS consensus algorithm. It supports approximately 100 transactions per second with a block generation time of about 60 seconds, potentially resulting in slower confirmation times compared to more modern platforms [20]. Nevertheless, the platform offsets this limitation through its native PoS implementation, which consumes significantly less energy than PoW systems – a critical alignment with TreeCycle's environmental sustainability objectives [3].

4.3 Ambify Project

Ambify is a project built on Binance Smart Chain (BSC), a Blockchain technology renowned for its high scalability and low transaction costs. The platform enables carbon credit offsetting through the creation, transfer, and retirement of ABFY tokens. These tokens represent certified carbon credits, ensuring secure trading and preventing double-counting. Each ABFY token is backed by pre-acquired carbon credits, allowing users to verifiably offset their carbon footprint as illustrated in Figure 4. A distinctive feature of Ambify is its fractional credit system, where each ABFY token represents one kilogram of avoided greenhouse gas emissions (one-thousandth of a carbon credit), making carbon offsetting accessible to smaller businesses and individuals [1].

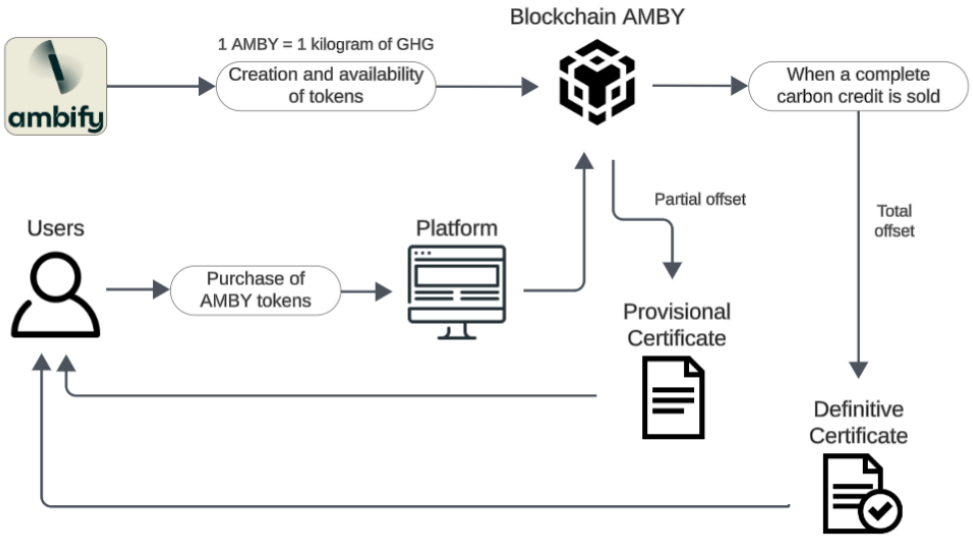


Figure 4: Token purchase and retirement process on the Ambify platform.

The BSC platform, which supports ABFY tokens, is compatible with the BEP-20 standard for efficient token and smart contract deployment. This Blockchain handles approximately 160 transactions per second with a block generation time of about three seconds, making it the fastest among the analyzed platforms. BSC utilizes the PoSA consensus algorithm, which combines elements of Proof-of-Authority (PoA) and PoS mechanisms [14].

5 Performance Evaluation

This section presents a comparative evaluation of the MCO_2, TreeCycle, and Ambify projects within the voluntary carbon market (VCM) context. The analysis begins with a literature-based comparison of these implementations, drawing on previous studies. Next, an experimental evaluation is conducted using the metrics defined in Table 1. This is followed by a theoretical assessment of the systemic security of each project. Finally, the main limitations of this research are discussed, highlighting directions for future work.

5.1 Literature-Based Comparison

Based on the works of [1], [2], and [3], Table 4 summarizes the general technical specifications of each project, including their respective blockchain platforms and consensus algorithms. We explain that Ethereum transitioned to PoS, reducing energy consumption by 99.5%, while increasing centralization as validation power, concentrated among major token holders. Overall, these projects are relatively recent initiatives, proposed around the same time frame. Nevertheless, they differ significantly in their technical attributes.

Table 4: General characterization of the projects.

Project	Year	Token	Platform	Consensus
MCO_2	2020	MCO2	Ethereum	PoW & PoS
TreeCycle	2020	TREE	IGNIS	PoS
Ambify	2021	ABFY	BSC	PoSA

Table 5: Blockchain platforms.

Platform	Base Platform	TPS	Block time
Ethereum	None	15	$\approx 15\,s$
IGNIS	NXT	100	$\approx 60\,s$
BSC	Cosmos	160	$\approx 3\,s$

Now, based on the works of [20] and [14], Table 5 characterizes the respective platforms deployed by the projects. There are two key metrics: transactions per second (TPS) capacity, which represents the

Table 6: Consensus algorithms.

Algorithm	Throughput	Decentralization	BFT	Energy
PoW	Low	High	$\leq 50\%$	High
PoS	Low	Medium	$\leq 50\%$	Medium
PoSA	Medium	Low	$\leq 33\%$	Low

Blockchain's processing capability; and block time, which represents the required time to create a new block. Finally, based on the works of [15] and [14], Table 6 evaluates the respective consensus algorithms of the projects. It considers four dimensions: i) throughput, an indicator of operational validation efficiency; ii) network decentralization level; iii) Byzantine Fault Tolerance (BFT), which assesses resilience against malicious attacks; and iv) energy consumption, which constitutes a very critical sustainability factor.

The joint analysis of the three tables above reveals that Ambify, developed on the BSC platform, stands out for its high scalability, handling 160 TPS with 3-second block times, which enables fast and low-cost transactions. This strategic advantage aligns with the project's goal of attracting diverse users and small businesses. Its PoSA algorithm balances energy efficiency and performance but achieves this through greater centralization, relying on a limited set of authorized validators. While practical, its lower BFT ($\leq 33\%$) may pose long-term security risks.

In contrast, MCO_2, developed on Ethereum, prioritizes decentralization and security over scalability and energy efficiency. With only 15 TPS and 15-second block times, its performance lags behind Ambify. Initially using PoW, however, Ethereum's mature ecosystem offers greater reliability than BSC, making it suitable for emerging markets despite throughput limitations.

Finally, TreeCycle, built on the IGNIS platform, has used PoS since its inception, thereby ensuring low energy consumption and aligning with the project's sustainability principles. With 100 TPS, the platform is positioned between Ambify and MCO_2 in terms of speed. The child-chain architecture of the ARDOR/IGNIS blockchain ensures high BFT, similar to Ethereum, but the 60-second block creation time may represent an operational bottleneck. Furthermore, the project could expand its scope by exploring the issuance of tokens linked to additional environmental benefits, such as biodiversity preservation. Currently, the narrow focus on tokens associated with harvestable trees, combined with the chosen technology, may limit its scalability.

In summary, when high transaction throughput and low operational cost are prioritized, Ambify exhibits a performance profile that is well-suited to transaction-intensive environments, albeit with increased centralization trade-offs. Conversely, MCO2 emphasizes robustness and decentralization at the expense of throughput, while TreeCycle prioritizes energy efficiency and sustainability. These results highlight that each solution reflects a distinct trade-off between performance, security, and sustainability, and that architectural choices should be aligned with the specific operational and governance requirements of a given REDD+ project.

5.2 Experimental Evaluation

This subsection presents the experimental evaluation of the analyzed Blockchain-based REDD+ projects. First, the simulation environment and adopted tool are described in Subsection 5.2.1, followed by the case study definition and modeling assumptions in Subsection 5.2.2. Subsection 5.2.3 then details the experimental scenarios under analysis, including variations in project scale and transaction demand. Subsequently, Subsection 5.2.4 discusses the adopted network parameterization choices and their implications for performance evaluation. Finally, the experimental results are presented and analyzed in Subsection 5.2.5.

5.2.1 JABS Simulator

The experimental evaluation uses the simulator named Just Another Blockchain Simulator (JABS) [22]. Implemented in Java, this simulator enables the modeling of various Blockchain network configurations, allowing the modification of parameters such as consensus algorithm, average block generation time, number of participating nodes, and simulation duration.

It is worth mentioning that JABS employs a discrete-event simulation model, where each event occurs at a specific point in time, modifying the state of the simulated system. The system state is described by properties such as node configuration, allocated memory, generated blocks, pending transactions, and packets in transit. Each discrete event is managed by a priority queue, where the execution of an event can add new events to the queue. Before and after each system event, it is possible to generate a log of the current system state data, enabling the measurement of the performance metrics regarding this analysis.

5.2.2 Case study and modeling

For the computational experiments, we look into a realistic case study based on the TreeCycle project, which envisions an initial planting of 10 million trees across 12500 hectares, with potential expansion to 59500 hectares and 47 million trees [3]. The rationale for considering this case study mainly lies in its narrower scope, since it focuses specifically on tokenizing tree planting and harvesting, which reduces modeling complexity, thereby allowing for an efficient evaluation of blockchain-enabled sustainability mechanisms.

The Blockchain network structure is modeled with two types of nodes: miners and non-miners. Miner nodes are responsible for transaction validation, credit creation, new block generation, and maintaining network consensus. Non-miner nodes, on the other hand, represent companies purchasing carbon credits, i.e., participants that only send and receive transactions, without engaging in the credit creation process.

To model the case study, we adopted a parameterization in which every 1000 hectares corresponds to one miner node in the Blockchain network. Additionally, purchasing companies are represented as non-miner nodes. For the MCO_2 system, the simulator is configured with a PoS consensus algorithm and a block generation time of 15 seconds, approximating the conditions of the Ethereum platform. For TreeCycle, the same consensus algorithm is used, but with a block generation time of 60 seconds, simulating the behavior of the IGNIS platform. Finally, the Ambify system is modeled using the PoSA consensus algorithm with a block time of 3 seconds, mimicking the BSC platform.

5.2.3 Scenarios under analysis

For the case study evaluation, two scenarios are explored. In the first scenario, the area varies from 12000 to 60000 hectares, for a fixed number of 1000 purchasing companies. The goal is to assess how the increase in carbon credit generation affects system performance. In the second scenario, the area is kept constant at 12000 hectares, while the number of purchasing companies varies from 100 to 1000. The goal is to evaluate the impact of increasing credit consumption on system performance.

As for the simulation execution, twenty independent rounds (runs) are conducted, using different random seeds for greater statistical robustness. As previously mentioned, we recall that the metrics herein analyzed are *block-finalization traffic*, C_b, and the *block-finalization time*, T_b. Furthermore, the numeric results shown in the graphs correspond to average values, accompanied by 95% confidence intervals.

Notwithstanding, before presenting the experimental results, the following subsection discusses the rationale behind the adopted network parameterization and examines how alternative configurations could influence the observed performance metrics.

5.2.4 Network Parameterization and Sensitivity Considerations

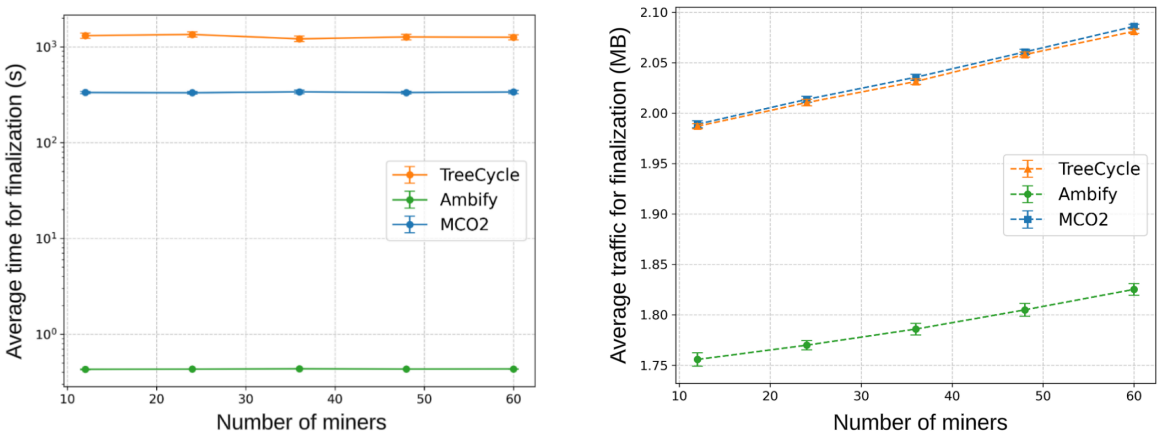
An important aspect in interpreting the simulation results presented in this work concerns the impact of network parameterization, particularly miner density and the buyer–miner ratio, on Blockchain performance metrics. Prior studies have demonstrated that consensus behavior, throughput, and latency are highly sensitive to the number of validating nodes and to the ratio between transaction-generating participants and consensus participants, especially under increasing load conditions [23, 24].

In the context of REDD+ platforms, higher miner densities may reduce block propagation delays at the expense of increased communication overhead, while higher buyer–miner ratios tend to increase transaction queuing and network traffic, directly affecting block-finalization traffic (C_b). Thus, the mapping between geographical coverage and network topology was derived from the following considerations: (1) TreeCycle's documented infrastructure aims to manage 10–50 million trees across 12,500–59,500 hectares, suggesting operational clusters at this scale [3]; (2) REDD+ implementations frequently occur in remote areas, such as Indonesia or the Congo Basin, with limited connectivity and precarious digital infrastructure [25]; and (3) uniform parameterization across all platforms enables fair and controlled comparison across heterogeneous Blockchain platforms, as recommended in recent performance evaluation studies [23]. This parameterization thus represents a mid-range operational scenario, balancing practical resource constraints with assumed decentralization. However, as acknowledged in the limitations section, sensitivity to this choice remains an important direction for future work.

5.2.5 Results and analysis

The results for the first scenario are presented in Figure 5. More specifically, Figure 5(a) displays T_b for each miner count, while Figure 5(b) shows C_b. Similarly, the results for the second scenario are illustrated in Figure 6. More specifically, T_b and C_b are presented in Figure 6(a) and Figure 6(b), respectively.

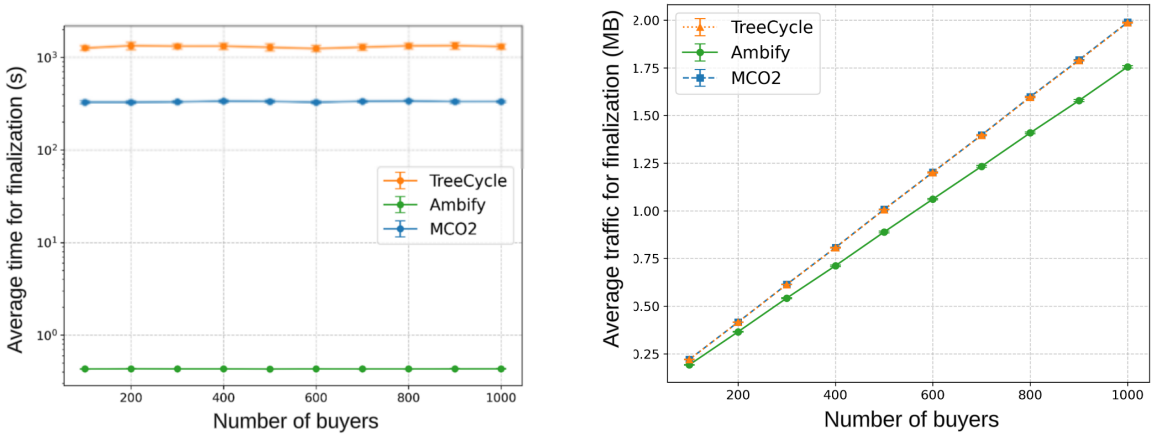
From Figure 5(a) and Figure 6(a), we observe that T_b remains essentially constant across all simulations, regardless of changes in the number of miners or buyers. The constancy of T_b reflects a characteristic of



(a) Block-finalization time

(b) Block-finalization traffic

Figure 5: Results obtained for the first scenario, where the number of miners is varied.



(a) Block-finalization time

(b) Block-finalization traffic

Figure 6: Results obtained for the second scenario, where the number of buyers is varied.

the analyzed Blockchain platforms: under stable network conditions and without packet loss or consensus failure, block-finalization time (T_b) is primarily determined by platform design rather than by variations in participant density or transaction volume. For this reason, in this study, T_b serves as a baseline indicator of platform-level performance design rather than a primary measure of operational scalability.

The resulting values of the Figure 5 are summarized in Table 7, highlighting the following findings:

- TreeCycle exhibits the highest T_b, consistent with its slower block generation rate;
- MCO_2 is 3.9 times faster (due to its 3.9 times shorter block generation time), despite using the same PoS consensus algorithm as TreeCycle; and
- Ambify achieves the lowest T_b, being three orders of magnitude faster than TreeCycle â a direct consequence of its PoSA algorithm, which prioritizes speed at the partial expense of decentralization.

Table 7: Block-finalization times (T_b) for each project.

Project	First scenario	Second scenario
Ambify	0.433 ± 0.003	0.432 ± 0.004
MCO_2	335 ± 11	332 ± 10
TreeCycle	1277 ± 81	1303 ± 97

The traffic consumption results are analyzed through linear regression, being presented in Table 8. The regression equations $C_b(n)$, where n represents the varied number of nodes in the scenario, reveal that the

Ambify project consumes less traffic as its Blockchain network scales up, indicating its bandwidth efficiency and demonstrating better scalability. The other projects show similar traffic consumption patterns in both scenarios, which suggests that their different block generation speeds do not affect the network's bandwidth consumption.

Table 8: Linear regression results for traffic consumption, $C_b(n)$,

Project	First scenario	Second scenario
Ambify	$0.001451n + 1.7360$	$0.001735n + 0.0195$
MCO_2	$0.002009n + 1.9646$	$0.001965n + 0.0233$
TreeCycle	$0.001966n + 1.9628$	$0.001963n + 0.0234$

In contrast to the fixed behavior of T_b, block-finalization traffic (C_b) exhibits clear variation with the number of participants, capturing the impact of network scale and load on communication overhead more directly. This differential behavior underscores that traffic metrics provide a more direct window into network-scaling properties than block intervals alone. Consequently, in the context of this study, C_b provides a more informative measure of scalability under the analyzed scenarios. We consider that future work may extend this analysis through sensitivity studies that jointly vary block parameters, miner density, and transaction load to further assess the conditions under which block-finalization time may become sensitive to network dynamics.

In a nutshell, the obtained results indicate that Ambify achieves higher scalability and communication efficiency under the analyzed transaction-intensive scenarios, reflecting design choices that favor throughput and low latency. However, this performance advantage is achieved through a more centralized consensus model, underscoring the trade-offs between efficiency, decentralization, and security inherent in different Blockchain architectures. In turn, MCO_2 and TreeCycle demonstrate comparable scalability performance, heavily influenced by their PoS consensus algorithms, with MCO_2 showing better efficiency due to its shorter block generation time.

5.3 Security Assessment

In cybersecurity, three fundamental principles guide information security, represented by the acronym CIA: Confidentiality, Integrity, and Availability. In the context of Blockchain technology, confidentiality is achieved through encrypted addresses, maintaining pseudo-anonymity even in public networks with traceable transactions, as long as the encrypted address remains uncompromised. Integrity pertains to data consistency, ensured by Blockchain's immutability. Availability, in turn, is guaranteed by the transparency and replicability of transactions across the entire network [14].

Although Blockchain technology ensures all CIA properties, Blockchain platforms differ in their degree of resistance to attacks such as DDoS, majority attacks, double-selling, or transaction flooding. A relevant metric for evaluating this resistance is BFT, which determines the number of malicious or malfunctioning nodes required to disrupt the network's proper functioning. This tolerance depends directly on the consensus algorithm used, eliminating the need for additional experiments to measure it [14].

As shown in Table 6, the PoSA algorithm, used in the Ambify project, is the most vulnerable among those analyzed, considering that successful attacks can occur when at least 33% of the nodes are compromised. In contrast, both MCO_2 and TreeCycle, which use the PoS algorithm, provide stronger security by withstanding up to 50% of malicious nodes. Thus, MCO_2 and TreeCycle are more secure against attacks than Ambify. However, Ambify compensates for this weakness with greater scalability and efficiency, as demonstrated in Section 5.2.5, allowing for an increase in the number of participating nodes and reducing the risk of a successful majority attack.

Beyond classical BFT thresholds, real-world Blockchain systems face a broader range of security risks that are not captured by consensus safety alone. Blockchain-based REDD+ platforms are vulnerable to smart contract defects, a category of risk that often exceeds consensus failures in real-world impact. While modern Solidity versions include safeguards, legacy contract code or third-party components may still be vulnerable [26, 27]. In token accounting, such bugs could silently cause balance underflows or supply miscalculations. The MCO_2 token operates as an ERC-20 contract on Ethereum, and the Ambify ABFY token uses the BEP-20 standard on Binance Smart Chain. Both standards implement basic security mechanisms, but projects must additionally implement domain-specific validations for carbon credit semantics.

Another point of attention is the reliance on trustworthy oracles that feed external data into contracts, introducing additional trust dependencies. If MRV verification data is falsified by a compromised oracle, incorrect numbers of credits could be minted. Mitigation strategies include adopting decentralized oracle networks, implementing time delays between oracle updates and contract execution, and establishing fallback

mechanisms. However, these issues add complexity and cost. REDD+ projects using Blockchain must carefully architect oracle interactions and conduct independent verification of critical data sources to prevent fraud.

Furthermore, decentralized governance mechanisms and validator selection processes can be susceptible to capture or cartelization, where disproportionate influence by a subset of stakeholders undermines the intended decentralization and can lead to decisions that compromise network integrity or unfairly advantage certain actors [28]. In permissioned and semi-permissioned systems such as PoSA, the criteria and transparency of validator selection, as well as the safeguards against collusion or concentration of voting power, are critical determinants of long-term security, even if they lie outside the reach of traditional BFT assumptions.

A comprehensive risk assessment requires considering these multifaceted vulnerabilities and governance structures, complementing consensus-level security analyses. While detailed modeling of such factors lies beyond the scope of the present experimental evaluation, acknowledging their relevance underscores avenues for future work to integrate richer threat models into Blockchain performance and dependability studies.

5.4 Limitations

Overall, the literature-based analysis, empirical performance evaluation, and theoretical security assessment presented in Subsections 5.1–5.3 provide consistent and complementary perspectives on the trade-offs inherent to different Blockchain-based REDD+ platforms. Nevertheless, while this study provides a valuable comparative analysis of three prominent Blockchain-based REDD+ projects, several limitations partially constrain the scope and generalizability of the findings, as discussed below.

First, the set of analyzed projects does not exhaust the diversity of existing REDD+ initiatives, which may differ substantially in technological stack, governance model, regulatory embedding, and environmental focus. Consequently, the observed performance and security characteristics should not be interpreted as representative of all Blockchain-based REDD+ implementations. Second, the experimental evaluation relies on a simplified simulation model that abstracts several real-world complexities inherent to REDD+ projects. Although such abstraction is necessary to enable controlled comparison across heterogeneous Blockchain platforms, it may affect the accuracy of absolute performance values. In particular, factors such as dynamic participation, heterogeneous network latency, regulatory compliance overhead, and off-chain verification processes are not explicitly modeled. More detailed simulations or real-world deployments would be required to capture these aspects more faithfully.

Moreover, while the results indicate that the Ambify project exhibits superior performance in terms of scalability and efficiency, these findings apply primarily to high-throughput, transaction-intensive environments where low latency and rapid block finalization are critical. In practical REDD+ contexts, however, projects often operate under regulatory, political, and social constraints that may prioritize transparency, decentralization, auditability, or institutional oversight over raw performance. In such settings, more conservative or permissioned Blockchain architectures may be preferable despite lower throughput, particularly when long-term governance stability and regulatory acceptance are key concerns.

Finally, this study focuses predominantly on technical performance and consensus-level security metrics, leaving broader ecological, socio-political, and governance dimensions largely unexplored. Issues such as land tenure rights, equitable benefit sharing with local and indigenous communities, jurisdictional regulatory compliance, and long-term project governance are critical to the legitimacy and sustainability of REDD+ initiatives. Addressing these dimensions requires interdisciplinary approaches that extend beyond the scope of the present work and represents an important direction for future research.

6 Conclusions and Future Work

This paper presented a comparative analysis of three Blockchain-based REDD+ projects, namely Ambify [1], MCO_2 [2], and TreeCycle [3], with the objective of examining how different architectural and consensus design choices influence operational efficiency, scalability, and systemic security. By combining a literature-based comparison with simulation-based performance evaluation and a theoretical security analysis, this study contributes empirical insights to a research domain that has so far been dominated by conceptual and business-oriented discussions. The main findings can be summarized as follows:

- The literature-based comparison revealed that the three projects are grounded in distinct architectural and governance priorities. Ambify adopts a performance-oriented design that emphasizes high throughput and low latency, MCO_2 prioritizes decentralization and robustness through a more conservative consensus model, and TreeCycle focuses on sustainability and energy efficiency. These architectural differences define clear trade-offs between efficiency, decentralization, and governance, establishing the

conceptual foundation for the quantitative performance and security behaviors observed in subsequent analyses.

- The experimental results confirmed that these design choices translate into markedly different performance profiles under transaction-intensive scenarios. Platforms optimized for higher throughput and shorter block intervals exhibited lower communication overhead and improved scalability, whereas more decentralized architectures incurred higher latency while offering alternative security and governance properties. From a security perspective, all evaluated systems satisfy core confidentiality, integrity, and availability requirements, although they differ in their tolerance to Byzantine behavior and exposure to governance-related risks. Taken together, these findings reinforce that no single Blockchain architecture is universally optimal for REDD+ initiatives; rather, suitability depends on the specific operational context, performance requirements, and governance constraints of each deployment.

Building on these findings, several directions for future research can be identified. First, expanding the analysis to include additional Blockchain-based REDD+ projects beyond the three examined in this study is recommended. Second, future evaluations should consider more realistic analytical contexts that incorporate specific regulatory constraints, policies, transparency requirements, decentralization expectations, and auditability standards that vary across jurisdictions and stakeholder governance frameworks. Third, empirical validation through pilot deployments or longitudinal case studies would help bridge the gap between simulated environments and real-world implementations. Finally, interdisciplinary research that incorporates regulatory, socio-political, and environmental perspectives remains essential to ensure that Blockchain-based solutions effectively support the long-term credibility, inclusiveness, and sustainability of REDD+ initiatives.

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