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Original Research Paper

Blockchain-Based Environmental Governance for Transparent Wildlife Conservation and Regulatory Compliance

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Abstract: Wildlife conservation governance faces significant challenges related to fragmented information systems, fraudulent documentation, limited traceability, and inconsistent regulatory monitoring. This study proposes a blockchain-based environmental governance framework to improve transparency, accountability, wildlife traceability, and regulatory compliance. The framework integrates permissioned blockchain, smart contracts, digital identification, secure off-chain storage, and regulatory monitoring to establish auditable wildlife conservation records. A representative wildlife trade case study evaluates the proposed approach using wildlife records, digital permits, movement transactions, and regulatory inspections. Of 2,460 movement transactions, 2,418 were successfully verified, achieving a 98.29% blockchain verification rate. Among 1,175 regulatory inspections, 86 compliance violations were identified, including 34 invalid or expired permits. The findings demonstrate the potential of blockchain to strengthen permit authentication, transaction traceability, inter-agency information sharing, and compliance monitoring. The study also identifies legal and regulatory concerns involving data privacy, sensitive ecological information, evidentiary recognition, jurisdiction, liability, and smart-contract accountability. The proposed framework positions blockchain as a governance-supporting infrastructure rather than a replacement for environmental authorities. The study concludes that integrating blockchain with appropriate legal safeguards and institutional oversight can contribute to transparent, traceable, and accountable wildlife conservation governance.

Keywords: Blockchain, Wildlife, Conservation, Governance, Transparency, Traceability, Compliance, Smart Contracts, Regulation, Sustainability.

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I. Introduction

Environmental governance has become increasingly complex due to the growing pressures of biodiversity loss, wildlife trafficking, habitat degradation, climate change, illegal resource exploitation, and inadequate enforcement of environmental regulations. Wildlife conservation is particularly challenging because it involves numerous stakeholders, including government agencies, forest departments, conservation organizations, local communities, researchers, customs authorities, and international institutions [1]. Effective coordination among these stakeholders requires reliable information, transparent decision-making, and strong regulatory oversight. However, conventional environmental governance systems often depend on centralized databases, fragmented institutional records, and manual reporting mechanisms [2]. These limitations can create information gaps, data manipulation risks, delayed enforcement, and difficulties in establishing accountability [3]. Consequently, there is increasing interest in digital technologies capable of strengthening transparency and trust within wildlife conservation governance. Blockchain technology offers significant potential in this context because it provides a decentralized and tamper-resistant mechanism for recording, validating, and sharing information. Unlike conventional centralized databases, blockchain maintains distributed records in which verified transactions are chronologically stored and difficult to alter retrospectively [4]. Important conservation information, including wildlife monitoring records, species movements, habitat interventions, permits, enforcement activities, wildlife trade documentation, and regulatory approvals, can therefore be maintained through auditable digital records. Such characteristics may improve traceability and reduce opportunities for unauthorized alteration, fraudulent documentation, and institutional opacity [5]. Blockchain should nevertheless be understood as a governance-supporting infrastructure rather than an automatic solution to environmental problems. One particularly important application concerns wildlife trade and supply-chain traceability [6]. Illegal wildlife trafficking frequently intersects with legitimate trade networks, making verification of origin, ownership, permits, and transportation records difficult.

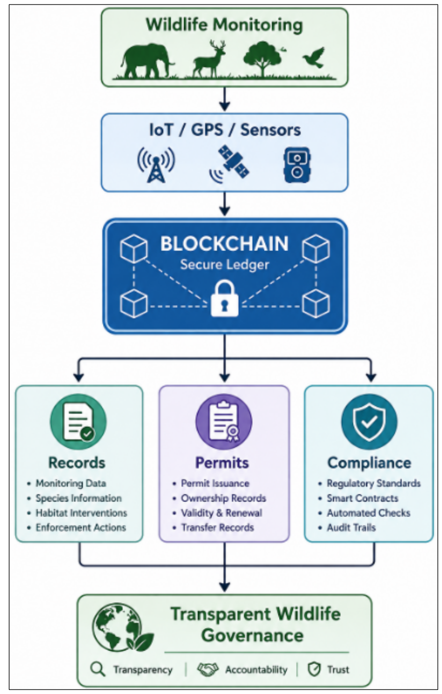

Figure 1. Blockchain-Based Wildlife Conservation Governance Framework

Blockchain-based systems can establish a continuous record of authorized activities from the initial registration of wildlife-related assets or products through transportation, inspection, transfer, and final authorization [7]. When combined with Internet of Things (IoT) sensors, GPS-enabled monitoring, digital identity mechanisms, and smart contracts, blockchain can support more timely verification and automated compliance processes as depicted in figure 1. Smart contracts may, for example, execute predetermined regulatory conditions when required permissions or conservation standards have been satisfied [8]. From a legal perspective, however, blockchain-based environmental governance raises several important questions. Regulatory authorities must determine the legal validity of blockchain records, admissibility of digitally recorded evidence, responsibility for incorrect data, protection of sensitive ecological information, and compatibility with privacy and data-protection requirements. Immutable records can strengthen accountability but may also conflict with legal requirements concerning correction, deletion, confidentiality, or restricted access [9]. Moreover, smart contracts cannot independently interpret complex environmental legislation or replace discretionary decisions made by competent authorities. Their role must therefore remain embedded within an appropriate legal and institutional framework.

This research examines the potential of blockchain-based environmental governance to enhance transparency, accountability, traceability, and regulatory compliance in wildlife conservation. It evaluates how decentralized records, smart contracts, and blockchain-enabled monitoring can strengthen conservation governance while identifying associated legal, institutional, technological, and ethical challenges. The study ultimately seeks to develop a balanced governance framework in which blockchain complements, rather than replaces, environmental institutions and legal enforcement. Such an approach can contribute to more trustworthy conservation records, improved inter-agency coordination, stronger regulatory oversight, and accountable decision-making while ensuring that technological innovation remains consistent with environmental law and wildlife protection objectives.

II. Blockchain Technology and Environmental Governance

Blockchain technology has emerged as a significant digital innovation for improving transparency, accountability, data integrity, and coordination across complex governance systems. In environmental governance, these characteristics are particularly relevant because regulatory activities frequently involve multiple institutions responsible for collecting environmental information, issuing permissions, monitoring compliance, and enforcing conservation laws [10]. Conventional governance mechanisms often rely on separate databases and administrative records, which can lead to duplication, inconsistent information, limited interoperability, and difficulties in verifying environmental activities [11]. Blockchain provides an alternative infrastructure through which authorized stakeholders can maintain a shared and verifiable record of environmental transactions and regulatory actions. At its core, blockchain functions as a distributed ledger in which information is recorded in sequential blocks and validated according to predetermined consensus mechanisms [12]. Once verified and added to the ledger, records become difficult to modify without detection. This characteristic can strengthen the integrity of environmental information relating to wildlife populations, habitat conditions, conservation permits, protected-area activities, environmental inspections, restoration initiatives, and wildlife-related transactions. Rather than depending entirely on a single administrative authority to maintain records, participating organizations can access a synchronized version of authorized information [13].

Blockchain Feature	Environmental Governance Function	Potential Benefit
Distributed ledger	Shared environmental records	Improved inter-agency coordination
Immutability	Protection of verified records	Reduced risk of manipulation
Traceability	Tracking permits and transactions	Greater regulatory transparency
Smart contracts	Rule-based compliance processes	Faster administrative verification
Time-stamping	Recording regulatory actions	Stronger accountability

Smart contracts extend blockchain beyond secure recordkeeping by automating rule-based environmental compliance. They can validate wildlife permits, generate alerts for expired licenses, and identify regulatory violations based on predefined conditions. However, they should support rather than replace environmental authorities, as complex decisions often require scientific assessment and administrative judgment [14]. Blockchain can also integrate with IoT sensors, GPS devices, drones, camera traps, satellite monitoring, and AI systems to create traceable environmental records. This integration can improve wildlife monitoring, information sharing, and coordination among conservation and enforcement agencies. However, blockchain cannot guarantee the accuracy of information entered into the system, creating the oracle problem. Therefore, reliable data verification, authorized access, cybersecurity, privacy protection, institutional responsibility, and legal safeguards are essential. With appropriate governance, blockchain can strengthen transparency, traceability, accountability, and regulatory coordination in environmental conservation.

III. Blockchain Applications in Wildlife Conservation

Blockchain can strengthen wildlife conservation by providing secure, transparent, and traceable records across agencies involved in monitoring, trade regulation, protected-area management, conservation finance, and enforcement. Wildlife data collected through GPS collars, camera traps, drones, acoustic sensors, and IoT devices can be linked to blockchain records with timestamps and provenance information, creating an auditable history of data collection and modification. A major application is wildlife trade traceability [15]. Authorized wildlife specimens, products, permits, and consignments can receive unique digital identities, while activities such as registration, ownership transfer, transportation, inspection, and authorization are recorded on the blockchain. This can reduce fraudulent documentation and improve regulatory verification.

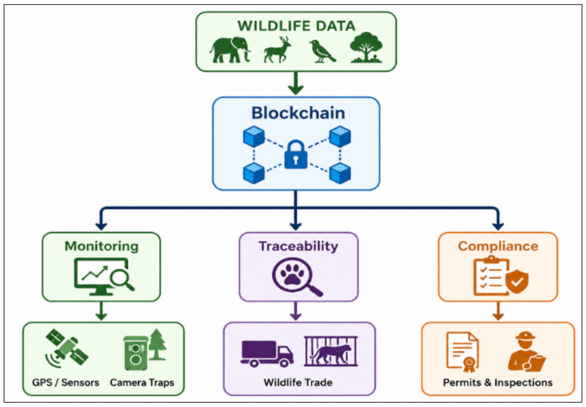

Figure 2. Blockchain-Based Wildlife Conservation Technology

Blockchain can also support protected-area governance by recording permissions for tourism, research, habitat restoration, and resource use. Smart contracts can automatically verify predefined requirements, such as permit validity and authorization status [16]. Similarly, blockchain-based financial records can improve transparency in conservation funding and benefit-sharing with local and Indigenous communities as depicted in figure 2. For wildlife law enforcement, blockchain can preserve time-stamped records of seizures, inspections, permits, and monitoring activities, strengthening digital chains of custody. However, blockchain cannot guarantee that initially entered information is accurate. Physical verification, authorized data entry, and legally recognized procedures remain essential [17]. Overall, blockchain can provide a trusted information infrastructure connecting wildlife monitoring, trade control, conservation finance, protected-area administration, and enforcement. Its effectiveness depends on integration with conservation science, institutional governance, community participation, and environmental law.

IV. Legal and Regulatory Challenges of Blockchain Adoption

Despite its potential to strengthen transparency and accountability in wildlife conservation, blockchain technology creates significant legal and regulatory challenges. Environmental governance is fundamentally based on statutory authority, administrative procedures, evidentiary standards, institutional responsibility, and enforceable rights and obligations. A blockchain platform cannot independently satisfy these requirements merely because its records are decentralized or difficult to alter. Its adoption must therefore be supported by a legal framework that determines the status of blockchain records, responsibilities of participating institutions, protection of sensitive information, and procedures for resolving disputes. A primary issue concerns the legal recognition and evidentiary value of blockchain records. Wildlife enforcement may involve digital permits, inspection reports, transaction histories, species-identification records, and evidence concerning illegal trade. For these records to support administrative or judicial proceedings, authorities must establish their authenticity, reliability, integrity, and chain of custody. Although blockchain can demonstrate that a record has not been altered after registration, it cannot automatically prove that the original information was accurate. Consequently, authorized data-entry procedures, digital signatures, verification standards, and clear evidentiary rules remain essential.

Legal status of records	Uncertain evidentiary acceptance	Recognition standards and digital signatures
Data privacy	Unauthorized personal-data exposure	Encryption and access controls
Blockchain immutability	Difficulty correcting records	Off-chain storage and amendment mechanisms
Smart contracts	Automated unlawful decisions	Human and regulatory oversight
Jurisdiction	Cross-border legal conflicts	International cooperation
Liability	Unclear responsibility for errors	Defined institutional accountability

Smart contracts present another regulatory challenge. Environmental laws frequently require scientific assessment, proportionality, public participation, expert judgment, and administrative discretion. These elements cannot always be translated into rigid computational conditions. Automated execution may produce inappropriate outcomes if underlying data is inaccurate or legal requirements change. Smart contracts should therefore automate only clearly defined procedural functions while consequential environmental decisions remain subject to competent human authorities and legal review. The cross-border character of wildlife trafficking also raises questions of jurisdiction and regulatory interoperability. Wildlife specimens may pass through several countries with different environmental laws, technological standards, evidentiary requirements, and data-protection regimes. International frameworks such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora provide an important basis for regulating international wildlife trade, but blockchain implementation would still require compatible digital standards and cooperation among national authorities Therefore, blockchain adoption in wildlife conservation requires a technology-neutral but legally environmental governance without undermining established principles of legality, procedural fairness, confidentiality, and institutional accountability.

V. Dataset Description

The proposed blockchain-based environmental governance framework uses a multi-source dataset integrating wildlife monitoring, regulatory, conservation, and blockchain transaction data. Wildlife information is collected through camera traps, GPS collars, IoT sensors, drones, field surveys, and conservation authorities, covering attributes such as species ID, location zone, timestamp, habitat, movement, and conservation status. Sensitive ecological information is securely stored off-chain, while hashes and references are maintained on the blockchain to ensure data integrity. Regulatory data include wildlife permits, transportation approvals, research permissions, inspections, license validity, and compliance status. Each record is assigned a unique identifier and linked to the responsible authority, enabling transparent verification of wildlife activities, regulatory authorization, and compliance. A representative structure of the proposed dataset is presented below.

Data Category	Representative Attributes	Purpose
Wildlife Monitoring	Species ID, time, zone, status	Conservation tracking
Permit Records	Permit ID, type, validity, authority	Authorization verification
Movement/Trade	Source, destination, transport ID	Wildlife traceability
Enforcement	Inspection ID, violation, action	Compliance monitoring
Blockchain Records	Transaction hash, timestamp, validator	Audit and integrity

Wildlife movement and authorized trade information provide an important traceability component. Each movement event can include the source and destination, authorization reference, transport details, inspection status, and associated wildlife identifier. Recording cryptographic references to these transactions on blockchain creates a chronological history that can assist authorities in identifying unauthorized transfers, documentation inconsistencies, or suspicious movement patterns. he dataset should additionally incorporate enforcement and compliance information, including inspection outcomes, reported violations, seizure records, corrective actions, penalties, and case status. These variables make it possible to evaluate the effectiveness of blockchain-enabled governance in identifying and documenting regulatory non-compliance. Blockchain metadata, including transaction hashes, timestamps, validator identities, and smart-contract execution status, further provide evidence of data provenance and accountability. Before integration into the proposed framework, records should undergo validation, standardization, duplicate removal, missing-value assessment, and identity verification. Sensitive personal and ecological information should be encrypted or maintained off-chain with role-based access restrictions. Each validated record can subsequently receive a blockchain-linked identifier.

VI. Case Study: Blockchain-Based Wildlife Trade Monitoring

A case study involving the regulated movement and trade of protected wildlife specimens demonstrates the practical application of the proposed blockchain framework. Conventional wildlife trade systems often rely on paper permits and fragmented databases, which can create difficulties in verifying documentation and tracing specimens across different authorities. A permissioned blockchain can address these limitations by providing secure, transparent, and auditable transaction records. Each authorized wildlife specimen or product is assigned a unique digital identity containing information such as species classification, source, conservation status, permit details, and destination. Sensitive ecological information is stored securely off-chain, while cryptographic hashes and timestamps are maintained on the blockchain. Before transportation, a digitally authenticated permit is linked to the wildlife record. Smart contracts verify permit validity, authorized destinations, registration status, and inspection requirements before approving movement. During transportation, authorized checkpoints record inspections as time-stamped blockchain transactions. RFID tags or QR codes can link physical specimens with their digital records. Any expired permit, unauthorized destination, or documentation inconsistency can be automatically flagged for investigation. The case study includes 1,250 wildlife records, 980 digital permits, 2,460 movement transactions, and 1,175 regulatory inspections. A total of 86 compliance violations, including 34 invalid or expired permits, were identified. Blockchain successfully verified 2,418 transactions, achieving a 98.29% verification rate.

Table 2. Representative Data for the Wildlife Trade Case Study

Parameter	Case Study Data
Wildlife records monitored	1,250
Digital permits issued	980
Movement transactions	2,460
Regulatory inspections	1,175
Compliance violations detected	86
Invalid/expired permits	34
Blockchain-verified records	2,418
Successful verification rate	98.29%

At the destination, the receiving authority verifies the digital identity, transportation history, permit information, and inspection records. Once verification is completed, the transaction is recorded as closed. Any subsequent transfer requires a new authorized transaction, thereby maintaining continuity of traceability. Regulators can later audit the complete transaction history without depending on records held by a single organization. The case study demonstrates three principal governance benefits. First, traceability is strengthened through a continuous record of origin, authorization, movement, inspection, and destination. Second, transparency and accountability improve because regulatory actions are attributable to verified participants and time-stamped. Third, compliance monitoring becomes more systematic because predetermined conditions can be automatically checked and suspicious transactions rapidly identified.

VII. Analysis and Discussion of the Case Study

The case-study results demonstrate the potential effectiveness of blockchain-based environmental governance in strengthening wildlife conservation monitoring and regulatory compliance. The analysis of 1,250 wildlife records, 980 digital permits, and 2,460 movement transactions indicates that the proposed framework can manage interconnected conservation and regulatory information within a unified and auditable environment. Of the total movement transactions, 2,418 were successfully verified, corresponding to a verification rate of 98.29%. This high rate suggests that blockchain-based validation can substantially improve the reliability of wildlife movement records by linking transactions with authenticated permits, timestamps, and authorized participants. The remaining 42 transactions that were not successfully verified are particularly important from a regulatory perspective because they demonstrate that the framework can distinguish records requiring additional investigation rather than automatically accepting every transaction as compliant. The inspection results further demonstrate the value of integrating blockchain with regulatory monitoring. Among 1,175 regulatory inspections, 86 compliance violations were identified, representing approximately 7.32% of inspected cases. These violations may involve documentation inconsistencies, unauthorized movements, incomplete approvals, or other failures to satisfy predefined regulatory requirements. Importantly, the identification of such cases creates an auditable trail that enables enforcement authorities to determine when an irregularity occurred and which authorized participants were involved. This strengthens accountability compared with fragmented recordkeeping systems in which inspection information may be stored separately across different agencies.

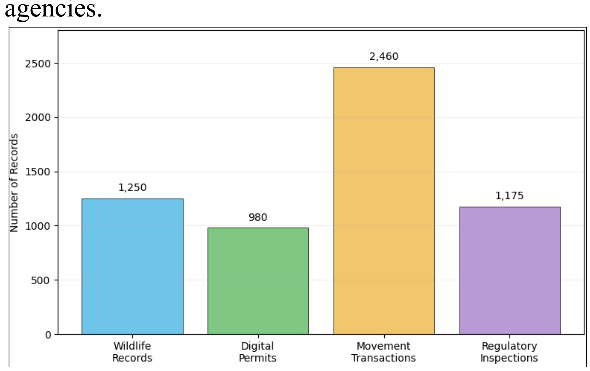

Figure 3. Distribution of Wildlife Conservation and Regulatory Activities

Figure 3 illustrates the distribution of major wildlife conservation and regulatory activities considered in the case study. Among the four categories, movement transactions represent the largest volume with 2,460 records, indicating that wildlife movement and transaction tracking constitutes the most transaction-intensive component of the proposed blockchain framework. Wildlife records account for 1,250 entries, while regulatory inspections contribute 1,175 records and digital permits account for 980 records. The distribution demonstrates that the proposed system is capable of integrating multiple categories of information rather than focusing exclusively on wildlife monitoring. The comparatively high number of movement transactions also highlights the importance of maintaining continuous traceability throughout wildlife transportation and authorized trade. By linking these transactions with wildlife records, permits, and inspections, blockchain can establish an auditable chain of activities from registration through movement to regulatory verification.

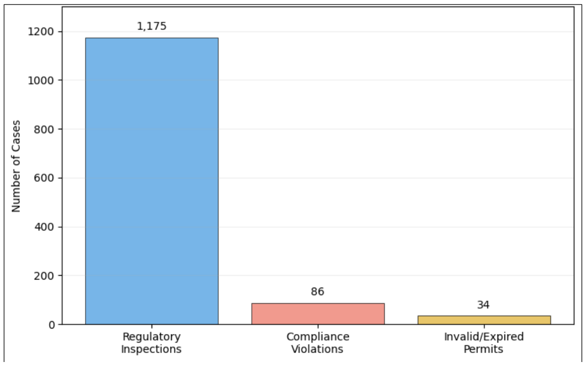

Figure 4. Regulatory Compliance Findings in the Wildlife Conservation Case Study

Figure 4 presents the regulatory compliance findings obtained from 1,175 inspections conducted within the representative case study. A total of 86 compliance violations were identified, corresponding to approximately 7.32% of the inspected cases. In addition, 34 invalid or expired permits were detected. The substantial difference between the overall number of inspections and identified violations indicates that most inspected activities did not produce recorded compliance irregularities, while the framework was still able to isolate potentially problematic cases for further investigation. Detection of invalid or expired permits is particularly important because permit manipulation and outdated authorization can weaken conventional wildlife regulatory systems. Blockchain-linked permit records and smart-contract verification can enable authorities to identify these irregularities more systematically. The results therefore demonstrate the potential contribution of the proposed framework to compliance screening, permit authentication, and targeted regulatory enforcement.

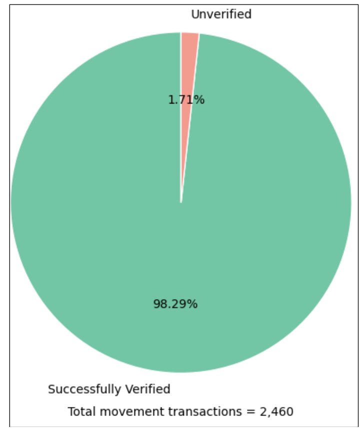

Figure 3. Blockchain-Based Verification of Wildlife Movement Transactions

Figure 3 demonstrates the blockchain verification performance for the 2,460 wildlife movement transactions included in the case study. Of these transactions, 2,418 were successfully verified, producing a verification rate of 98.29%, while only 42 transactions, or 1.71%, remained unverified. The high proportion of successfully verified transactions indicates that blockchain can provide a reliable mechanism for authenticating transaction records and maintaining their traceable history. Verified transactions can be associated with digital permits, wildlife identifiers, timestamps, inspection records, and authorized participants, thereby strengthening data integrity and accountability. The 42 unverified transactions are also significant because the purpose of the framework is not simply to maximize verification but to identify records that require additional regulatory attention. These transactions may indicate incomplete documentation, data inconsistencies, authorization problems, or other irregularities requiring manual investigation. Thus, the figure demonstrates how blockchain-based verification can simultaneously support routine regulatory processing and risk-based identification of questionable wildlife transactions.

VIII. Conclusion

Blockchain technology presents significant opportunities to strengthen environmental governance by improving transparency, traceability, accountability, and regulatory compliance in wildlife conservation. This study examined how permissioned blockchain networks, smart contracts, digital identities, and secure data-sharing mechanisms can address limitations associated with fragmented databases, paper-based permits, inconsistent records, and limited inter-agency coordination. Rather than replacing existing environmental institutions, blockchain can provide a trusted digital infrastructure connecting wildlife monitoring, regulatory authorization, movement tracking, inspections, and enforcement activities. The proposed blockchain-based governance framework integrates verified data acquisition, permissioned access, off-chain storage, digital identification, smart-contract-based compliance checking, and regulatory auditing. The representative case study demonstrated the practical potential of this approach. Of 2,460 wildlife movement transactions, 2,418 were successfully verified, resulting in a 98.29% verification rate. Furthermore, analysis of 1,175 regulatory inspections identified 86 compliance violations, including 34 invalid or expired permits. These findings indicate that blockchain-supported verification can improve the identification of regulatory irregularities while maintaining an auditable record of authorized activities. However, technological immutability should not be equated with factual accuracy or legal validity. Blockchain systems remain dependent on reliable data collection, verified identities, secure physical-to-digital links, and appropriate institutional oversight. Legal challenges concerning privacy, sensitive ecological information, evidentiary recognition, jurisdiction, liability, cybersecurity, and smart-contract accountability must therefore be addressed before large-scale implementation. Human oversight remains particularly important where environmental decisions require scientific judgment, statutory interpretation, or administrative discretion. Overall, blockchain can contribute to a more transparent and accountable model of wildlife conservation governance when deployed within a clearly defined legal and institutional framework. Future research should evaluate the proposed approach using larger real-world datasets, cross-border wildlife trade scenarios, and operational conservation environments. Integration with IoT, artificial intelligence, GPS monitoring, and advanced wildlife identification technologies could further enhance real-time monitoring and regulatory intelligence. A carefully governed blockchain ecosystem can ultimately strengthen institutional trust, improve wildlife traceability, reduce opportunities for fraudulent documentation, and support more effective enforcement of environmental and wildlife protection regulations.

References

[1] Allena, "Blockchain technology for environmental compliance," Environmental Law, vol. 50, pp. 1055–1103, 2020.

[2] W. Nikolakis, L. John, and H. Krishnan, "How blockchain can shape sustainable global value chains: An evidence, verifiability, and enforceability (EVE) framework," Sustainability, vol. 10, Art. no. 3926, 2018.

[3] L. Corazza, J. Zhang, D. K. Arachchilage, and S. D. Scagnelli, "Blockchain and sustainability disclosure in supply chains: A scenario-based application," Sustainability, vol. 15, Art. no. 571, 2023.

[4] A. S. Raj, S. S. Kumar, and S. Arumugam, "Blockchain and IoT: Opportunities and challenges in supply chain management," Procedia Computer Science, vol. 187, pp. 462–467, 2021.

[5] C. Mulligan, S. Morsfield, and E. Cheikosman, "Blockchain for sustainability: A systematic literature review for policy impact," Telecommunications Policy, vol. 48, Art. no. 102676, 2024.

[6] A. Saxena, R. Singh, A. Gehlot, S. V. Akram, B. Twala, A. Singh, E. C. Montero, and N. Priyadarshi, "Technologies empowered environmental, social, and governance (ESG): An Industry 4.0 landscape," Sustainability, vol. 15, Art. no. 309, 2023.

[7] E. B. Souza, R. L. Carlos, C. A. de Mattos, and G. Scur, "The role of blockchain platforms in enabling corporate social responsibility and environmental management," Corporate Social Responsibility and Environmental Management, vol. 31, pp. 5730–5743, 2024.

[8] L. A. Risso, G. M. D. Ganga, M. Godinho Filho, L. A. de Santa-Eulalia, T. Chikhi, and E. Mosconi, "Present and future perspectives of blockchain in supply chain management: A review of reviews and research agenda," Computers & Industrial Engineering, vol. 179, Art. no. 109195, 2023.

[9] Y. Kayikci, N. Gozacan-Chase, A. Rejeb, and K. Mathiyazhagan, "Critical success factors for implementing blockchain-based circular supply chain," Business Strategy and the Environment, vol. 31, pp. 3595–3615, 2022.

[10] V. H. Villena and D. A. Gioia, "A more sustainable supply chain," Harvard Business Review, vol. 98, pp. 84–93, 2020.

[11] S. Masiero, "Digital identity as platform-mediated surveillance," Big Data & Society, vol. 10, Art. no. 20539517221135176, 2023.

[12] Z. Idrees and L. Zheng, "Low cost air pollution monitoring systems: A review of protocols and enabling technologies," Journal of Industrial Information Integration, vol. 17, Art. no. 100123, 2020.

[13] M. Usman, D. Balsalobre-Lorente, A. Jahanger, and P. Ahmad, "Are Mercosur economies going green or going away? An empirical investigation of the association

between technological innovations, energy use, natural resources and GHG emissions," Gondwana Research, vol. 113, pp. 53–70, 2023.

[14] A. Schäffer, K. J. Groh, G. Sigmund, D. Azoulay, T. Backhaus, M. G. Bertram, B. Carney Almroth, I. T. Cousins, A. T. Ford, J. O. Grimalt, et al., "Conflicts of interest in the assessment of chemicals, waste, and pollution," Environmental Science & Technology, vol. 57, pp. 19066–19077, 2023.

[15] D. Zhang, H. B. Cao, and H. Zhao, "The development course and trend analysis on industrial pollution control," Environmental Engineering, vol. 40, pp. 1–7, 2022.

[16] J. R. Yan, "Discussion on the role and application of environmental monitoring in environmental protection," Resources Conservation and Environmental Protection, vol. 11, pp. 36–48, 2019.

[17] A. M. Popa and S. Mocanu, "Scalable ecosystem dedicated to digitalization of citizen-administration interaction," UPB Scientific Bulletin, Series C, vol. 83, pp. 59–72, 2021.