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Blockchain-Enabled Environmental Governance and Climate Justice

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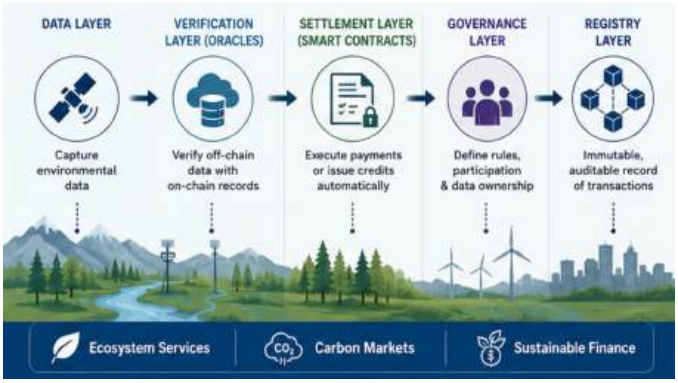
Abstract— Climate change and environmental degradation continue to expose deep structural weaknesses in how natural resources, emissions, and ecological benefits are governed, monitored, and distributed. Conventional environmental governance systems are frequently criticized for opacity, weak enforcement, fragmented monitoring, and unequal participation of vulnerable and indigenous communities in decision-making. Blockchain technology, with its properties of decentralization, immutability, transparency, and programmable smart contracts, has emerged as a candidate infrastructure for addressing these governance gaps. This manuscript examines how blockchain-enabled systems can strengthen environmental governance while advancing climate justice, understood as the fair distribution of environmental benefits, burdens, and decision-making power across communities. Drawing on verifiable peer-reviewed literature on blockchain applications in payments for ecosystem services, carbon credit markets, sustainable finance, and indigenous data sovereignty, this paper develops a conceptual framework linking blockchain architecture to justice outcomes. The paper also identifies persistent challenges including energy consumption, digital exclusion, regulatory uncertainty, and the risk of reproducing existing power asymmetries under a technocratic guise. The paper concludes that blockchain can meaningfully support environmental governance and climate justice only when its deployment is paired with inclusive institutional design, community consent, and policy safeguards, rather than treated as a purely technical fix.

Keywords— blockchain, environmental governance, climate justice, carbon markets, smart contracts, indigenous data sovereignty, sustainability

INTRODUCTION

The governance of environmental resources, carbon emissions, and ecological services has historically depended on centralized institutions, including national regulatory agencies, multilateral bodies, and certification schemes. These institutions, while essential, have repeatedly faced criticism for limited transparency, inconsistent enforcement, high administrative costs, and the exclusion of frontline and indigenous communities from meaningful participation. As the climate crisis intensifies, the shortcomings of these arrangements become more consequential, particularly for populations that bear the greatest environmental burdens while holding the least influence over governance decisions.



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Climate justice foregrounds the ethical dimension of environmental governance. It asks not only whether emissions are reduced or ecosystems protected, but who benefits, who is harmed, and who decides. A governance architecture that is technically sound but socially exclusionary cannot deliver just outcomes. It is against this backdrop that blockchain technology has attracted growing scholarly and policy interest. Blockchain systems distribute record-keeping across a network of nodes rather than a single authority, use cryptographic verification to secure transaction history, and can execute self-enforcing smart contracts once predefined conditions are met. These properties appear well suited to problems that have long troubled environmental governance, including double counting of carbon credits, opaque supply chains, weak monitoring of land use, and difficulty verifying ecological claims.

This manuscript investigates the intersection of blockchain-enabled governance mechanisms and climate justice. It reviews verifiable academic literature on blockchain applications across ecosystem service payments, carbon markets, sustainable finance, and indigenous data sovereignty, and it develops an analytical framework that connects technical design choices to justice outcomes. The paper is structured to first review the relevant literature, then to present a conceptual architecture for blockchain-enabled environmental governance, followed by a discussion of climate justice dimensions, persistent challenges, and policy implications.

Literature Review

A growing body of peer-reviewed research documents blockchain applications across environmental governance domains, though most existing work remains fragmented across specific use cases rather than integrated around justice concerns.

Early empirical work by Wehkamp and colleagues investigated a proof-of-concept blockchain-based payment for ecosystem services mechanism combining an Ethereum smart contract for benefit distribution with remote sensing algorithms for detecting land cover change, applying this design hypothetically to the Wildlife Credits scheme in Namibia. That study is significant because it addresses a documented weakness in payment for ecosystem services programs in the Global South, where conventional schemes face recurring implementation challenges that blockchain-based tamper-proof contracts were proposed to help resolve.

Carbon markets represent the most extensively studied domain of blockchain-enabled environmental governance. A recent systematic review in *Discover Environment* examined how blockchain technology addresses persistent carbon market weaknesses such as lack of transparency, inefficiency, and governance gaps by automating verification and validation through smart contracts, situating blockchain within a framework of decentralization, decarbonization, and digitization. The same review found that blockchain operates on a decentralized ledger distributed across a network of nodes rather than a central database, which prevents any single entity from controlling the system and thereby promotes transparency while reducing the risk of manipulation or fraud, while peer-to-peer transaction structures reduce reliance on centralized intermediaries and lower transaction costs.

Complementary empirical work reinforces these findings. Research on blockchain-enabled carbon credit trading found that blockchain allows every credit issued, traded, or retired to be verified in real time, reducing risks of fraud, double-counting, and greenwashing, with smart contracts further automating transactions to improve efficiency. Similarly, a proposed democratized carbon credit trading architecture published in a peer-reviewed journal formalizes the roles of producers, regulators, and market participants across the lifecycle of carbon credits, arguing that a peer-to-peer exchange without a centralized authority prone to regional bias can enable standardized cross-border transactions on tamper-resistant and auditable infrastructure. Related work on fraud detection demonstrates that blockchain-based visualization techniques can support transparency and traceability in carbon credit trading and assist in mitigating fraud while supporting compliance with international carbon trading standards.

Beyond carbon markets, broader sustainability-oriented reviews situate blockchain within wider development goals. A systematic literature review covering 131 peer-reviewed articles published between 2015 and early 2025 found that blockchain is increasingly recognized as a transformative digital infrastructure for advancing environmental, economic, and social sustainability, though academic research on its

potential remains fragmented with limited integration of theoretical models and system-level impacts, and this review specifically categorized environmental-domain literature around renewable energy transactive markets, climate mitigation and carbon accountability, and ecological conservation applications. A separate policy-oriented systematic review analyzing over ten thousand technical and policy papers examined the regulatory environment relevant to blockchain-enabled ESG governance, including alignment with the SDGs, IPCC guidance, and reporting frameworks such as TCFD and GRI, concluding that most existing papers lack a structured approach for applying blockchain within emerging regulatory environments.

Legal scholarship has also begun to examine blockchain as a governance instrument rather than purely a technical tool. A qualitative legal study examined how blockchain-based smart contracts can support environmental law enforcement by enhancing transparency and compliance, reviewing pilot programs across cross-jurisdictional pollution agreements, natural resource management, and carbon offset transactions, and calling for clearer guidelines for policymakers and legal practitioners.

Not all scholarship is optimistic. Critical political science literature cautions against uncritical adoption of blockchain narratives in climate governance. A widely cited critical analysis interrogates the dominant discourse around blockchain-enabled climate governance and argues that its component elements tend to privilege a technocratic, market-oriented approach, raising concern that this risks reinforcing a problematic post-political turn in environmental governance. This critique is central to any discussion of climate justice, since a technically transparent system can still concentrate power and marginalize non-market forms of environmental stewardship.

Indigenous data sovereignty research extends this justice-oriented critique into the design of blockchain systems themselves. A study published in *Cell* on indigenous data governance proposed a consortium blockchain framework specifically adhering to the core principles of indigenous data sovereignty, establishing indigenous peoples' rights to govern the collection, ownership, privacy, and application of their own data, purposefully coded into the blockchain's governance environment including through smart contract execution language. The same study noted an important tension, observing that given the heavy carbon footprint of some blockchain-based data governance ecosystems, engineers, data scientists, and traditional knowledge keepers would need to co-design more climate-resilient systems. Related work on Indigenous Environmental Data Justice frames a distinct set of practices and principles that indigenous communities have developed in response to colonial environmental datafication, arguing that environmental agencies and companies have historically supplied inadequate colonial data that indigenous communities must confront through their own sovereign data governance practices. Complementing this, a participatory digital platform study for climate change preparedness among indigenous communities in Canada combined traditional knowledge with citizen science and digital dashboards for early detection of climate change impacts on food sovereignty and security, motivated by the recognition that inequities in food acquisition and distribution worsen food insecurity under climate stress.

Finally, applied policy commentary underscores that governance design, not technology alone, determines justice outcomes. A climate policy analysis observes that emerging climate technologies, including blockchain-enabled carbon markets, are reshaping mitigation and adaptation efforts, but warns that as these innovations scale, so do risks of exclusion, bias, and inequity, particularly for frontline communities left out of digital and policy infrastructures.

Taken together, the literature supports three broad conclusions. First, blockchain has demonstrated technical feasibility for improving transparency and reducing fraud across ecosystem service payments and carbon markets. Second, most existing research remains sector-specific and does not integrate governance design with justice outcomes. Third, a smaller but important body of critical and indigenous-focused scholarship warns that blockchain deployment can reproduce or deepen existing inequities unless governance and consent mechanisms are deliberately embedded in system design.

RESEARCH OBJECTIVES

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The study pursues the following objectives, drawn directly from the gaps identified in the literature review:

- To examine how blockchain architecture can strengthen transparency and accountability in environmental governance mechanisms such as carbon markets and ecosystem service payments
- To develop a conceptual framework connecting blockchain design features to climate justice outcomes
- To identify structural and social risks that may limit blockchain's contribution to equitable environmental governance
- To propose policy-relevant safeguards for justice-oriented blockchain deployment

METHODOLOGY

This paper adopts a qualitative, conceptual research design based on a structured review of verifiable peer-reviewed and institutionally published literature on blockchain applications in environmental governance, carbon markets, sustainable finance, and indigenous data sovereignty. Sources were selected based on relevance to environmental governance and climate justice themes, verifiable publication in indexed journals or reputable academic repositories, and recency, with priority given to studies published between 2019 and 2026. The review followed a thematic synthesis approach, organizing findings around four recurring domains identified across the literature: ecosystem service payment mechanisms, carbon credit market infrastructure, sustainable finance and ESG reporting, and indigenous and community data sovereignty. From this synthesis, a conceptual framework was developed linking specific blockchain design features to climate justice dimensions of recognition, participation, and distribution. This approach is appropriate for an emerging and interdisciplinary field where empirical deployment data remains limited and where the central research problem concerns institutional design rather than a testable quantitative hypothesis.

Blockchain Architecture for Environmental Governance

Blockchain-enabled environmental governance systems generally combine three architectural layers: a data layer responsible for capturing environmental information such as land cover change, emissions data, or ecosystem condition; a verification layer that reconciles this data with real-world claims, often through oracles linking off-chain sensors or satellite data to on-chain records; and a settlement layer where smart contracts execute payments, credit issuance, or compliance actions once verification conditions are met. Table 1 summarizes how these architectural components map onto specific environmental governance functions identified in the literature reviewed above.

Table 1: Blockchain Architectural Components and Environmental Governance Functions

Architectural Layer	Core Function	Example Application from Literature
Data layer	Captures environmental observations (land cover, emissions, biodiversity indicators)	Remote sensing linked to ecosystem service payments in Namibia
Verification layer (oracles)	Reconciles off-chain environmental data with on-chain records	Land cover change detection triggering smart contract payments
Settlement layer (smart contracts)	Executes payments, credit issuance, or compliance actions automatically	Automated verification and trading of carbon credits
Governance layer	Defines participation rights, consensus rules, and data ownership	Indigenous data sovereignty principles coded into consortium blockchain rules
Registry layer	Maintains an immutable, auditable record of transactions	Carbon credit issuance, trading, and retirement tracking

This layered view clarifies an important point often obscured in purely technical discussions: the governance layer, which determines who can participate, whose data is recorded, and under what consent conditions, is not a neutral technical add-on. It is the layer most directly responsible for whether a blockchain system advances or undermines climate justice.

Climate Justice Dimensions of Blockchain Governance

Climate justice scholarship commonly distinguishes between distributive justice, concerning the fair allocation of environmental benefits and burdens; procedural justice, concerning fair and inclusive participation in decision-making; and recognitional justice, concerning respect for the identities, knowledge systems, and rights of affected communities. Applying these dimensions to blockchain-enabled

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environmental governance produces the following observations.

Distributive justice is potentially strengthened where blockchain reduces intermediary capture of ecosystem service payments and carbon credit revenues, allowing benefits to flow more directly to the communities generating environmental value, as illustrated in the Namibia ecosystem service payment case. Procedural justice depends heavily on who controls the governance layer, meaning who sets consensus rules, who can validate transactions, and who can appeal or contest recorded outcomes. Recognitional justice is most directly engaged by the indigenous data sovereignty literature, which insists that data governance frameworks must be co-designed with affected communities rather than imposed upon them.

Table 2 summarizes the relationship between these justice dimensions, the governance risks identified in the literature, and the design responses proposed by researchers.

Table 2: Climate Justice Dimensions in Blockchain-Enabled Environmental Governance

Justice Dimension	Governance Risk Identified in Literature	Proposed Design Response
Distributive justice	Intermediary capture of ecosystem service or carbon credit revenues	Direct smart contract-based benefit distribution to resource stewards
Procedural justice	Technocratic, market-oriented governance excluding frontline communities	Participatory, multi-stakeholder consensus and governance design
Recognitional justice	Colonial data structures and inadequate community consultation	Indigenous data sovereignty principles embedded in smart contract rules
Environmental integrity	Double counting, greenwashing, and unverifiable claims	Immutable, auditable registries with independent verification oracles

DISCUSSION

The literature reviewed indicates that blockchain technology offers genuine technical improvements for specific environmental governance problems, particularly the verification and transparency challenges that have long undermined carbon markets and ecosystem service payment schemes. The convergence of independent studies on transparency, reduced fraud, and lower transaction costs across different carbon market contexts strengthens confidence that these are not isolated findings but a consistent pattern across the literature.

However, the discussion cannot stop at technical performance. The critical political science literature reviewed above cautions that framing climate governance primarily through market-oriented, technocratic language can obscure questions of power and participation. This is precisely the tension climate justice scholarship highlights. A blockchain-based carbon registry may be immutable and auditable while still excluding the communities whose land or resources generate the underlying environmental value from meaningful decision-making authority. Immutability guarantees that a record cannot be altered after the fact, but it says nothing about whether the process that produced that record was fair or inclusive.

The indigenous data sovereignty literature offers the clearest pathway for reconciling these tensions. By embedding governance rules, consent requirements, and ownership rights directly into smart contract logic, blockchain systems can be designed so that community control is not merely a policy aspiration layered on top of the technology but a structural feature of the system itself. This suggests that the justice potential of blockchain-enabled environmental governance depends less on the underlying cryptographic architecture and more on the institutional and participatory design choices made before deployment.

A further discussion point concerns environmental integrity. Several carbon market studies highlight blockchain's capacity to reduce double counting and greenwashing, which are themselves justice-relevant problems, since fraudulent or exaggerated emissions claims ultimately shift real mitigation burdens onto communities least responsible for causing climate change. In this sense, technical integrity and distributive justice are connected rather than separate concerns.

CHALLENGES AND LIMITATIONS

Despite its potential, several challenges limit the contribution of blockchain to just environmental governance outcomes.

Energy consumption remains a concern for certain consensus mechanisms, creating a tension between the carbon accounting goals of these systems and their own environmental footprint, a concern explicitly raised in the indigenous data sovereignty literature. Digital infrastructure gaps mean that communities most affected by environmental harm, including many indigenous and rural populations, may lack reliable internet access or digital literacy needed to participate meaningfully in blockchain-based governance systems, risking a new form of exclusion even as older forms of exclusion are addressed. Regulatory uncertainty across jurisdictions complicates the standardization of blockchain-based carbon registries, an issue underscored by the systematic policy review referenced earlier. Finally, there remains a genuine risk that blockchain systems, if designed without community input, could formalize and entrench existing power asymmetries under the appearance of neutral, decentralized technology.

POLICY IMPLICATIONS

The findings suggest several policy directions. Regulators and standard-setting bodies should require that blockchain-based environmental governance systems include documented community consent and participation mechanisms as a condition of registry recognition. Interoperability standards should be developed so that blockchain-based carbon and ecosystem service registries can be independently audited by third parties, consistent with recommendations from the carbon market literature. Where indigenous or frontline communities are directly affected, governance layer design should follow established data sovereignty principles rather than generic technical templates. Finally, given the diversity of institutional contexts across jurisdictions, policy frameworks should avoid a one-size-fits-all approach and instead support context-specific pilots, similar in spirit to the ecosystem service payment proof of concept studied in Namibia, before scaling systems more broadly.

CONCLUSION

Blockchain technology offers a credible, evidence-supported set of tools for addressing long-standing transparency, verification, and accountability problems in environmental governance, particularly within carbon markets and ecosystem service payment schemes. The reviewed literature consistently demonstrates that decentralized, immutable, and auditable ledgers can reduce fraud, double counting, and administrative inefficiency. Yet climate justice requires more than technical integrity. It requires that the communities bearing the greatest environmental burdens have meaningful recognition, participation, and a fair share of the benefits generated by these systems. The critical and indigenous data sovereignty literature reviewed here makes clear that blockchain systems designed without deliberate attention to governance, consent, and community control risk reproducing the very exclusions they are meant to resolve. The path toward genuinely just environmental governance therefore lies not in the blockchain technology itself, but in the institutional choices, participatory processes, and policy safeguards that shape how it is designed, governed, and deployed.

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