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REVIEW

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Blockchain in REDD+ Projects: Potential and Challenges for Transparency and Efficiency in the Forest Carbon Market

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Abstract: Green finance and carbon markets are key to the global fight against climate change. Among them, Reducing Emissions from Deforestation and Forest Degradation (REDD+) projects represent a critical mechanism for channeling resources into forest conservation. However, these projects face challenges related to monitoring, reporting, and verification, which require transparency and low operating costs. These challenges, including opaque data, high operational costs, manual processes, and reliance on trusted intermediaries, fuel market skepticism, increase fraud risks, and ultimately constrain project financing. This systematic review examines the growing role of Blockchain technology in addressing these systemic challenges. By synthesizing the existing literature, this article analyzes how the inherent properties of Blockchain, such as decentralization, immutability, and transparency, can increase the credibility of carbon credit management, mitigate the risks of double-counting and fraud, and democratize access to carbon markets through credit tokenization. However, the findings indicate a significant gap between theoretical promise and practical application. Conceptual proposals, lacking empirical validation and detailed technical architectures, dominate the field. The review also critically assesses persistent barriers, including regulatory uncertainty, technological complexity, and concerns about energy consumption and governance. The study's main contribution is a synthesis that reframes the problem, moving beyond technological optimism to underscore the necessity of holistic, interdisciplinary integration. It concludes that successful integration of Blockchain technology requires multidisciplinary collaboration, standardized frameworks, and inclusive governance models. Finally, the review identifies key research gaps and proposes research directions for advancing the field beyond conceptual discourse toward practical implementation.

Keywords: blockchain, REDD+, carbon credits, carbon market

1. Introduction

Climate change is one of the main global challenges of the 21st century, requiring mitigation strategies that combine environmental conservation with economic sustainability [1]. In this context, Reducing Emissions from Deforestation and Forest Degradation (REDD+) projects, established under the United Nations Framework Convention on Climate Change (UNFCCC), have emerged as a relevant international initiative. REDD+ projects aim to promote tropical forest conservation by linking verified emissions reductions to financial incentives for sustainable management and forest preservation practices [2, 3].

The financial sustainability of these projects depends on revenue from carbon credit sales. However, the credibility and, consequently, the value of the carbon credits are linked to the quality, reliability, and transparency of their monitoring, reporting, and verification (MRV) mechanisms [2, 3]. In addition, the volume of carbon credits from REDD+ projects increased significantly between 2006 and 2015. Still, this expansion was accompanied by widespread concerns about governance and the effectiveness of carbon dioxide (CO_2) emissions reduction, reinforcing the need for improvements in MRV systems [4, 5].

MRV involves activities such as baseline setting, carbon stock measurement, continuous monitoring, independent audits, and technical validation [2, 4]. This mechanism helps ensure that emission reductions are real, measurable, additional, and permanent and prevents recurring problems such as double-counting, leakage, and methodological inconsistencies [6]. However, the literature identifies significant challenges in operationalizing these systems, including high operating costs, information asymmetry, lack of standardization, and reliance on trusted intermediaries [7, 8]. These fundamental flaws in the MRV process create a cascade of adverse effects: high costs lead to expensive credits, data opacity breeds verification doubts, and manual processes increase the risk of fraud. Together, these effects culminate in market skepticism, which directly leads to weak project financing. This systemic erosion of trust, driven by core operational inefficiencies,

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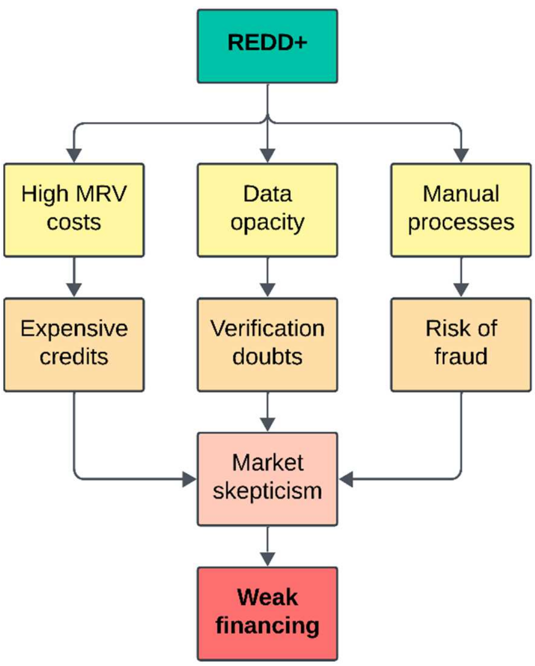
ultimately constrains the scalability and impact of REDD+ initiatives [5]. Figure 1 illustrates this causal chain, mapping how integrity flaws in REDD+ projects propagate into market distrust and financing shortfalls.

Over the past two decades, emerging digital technologies have come to be seen as tools for improving MRV processes. Among them, Blockchain technology stands out for its ability to provide transparency, security, immutability, and data traceability in distributed systems [3, 4, 6, 7]. When applied to REDD+ projects, this technology has the potential to strengthen governance mechanisms, reduce asymmetries, and increase the confidence of buyers and investors in the carbon market [9]. The use of Blockchain can also facilitate contract automation, environmental results auditing, and the traceability of carbon credits throughout their life cycle [6, 10].

In this scenario, a growing body of scientific literature examines the integration of REDD+ and Blockchain technology. However, the literature is fragmented into isolated conceptual discussions, theoretical analyses, and political-institutional reflections and offers little empirical validation [7, 11]. There is also a scarcity of frameworks and synthesized guidance on how specific Blockchain design choices map to the distinct technical and governance needs of REDD+ contexts. This fragmentation leaves architects without a clear roadmap for implementation.

Given this context, this article addresses the gap by conducting a systematic review to answer the central research question: how Blockchain technology can be effectively designed and integrated into REDD+ projects, and what the principal barriers to its successful adoption are. To address this issue, the review pursues the following specific research objectives: (i) to analyze and synthesize the existing literature on Blockchain applications in REDD+; (ii) to identify and critically assess the technical, governance, and social challenges impeding the practical implementation of Blockchain-based solutions; and (iii) to propose a structured research agenda that prioritizes the future work necessary to translate theoretical potential into viable, scalable, and equitable implementations.

Figure 1
Causal chain of integrity issues in REDD+ projects



In response to this question, this article is organized as follows. Section 2 presents the theoretical foundation addressing the carbon market, REDD+ projects, and the fundamentals of Blockchain technology. Section 3 describes the methodology used in conducting this review. Section 4 presents the results and a critical discussion of the literature. Section 5 discusses the fundamental areas of future study needed in this field. Finally, Section 6 presents the conclusions and points to directions for future research. Still, for ease of reading, a list of key acronyms used throughout the paper is provided in Table 1.

Table 1
Acronyms

Acronym	Meaning
DLT	Distributed Ledger Technology
IoT	Internet of Things
MRV	Monitoring, Reporting, and Verification
REDD+	Reducing Emissions from Deforestation and Forest Degradation
UNFCCC	United Nations Framework Convention on Climate Change
VCM	Voluntary Carbon Market

2. Theoretical Foundation

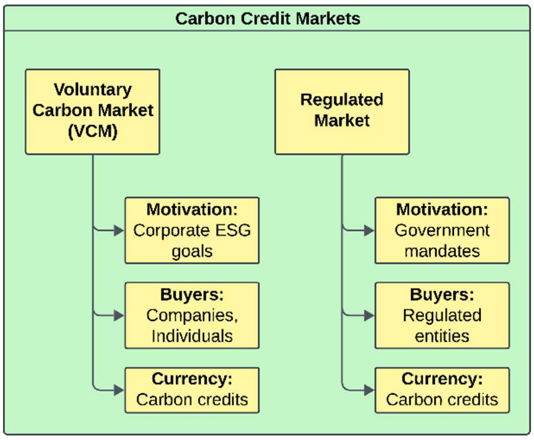
2.1. The carbon market and financing

The carbon market is a systematized environment for trading carbon credits, intangible units that correspond to one ton of CO_2 avoided or removed from the atmosphere [9, 12]. This market operates as a compensation mechanism, in which entities that implement Verified Emission Reduction projects sell credits to companies or governments that need or wish to offset their own emissions [2, 3].

In general, this market is divided into two segments: the Regulated Market and the Voluntary Carbon Market (VCM) [2, 3, 4]. This dual structure is illustrated in Figure 2, which highlights key actors and motivations of each market. The Regulated Market stems from international agreements, legal frameworks, and national policies that set mandatory emission limits. On the other hand, the VCM is based on voluntary offsetting initiatives promoted by companies, subnational governments, and individuals [6, 9]. The motivations for participating in the VCM are diverse, including obtaining climate certifications, meeting stakeholder demands, gaining recognition from end consumers, and preparing for future regulatory milestones [6, 7, 9].

The legitimacy of traded credits is ensured by compliance with international standards, which provide rigorous methodologies for MRV of emission reductions. Independent Designated Operational Entities perform validation and verification of these reductions [1, 2, 3]. With this structure, the market faces profound challenges: high transaction costs, information asymmetry between project developers and buyers, methodological complexity, and, crucially, risks of fraud and double-counting, where the same credit is sold or accounted for more than once [2, 9]. These factors raise costs, reduce liquidity, and undermine market confidence, making it challenging to access stable, long-term financing for forest conservation projects [6, 7, 9].

Figure 2
Structure of the carbon credit market



This combination of factors weakens financiers' confidence and can make it impossible to maintain community and conservation projects. For this reason, adopting more transparent and auditable technological tools can play a strategic role in increasing reliability and facilitating access to climate capital, especially in traditional communities that depend on REDD+ as a source of income and for territorial strengthening [7, 12].

2.2. REDD+ projects and criticism

In the context of the carbon market, REDD+ projects play a significant role by issuing carbon credits resulting from forest conservation [1, 2, 3, 6]. These projects aim to conserve and restore tropical forests by integrating financial incentives with the preservation of ecosystems critical to global climate balance. Their activities fall into four main categories, as illustrated in Figure 1: (i) Avoiding Planned Deforestation (APD); (ii) Avoiding Unplanned Deforestation and Degradation (AUDD); (iii) Reduced Impact Logging (RIL); and (iv) Afforestation, Reforestation, and Revegetation (ARR) [2, 3].

The financial sustainability of REDD+ projects depends on their ability to attract resources from investors, corporate buyers, and climate funds, which highlights the centrality of external financing [2, 3]. Much of the revenue comes from the sale of the generated carbon credits, making them financially viable in the long term [3, 6].

The life cycle of a REDD+ project begins with the proponents, who may be private companies, landowners, local communities, NGOs, or government entities. Those proponents prepare the Project Design Document [2, 3]. Furthermore, the project's implementation is often supported by specialized consultancies that provide technical and methodological support. After raising funds from financiers, the project is implemented, generating environmental and socio-economic benefits for local communities [3]. The crucial Monitoring, Reporting, and Verification (MRV) phase is conducted by independent auditors, whose reports validate emissions reductions for registration and trading on the carbon market. The financial flow generated by the sale of credits sustains the project, and the credits can be used for offsetting emissions or resold on the secondary market [2, 3, 6, 7].

However, access to financing for REDD+ projects faces four main barriers: (i) limited or unsustainable financing; (ii) information asymmetry in MRV processes; (iii) uneven distribution of financing; and (iv) failure to secure the rights of communities adjacent to forests [6]. These barriers are compounded by sector-specific challenges, such as methodological uncertainties in carbon stock estimates, high MRV operating costs, latent land conflicts, and significant risks of reversal of avoided emissions [9, 12].

The MRV process is the target of constant criticism. It begins with the establishment of a baseline, involving complex modeling of reference scenarios, accurate calculations of initial carbon stocks, and careful additionality analyses to demonstrate that the reductions would not have occurred in the absence of the project. Continuous monitoring combines remote sensing with on-site checks and final verification by accredited auditors. This process must certify the permanence of reductions, the absence of displacement emissions, and compliance with technical protocols [2, 3, 4, 7].

This process is labor-intensive, prone to human error, and often relies on physical or digital documentation that can be manipulated [5, 6]. The lack of transparency in raw data and calculation methods hinders independent third-party auditing. In addition, long intervals between verifications and credit releases create a mismatch between environmental performance and cash flow, thereby compromising the project's viability [8]. These inefficiencies and opacities result in high costs, delays, and, fundamentally, a crisis of confidence that severely limits the potential for scaling up REDD+ projects [5, 6, 7, 12].

2.3. Blockchain and traceability

Blockchain technology, designed as a distributed, immutable, and decentralized ledger, has properties that directly address the shortcomings of traditional MRV in REDD+ [13, 14]. Blockchain architecture is organized into four layers: infrastructure, platform, distributed computing, and application, ensuring decentralization, immutability, transparency, traceability, and trustful automation [15]. These core properties of Blockchain and their specific relevance to REDD+ are summarized in Table 2.

Its decentralized and distributed consensus architecture reduces the need for a single central authority to validate transactions, thereby reducing single points of failure and corruption [16, 17]. Consensus is achieved among multiple network nodes

Table 2
Core properties of blockchain and their relevance to REDD+

Property	Relevance
Decentralization	Reduces reliance on a single, potentially corruptible authority for verification
Immutability	Creates a permanent, fraud-resistant record of credit issuance and retirement
Transparency	Enables real-time audit by buyers, regulators, and communities, building market trust
Traceability	Allows credit origin tracking, project source verification, and benefit sharing
Automation with Smart Contracts	Automates payments upon verification and enforces contractual terms, reducing costs

through consensus algorithms, ensuring that no single entity controls the system unilaterally [13, 14]. In the context of REDD+ projects, it is crucial to select a consensus protocol appropriate to the project's specific security, scalability, and energy-efficiency requirements [7].

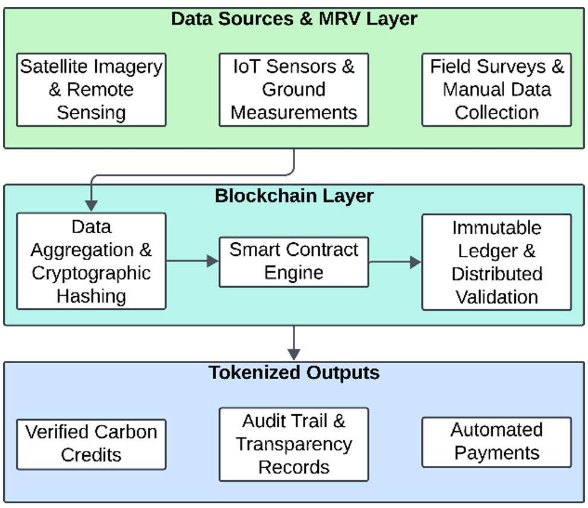
Combined with this feature, the immutability and integrity of Blockchain technology ensure that once a transaction is registered, it cannot be altered or deleted, creating a permanent, tamper-proof historical record [14]. The cryptographic link between blocks ensures immutability by using hashes that summarize all transactions in a block [14, 15]. This property is crucial for preventing double-selling of credits and ensuring the integrity of MRV data [6].

At the same time, the transparency and traceability inherent in Blockchain technology allow all transactions to be visible and auditable by authorized participants in public or permissioned networks with appropriate levels of access [14]. This enables complete tracking of the origin, transfer, and compensation of each carbon credit, from its generation to the final buyer. This traceability capability is particularly relevant in multi-party ecosystems with low mutual trust, such as REDD+ projects [18].

Beyond recording, smart contracts enable process automation. These self-executing programs can automate the issuance of credits after MRV data validation and auditing. Another automation is the automatic payment to local communities upon meeting conservation targets, as well as the management of the entire credit lifecycle [4, 6]. The ability to support smart contracts varies across Blockchain platforms and is a decisive criterion in technology selection, as evidenced by comparative analyses [18, 19].

Thus, Blockchain technology can be a relevant component of a broader governance ecosystem. Figure 3 presents a conceptual model of this integration, showing how data from MRV sources are processed through Blockchain layers to produce verified carbon credits and automated outputs for relevant stakeholders. This technology can dramatically reduce verification and transaction costs, accelerate capital flow to projects, and, fundamentally, restore investor and buyer confidence in the forest carbon market [9]. The adoption of Blockchain in REDD+ must, however, consider challenges such as scalability, energy consumption, interoperability between different Blockchain technologies, and reliable integration with external data sources, such as IoT sensors and satellite imagery [15]. Such challenges are echoed in many data-intensive environmental monitoring domains, including REDD+ projects. In these situations, processing large volumes of IoT and sensor data strains network performance and increases operational costs [20, 21]. Therefore, selecting an appropriate Blockchain architecture and an energy-efficient consensus protocol is a critical technical decision to ensure the system remains viable, sustainable, and accessible in infrastructure-constrained project regions.

Figure 3
Conceptual model of blockchain integration in REDD+ projects



3. Review Methodology

This article adopts a literature review approach to analyze and synthesize existing knowledge on the application of Blockchain technology in REDD+ projects. Adopting a structured, replicable approach aligned with PRISMA-ScR (Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews) guidelines, as shown by Figure 4. This figure provides a visual overview of the review process, from identification and screening to inclusion and synthesis of relevant literature. The methodology was designed to address the primary research question of how Blockchain technology can be effectively designed and integrated into REDD+ and to identify the key technical, governance, and social barriers for its successful adoption. The methodology was structured in five stages: (1) definition of the research question; (2) definition of search and selection criteria; (3) analysis and categorization of material; (4) integrative synthesis; and (5) critical discussion.

Searches were conducted between January and October 2025 in Scopus, Web of Science, ScienceDirect, Google Scholar, SSRN, and specialized journals databases. The following keywords were used in combination: Blockchain, REDD+, carbon markets, MRV, forest offsets, smart contracts, DLT, and carbon credits.

Figure 4
PRISMA flow diagram of the systematic review process

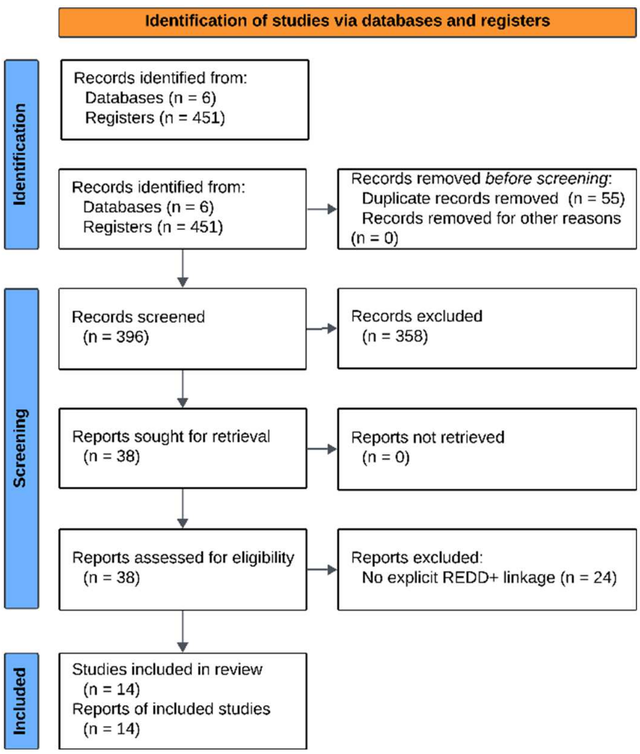


Table 3
Inclusion and exclusion criteria

Inclusion	Inclusion	Exclusion
Topic	Explicitly addresses Blockchain or DLT in REDD+ projects	Focuses on Blockchain in other sectors, without a specific REDD+ linkage
Content Type	Presents theoretical analyses, system proposals, case studies, or empirical experiments	Purely promotional material, nontechnical news articles, or brief abstracts without substantive content
Language	Published in English or Portuguese	Published in other languages
Access	Full text available	Full text unavailable

Regarding the quality assessment methods or criteria for evaluating each article's rigor, we proceeded as follows. After removing duplicates, the screening process used predefined inclusion and exclusion criteria, as shown in Table 3. The records were screened against the requirements based on their titles and abstracts. This initial filtering phase resulted in a subset of articles deemed potentially relevant for deeper analysis. The full texts of the articles selected were then retrieved and evaluated. Each article was assessed to confirm its alignment with the inclusion criteria and to evaluate its contribution to the research question. Articles were excluded at this stage primarily for reasons such as insufficient technical depth, tangential focus despite keyword matches, or inaccessibility in their entirety.

The following synthesis sought to identify convergences, divergences, knowledge gaps, and emerging trends in the field, providing a basis for critical discussion and proposals for future research directions. The review aimed to determine how Blockchain technology has been applied to enhance the transparency, traceability, and credibility of REDD+ projects, particularly in MRV and carbon credit management.

4. Results

The structured screening process, detailed in Section 3, identified a focused body of literature for analysis of key trends and gaps. The initial articles search yielded approximately 396 unique records. Through sequential title and abstract analyses, 38 articles were selected for full-text retrieval and evaluation. A further 24 articles were excluded at this stage, primarily for lacking technical depth or focusing on tangential topics. The final corpus for analysis comprised 14 articles.

The analysis of this corpus confirms that the development of technological solutions for REDD+ projects based on Blockchain is still in the early stages of scientific maturation. Although the number of publications has increased in the last five years, the literature shows a predominance of theoretical contributions, exploratory analyses, and conceptual proposals with limited technical detail and a scarcity of empirical experiments. The articles can be grouped into two primary areas: conceptual studies and system proposals.

The literature shows enthusiasm for Blockchain's potential to improve MRV, transparency, and investor confidence. Still, most proposals remain at the conceptual level—only a small number of studies detail system proposals, and even fewer present experimental results.

4.1. Analysis of conceptual studies

Conceptual studies investigate the potential of Blockchain technology to address recurring failures in REDD+ projects, particularly in MRV, benefit distribution, governance, and transparency. This body of literature highlights that the lack of trust in forest credits stems from the opacity of measurement processes and excessive intermediation, which creates information asymmetries between developers, local communities, and buyers [6, 7].

Researchers agree that technology can improve traceability, reduce the number of intermediaries, and increase credibility [4, 9, 13]. The literature highlights that REDD+ projects are among the most benefited, with technology solving problems such as double-counting through non-fungible tokens (NFTs) and double-selling, thanks to the immutability of the registry [9, 13].

Most authors identify that the use of smart contracts can reduce costs and ensure fairer financial transfers to communities [7, 22]. The incorporation of socio-environmental safeguards directly into payment flows and project execution adds an extra layer of protection for communities adjacent to forests against exploitation [7].

However, other authors take a critical stance, emphasizing that the isolated use of Blockchain does not resolve the structural tensions inherent in REDD+, such as land disputes, unequal governance, and the risk of exclusion for communities with low digital inclusion [8, 13]. The analysis of some REDD+ projects, such as Rimba Raya, concludes that their success was due to factors external to technology [8]. In these cases, the use of Blockchain technology posed challenges, including high implementation costs, difficulties in codifying socio-environmental benefits, and the risk of digital exclusion for communities adjacent to forests [8, 13]. These studies reinforce the need to consider social, legal, and political factors in its implementation.

The studies also reinforce that the use of this technology does not entirely resolve issues such as data leakage and property rights [7, 8]. There is also little clarity on how to reliably integrate MRV data without assurances about the security of external sources [22].

There is a lack of standardization in MRV methodologies, APIs, and data models, along with the dispersion of market solutions. This scenario creates fragmentation and hinders the acceptance of Blockchain-based credits, especially in MVC [9, 11]. REDD+ projects involve a multitude of actors, which means that any technological system must integrate into this complex ecosystem rather than operate as an isolated solution.

4.2. Analysis of system proposals

A second group of studies seeks to detail technical applications of Blockchain in REDD+, proposing computer systems, decentralized platforms, or credit registration models. These proposals represent a significant effort to apply Distributed Ledger Technologies (DLTs), smart contracts, and, in some cases, integrations with other emerging technologies to solve concrete problems of MRV, traceability, and governance. However, critical analysis reveals that such work often remains at the conceptual or business-requirements level, with limited technical depth, practical validation, or systematic comparison of implementation alternatives.

In [22], the authors explore the application of smart contracts to enable REDD+ projects aligned with the Paris Agreement. The author identifies clear opportunities, such as automating results-based payments, increasing transparency and trust among private actors, and enabling credit transactions without intermediaries. The study focuses on legal and financial feasibility, identifying critical challenges, including dependence on reliable external data (oracles), the complexity of backing tokens with tangible assets, and the diversity of MRV methodologies, which hinder interoperability. However, it does not detail the infrastructure aspects of the systems, such as the types of Blockchain or the underlying consensus mechanisms.

Moving on to architectural proposals, the authors in [4] define a general DLT-based architecture for the carbon market. The authors argue that distributed systems have the potential to revolutionize the certification and trading of credits, especially when integrated with other technologies. Despite this valuable conceptual contribution, the proposal is limited to a high-level architecture, does not compare distinct types of Blockchain technologies, and does not present practical experiments or performance metrics that validate the effectiveness of the proposed solution.

In [23], the authors analyze the financialization of nature in the Amazon, focusing on the REDD+ Nemus project, which uses NFTs backed by biodiversity through Blockchain technology. The author exposes fundamental governance challenges, such as land grabbing, the marginalization of local communities, and the lack of transparency in compensation mechanisms, and concludes that technology alone is insufficient to address these problems without strict regulation. Although the study highlights critical operational and social risks, it does not detail the project's underlying technological implementations, creating a gap in the system's technical understanding.

In a more recent study in [11], the authors discuss the potential of Blockchain and Artificial Intelligence to improve the integrity of MRV in REDD+ projects, addressing issues such as fraudulent credits and greenwashing. The author proposes a reform based on six pillars, including transparency, accountability, and the use of innovative technologies. Despite positioning Blockchain as a central solution to fraud and transparency issues, this article also does not detail which types of Blockchain would be most appropriate for the specific contexts of REDD+ projects, making it difficult to assess the feasibility of implementing the proposal in practice.

In summary, the analysis of works proposing Blockchain systems for REDD+ projects reveals a field of research that is still maturing. The discussion is restricted to conceptual, legal, or business levels. Studies that advance architectural proposals often refrain from comparing or experimentally validating different protocols and configurations, limiting themselves to general theoretical propositions [4, 7, 11]. This gap in the state of the art justifies and motivates further research, such as the present review, which seeks to consolidate existing knowledge and identify paths to develop robust solutions, evaluated not only for their conceptual potential but also for their technical feasibility, efficiency, and socio-environmental impact.

5. Future Research Directions

A systematic analysis of the literature reveals substantial gaps that hinder the large-scale implementation of Blockchain-based solutions for REDD+ projects. Based on a critical synthesis of the challenges identified, four priority areas for future research are outlined, each requiring specific methodological approaches and interdisciplinary collaboration.

5.1. Specialized technical architectures

The lack of computational architecture adapted to the particularities of tropical forest ecosystems is a significant limitation in the state of the art. Future research should focus on designing and validating consensus protocols that optimize the balance among security, scalability, and energy efficiency, while accounting for the infrastructure constraints in regions where REDD+ projects are typically implemented.

At the same time, it is imperative to develop robust frameworks for reliable integration between Blockchain systems and established MRV methods, including the creation of cryptographically secure protocols for incorporating heterogeneous data from remote sensing, IoT devices, and on-site verifications. Interoperability among Blockchain platforms in the carbon market demands equal attention, as it requires harmonizing different standards and protocols.

5.2. Empirical validation

The lack of empirical evidence on the operational effectiveness of Blockchain technology in real REDD+ contexts is a significant shortcoming in the existing literature. Future research should prioritize implementing monitored pilots. This research will enable the systematic collection of quantitative performance metrics on transaction costs, operational efficiency, and impacts on the trust of the entities involved.

The development of standardized methodologies for a comprehensive assessment of the socio-environmental impact of these technological implementations is equally crucial, particularly regarding the effects on benefit-distribution mechanisms. Comparative studies of different technological approaches in similar ecosystem contexts would significantly advance knowledge, enabling the identification of best practices and critical success factors.

5.3. Governance and regulation

The lack of specific regulatory frameworks for the application of Blockchain technology in REDD+ projects is a substantial obstacle to its widespread adoption. Future research should focus on developing multisectoral governance models that adequately involve all relevant actors, including traditional communities, project developers, independent certification bodies, and national and international regulatory agencies.

In addition, the development of international technical standards for the certification of Blockchain-based credits, compatible with the requirements of bodies such as the UNFCCC and with the main voluntary standards recognized by the market, is another necessary area of research. At the same time, in-depth studies on digital inclusion models adapted to the sociocultural realities of traditional communities are essential to prevent technological marginalization and ensure participatory equity.

5.4. Financial and operational viability

The financial viability of implementing and maintaining Blockchain technology across REDD+ projects of varying sizes and characteristics remains insufficiently explored in the specialized literature. Research on business models that equitably distribute costs and benefits among ecosystem actors is necessary, given the economic asymmetries often present in these contexts. To this end, research on mechanisms to reduce transaction costs without compromising security and decentralization is promising.

In addition, studies on the long-term operational sustainability of these technological solutions are also necessary. These studies should cover aspects such as long-term maintenance, periodic technological updates, and structured local training programs.

When adequately developed through rigorous methodological approaches and interdisciplinary collaboration, these research directions have the potential to transform the current theoretical potential of Blockchain technology into tangible benefits for the integrity, transparency, and effectiveness of REDD+ projects, while advancing scientific knowledge and conserving tropical forest ecosystems.

6. Conclusions

This systematic review of the literature demonstrates that Blockchain technology is emerging as a transformative paradigm for addressing the structural limitations of conventional MRV systems in REDD+ projects. A critical analysis shows that the technology's fundamental properties are directly aligned with the pressing needs for credibility, traceability, and operational efficiency that have historically limited the potential to scale these projects. However, the practical implementation is more complex than the theoretical proposition, as evidenced by a nascent research field dominated by conceptual discussions rather than empirical applications.

The review underscores that the primary barriers to effective integration are not merely technological but rather deeply rooted in socio-economic complexities. The tokenization of carbon credits, while promising for liquidity and accessibility, must be coupled with robust governance mechanisms to prevent market fragmentation and ensure environmental integrity. For project developers, this means that pilots must be designed as multidisciplinary experiments that rigorously measure impact on key performance metrics, such as reductions in verification costs, time to credit issuance, and enhancements in stakeholder trust.

A central conclusion is that purely technological solutions are insufficient to overcome deeply rooted structural challenges, such as power asymmetries, unresolved land conflicts, and inadequate mechanisms for community participation. When implemented without proper socio-environmental safeguards, Blockchain technology can inadvertently exacerbate existing inequalities and create new forms of digital exclusion.

The analysis of the identified challenges reveals that the successful integration of Blockchain into REDD+ projects requires holistic approaches that transcend the technical domain. Overcoming the identified barriers requires multidisciplinary frameworks that harmonize technological innovation with appropriate regulation. Surpassing these barriers involves designing digital interfaces with forest communities, ensuring data sovereignty, and creating transparent grievance mechanisms. The maintenance of the technology itself, such as decisions on network access and protocol upgrades, must be scrutinized as thoroughly as the environmental outcomes it seeks to measure.

Building upon this analysis, the critical analysis in Sections 4 and 5 identified persistent gaps that chart a clear direction for future research. Advancing beyond conceptual discourse requires focused interdisciplinary efforts in the priority areas previously outlined: (i) developing and empirically validating specialized technical architectures; (ii) creating frameworks for reliable data integration and interoperability; (iii) establishing harmonized regulatory standards for Blockchain-verified credits; and (iv) designing participatory digital governance models to ensure equitable benefit sharing. Thus, these directions are essential to translate theoretical promise into tangible, scalable, and just implementations.

In addition, the insights from this review offer actionable guidance for key stakeholders. There is an urgent need to develop and pilot technical standards for Blockchain-based MRV and credit issuance, including guidelines for oracle security and smart contract audits. For REDD+ project developers and investors, pilots should be designed as multidisciplinary experiments that measure key performance indicators, such as reduced verification costs, thereby de-risking projects and directing capital toward transparent ventures. For regulatory agencies, proactive engagement is required to create regulatory sandboxes for testing Blockchain applications while safeguarding against market fragmentation and to support interoperability protocols and digital literacy initiatives for forest communities.

In summary, this review concludes that the transformative potential of Blockchain technology for the REDD+ ecosystem will only materialize through integrated approaches that recognize the inherently socio-technical nature of these systems. Future research should transcend simplistic dichotomies between technological innovation and socio-environmental conservation, embracing interdisciplinary perspectives that translate current theoretical potential into tangible benefits for the environmental integrity, social equity, and climate effectiveness of tropical forest conservation projects.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Marcela Ceschim Caburlão: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Carlo Kleber da Silva Rodrigues:** Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Supervision, Project administration.

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