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Strategic integration of blockchain technology into (agro) forestry forensics and governance in western Balkan 6 region: stakeholders - technology - policy nexus analysis

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This study examines the feasibility and institutional capacity of integrating blockchain technologies (BT) into (agro)forest governance and forensic (FFG) traceability systems across the Western Balkans 6 region (WB6). Through a systematic desk-based analysis of 13 (agro)forestry case studies, regulatory frameworks, stakeholder ecosystems, and species-marker-blockchain interfaces, the research identifies the most suitable digital architectures and policy pathways for implementation. Results show that all WB6 countries possess basic legal and institutional capacity, particularly anti-money laundering (AML), countering the financing of terrorism (CFT) and digital-signature frameworks, to support permissioned blockchain pilots, though enforcement gaps and limited forensic laboratory capacities remain major constraints. Among evaluated technologies, Hyperledger Fabric and Private Ethereum (Proof of Authority) emerge as optimal for national traceability systems, while Corda and EBSI-linked Verifiable Credentials (VCs) provide interoperability and confidentiality for cross-border applications. The analysis highlights the potential of blockchain-anchored genetic and forensic data to enhance legality assurance, transparency and compliance with the EU Deforestation-Free Regulation (EUDR) and several Sustainable Development Goals (SDGs). A stepwise roadmap for the period from 2027 to 2031 outlines harmonized metadata structures, phased deployment of permissioned blockchain systems and coordinated regional governance measures designed to achieve reliable and interoperable traceability across the WB6. Findings demonstrate that a hybrid, permissioned blockchain ecosystem can substantially strengthen transparency, accountability and cross-border cooperation in WB6 FFG. A central bottleneck identified is the limited availability of courtroom-grade proof-of-origin in the WB6, driven by sparse genetic reference baselines and the lack of publicly documented national timber-forensic laboratory capacity, which constrains the evidentiary value of otherwise robust blockchain traceability systems.

KEYWORDS

digital sequence information, forestry forensics, illegal logging, policy alignment, sustainable development goal(s), traceability

1 Introduction–types of blockchain

Blockchain technology (BT) represents a fundamental evolution in the architecture of digital systems, enabling decentralized consensus and immutable record-keeping without the need for a central authority (Zheng et al., 2017). As a subset of distributed ledger technologies (DLTs), blockchain systems distribute data across a network of nodes, ensuring redundancy, transparency and resistance to tampering (Antal et al., 2021). Each block in a blockchain contains a series of verified transactions and is cryptographically linked to the previous block, forming a chain that is both temporally ordered and structurally resilient. The verification of new blocks is governed by consensus mechanisms such as Proof of Work (PoW) or Proof of Stake (PoS), which enforce collective agreement on the state of the ledger while preventing double-spending (fraudulent reuse of the same digital asset or token in more than one transaction, Bolt, 2017) and other forms of malicious manipulation (Düdder and Ross, 2017; He and Turner, 2022). These core principles make blockchain exceptionally well-suited for environments where trust, security and data transparency are paramount. Initially conceptualized as the backbone of Bitcoin, blockchain's practical utility has since expanded into sectors as diverse as finance, supply chain management, digital identity, healthcare and environmental monitoring (He and Turner, 2022).

The ability of blockchain to reconfigure institutional trust architectures is central to its broader appeal. By replacing centralized intermediaries with distributed consensus, blockchain shifts the epistemology of verification from organizational authority to algorithmic objectivity (Werbach, 2018). This is particularly relevant in domains where record manipulation, fragmented oversight and information asymmetries undermine compliance and transparency. Forestry governance exemplifies such a domain, where decentralized systems may bridge existing governance gaps (Werbach, 2018). In the WB6 context, the transition toward data-driven and verifiable governance is already supported by the uptake of geospatial sensing and data-driven technologies in agriculture and agroforestry. These approaches generate standardized, time-stamped and geo-referenced datasets, such as UAV- and satellite-based monitoring outputs and intervention records, which are inherently suitable for audit, verification and regulatory oversight and can be directly anchored to permissioned blockchain architectures to strengthen compliance and traceability (Trudić et al., 2025).

Blockchain technology is generally categorized into three main types based on the criterion of transparency: public, private and consortium blockchains (He and Turner, 2022). A public blockchain is fully open and decentralized, allowing anyone to join the network, verify transactions and access the data without restrictions. These networks provide transparency but offer limited privacy, as all activities are visible to participants, although users remain pseudo-anonymous (He and Turner, 2022). Well-known examples of public blockchains include Bitcoin and Ethereum. In contrast, a private blockchain is a closed network where access is limited to selected participants, typically managed by a single organization. This type of blockchain provides higher levels of control and privacy, making it suitable for internal business processes; examples include Hyperledger Fabric and Ripple (Tripathi et al., 2023). A consortium blockchain represents a hybrid model, where the network is governed by a group of predefined organizations rather than a single entity (He and Turner, 2022). It is also permissioned, but control is shared and it is often used across multiple institutions within an industry. This structure allows for partial decentralization and collaboration while maintaining restricted access (He and Turner, 2022). Smart contracts are self-executing software programs deployed on blockchain networks that automatically execute the terms of an agreement once predefined conditions are met (Swan, 2015; Kirli et al., 2022). These blockchain-based contracts eliminate the need for a central authority or intermediary, leveraging the technology's decentralized and tamper-resistant ledger to ensure transparent, trustless execution of agreements between parties (Chen et al., 2022; Taherdoost, 2023).

Hyperledger Fabric is a modular, permissioned blockchain platform built to support enterprise applications that need secure, transparent and scalable data management. Unlike public blockchains, it allows controlled access through membership-based participation. This makes it a good fit for industries that have strict data governance requirements (Androulaki et al., 2018). One of its main features is the separation of transaction execution, ordering and validation processes. This improves scalability and flexibility compared to traditional blockchain models (Androulaki et al., 2018). Current research indicates that Hyperledger Fabric supports smart contracts, known as "chaincode". Its architecture lets organizations implement customized consensus mechanisms and private channels for confidential transactions. This is especially beneficial for supply chains, finance and government systems (Pfeil et al., 2025). Lo et al. (2022) point out that blockchain systems like Hyperledger Fabric can support citizen-focused permit management by enabling secure storage and sharing of verifiable credentials. Their model integrates off-chain data storage with on-chain access control, utilizing InterPlanetary File System (IPFS) for secure data storage, thereby enhancing privacy and trust within a decentralized framework.

Ethereum smart contracts are self-executing programs on the Ethereum blockchain. They automatically enforce the terms of an agreement without intermediaries. These contracts become unchangeable once deployed, providing transparency and trust among users (Christidis and Devetsikiotis, 2016). However, they also present important security risks, including reentrancy attacks, gas limit vulnerabilities in which contract execution fails or becomes exploitable when computational demands exceed the transaction or block gas allowance and various denial of service weaknesses (Atzei et al., 2017; Wu et al., 2024). Studies on performance found that the computational and storage costs linked to running smart contracts can greatly impact transaction speed and miner incentives, especially for complex tasks (Kushwaha et al., 2022). By using Ethereum smart contracts, we can manage and trade tokenized permits transparently, without needing intermediaries. Shahab and Allam (2020) state that tokenizing tradable permits on Ethereum lowers administrative and transaction costs. It does this by automating enforcement, transfers and verification directly on the blockchain. This method builds trust, reduces fraud and enables real-time tracking of permit ownership and compliance.

The VechainThor blockchain is the foundation of the Vechain ecosystem (Izaguirre Díaz, 2024); it is built on the Ethereum platform and keeps a clear, public record of transactions through the Vechain Explorer. With a focus on business applications, the system prioritizes scalability and efficiency. Its design supports asynchronous transactions by using clauses and dependencies, enabling it to handle rising demand without losing performance (Izaguirre Díaz, 2024). A key feature of VechainThor is its dual-token economic model, which helps keep transaction fees stable even when the network is busy, ensuring predictable costs. The blockchain employs the Proof of Authority (PoA) consensus method, which provides a mix of high security, operational scalability and energy efficiency. This sets it apart from more energy-consuming consensus systems (Izaguirre Díaz, 2024). Since launching in 2018, the VechainThor blockchain has functioned smoothly, with no recorded downtime. Additionally, its design allows it to work with other blockchain platforms, improving its potential for integration and broader technological connections. Urtecho et al. (2024) stated that VeChainThor offers supply chain tracking by giving unique product codes to verify authenticity. This makes it very valuable for both agriculture and industry. Its ToolChain platform provides tailored solutions for various users, like tracking food safety and monitoring carbon footprints. Because of the blockchain's permanent ledger, data stays secure, transparent and easy to audit. This boosts trust between consumers and producers (Urtecho et al., 2024).

Cardano is a decentralized blockchain platform that focuses on network stability, scalability and resilience through continuous network monitoring and analysis (CardanoSpot, 2025). Key metrics such as block production rate, transaction throughput and node uptime are tracked to ensure efficient block creation, high transaction capacity and reliable node operation. This ongoing monitoring helps identify potential issues early, supports decentralization by preventing the dominance of any single entity and optimizes resource use to manage increasing demand (CardanoSpot, 2025). Cardano uses official tools like the Cardano Explorer and a strong community to provide transparent access to network data. This shows its commitment to openness and ongoing improvement as it develops into a global decentralized financial operating system (CardanoSpot, 2025).

Hyperledger Sawtooth is an open-source distributed ledger platform designed for enterprise applications, focusing on use cases such as supply-chain management rather than cryptocurrency-centric, permissionless public blockchains (Ampel et al., 2019). The transaction process starts when a client gathers transactions into a block, signs the batch and sends it to a validator. The validator then uses the appropriate transaction processors to check integrity before adding the block to the ledger (Ampel et al., 2019). A key feature of Sawtooth is its ability to execute transactions in parallel, which boosts system performance and scalability (Ampel et al., 2019). Additionally, Sawtooth has a modular design, allowing developers to pick consensus algorithms, define rules and create smart contracts in various programming languages. This flexibility makes it suitable for many enterprise-grade applications. The Proof of Elapsed Time (PoET) consensus mechanism was developed specifically for Hyperledger Sawtooth (Ampel et al., 2019). PoET is a trusted-execution-environment consensus mechanism in which each validator obtains a verifiably random wait time from a secure enclave and the validator whose timer expires first is allowed to create the next block, thereby ensuring fair leader election with minimal energy use (Ampel et al., 2019).

Hyperledger Besu is a blockchain platform focused on businesses (Alam et al., 2024). It works on both public and private permissioned networks. It is fully compatible with Ethereum protocols and supports consensus methods like PoW and PoA (Alam et al., 2024). It also integrates with the Ethereum Virtual Machine (EVM). This compatibility allows developers to write smart contracts and use common Ethereum token standards (Alam et al., 2024). By using these established standards, Hyperledger Besu offers a flexible and dependable framework for creating, issuing and managing digital assets with various functions in business applications (Alam et al., 2024).

1.1 BT in agriculture and nature-based solutions (NbS)

BT is rapidly transforming agriculture by enabling transparent and secure data management throughout the agricultural supply chain (ASC) (Kraft and Kellner, 2022). One of the key benefits of BT is its ability to ensure traceability in food production, which significantly enhances food safety and consumer trust (Xiong et al., 2020). This potential is particularly relevant for organic agriculture, where compliance with strict production standards, input restrictions and origin claims rely heavily on transparent and trustworthy certification systems. Tegeltija et al. (2022) proposed a blockchain-enabled framework for organic agriculture certification that secures field-level and sensor-generated data in an immutable ledger, thereby reducing certification fraud, improving traceability and strengthening consumer trust in organic products. BT provides a secure way of storing and managing data, facilitating the development of data-driven innovations for smart farming and index-based agricultural insurance (Tian, 2016; Kamilaris et al., 2019). This technology also has the potential to reduce transaction costs, improving farmers' access to markets and creating new revenue streams (Xiong et al., 2020). One of the earliest documented uses of blockchain in agriculture dates back to 2016, when it was applied to supply chain tracking, marking a significant shift toward digital transparency in agri-food systems (Tian, 2016). On the other side, a recent review by Mashanye et al. (2025) indicates that the roots of the NbS were first implemented in agricultural scientific contexts in the early 2000s with the goal of addressing various agricultural challenges (e.g., pest management, reducing runoff, etc.). Since then, its application in agriculture has expanded rapidly, particularly in enhancing traceability, improving food safety and integrating with technologies such as the Internet of Things (IoT) and smart contracts (Xiong et al., 2020). Recent analyses of the WB6 region demonstrate that such geospatial sensing and data-driven technologies are already widely applied across agricultural and agroforestry systems, providing an operational evidence base that can be further integrated with blockchain-based governance frameworks (Trudić et al., 2025).

Nature-based solutions (NbS) are diverse, ecosystem-centered approaches that range from protecting natural habitats to integrating green infrastructure in urban areas (Zarei and Shahab, 2025; Kapović Solomun et al., 2025). NbS can gain greater transparency, trust and efficiency when combined with blockchain by securely tracking ecological outcomes, verifying carbon credits and enabling data-driven participation in environmental governance (Zhao et al., 2022; Mulligan et al., 2024; Bhatt and Emdad, 2025). One emerging application is the use of blockchain for fundraising and investment in biodiversity and ecosystem restoration projects. For instance, in Australia, BioTokens have been developed as blockchain-based biodiversity credits that are tradeable on a digital marketplace, directing investment toward the conservation of natural habitats (Commonwealth Bank of Australia, 2019). Similar models include NFT-based (Non-Fungible Tokens, refer to unique, blockchain-based digital assets that certify ownership or provenance of a specific item or piece of data, Wang et al., 2021) initiatives such as Nemus and Fund the Planet, which tokenize specific geolocated rainforest areas in the Amazon. These NFTs represent real parcels of land and fund conservation efforts, while allowing contributors to monitor their impact through digital platforms (https://fundtheplanet.net/, https://nemus.earth/).

However, challenges remain, such as motivating all transacting parties, especially smallholder farms, to provide accurate data on the blockchain ledger, as the farming data is often scattered and owned individually (Xiong et al., 2020). Further research highlights the critical role of traceability as the main driver for BT adoption in ASC, followed by auditability, immutability and provenance (Kamble et al., 2020). These factors help design real-time data-driven agricultural supply chains that improve food safety and sustainability. The use of advanced methodologies such as Interpretive Structural Modeling (ISM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) assists in understanding complex relationships between these enablers, guiding effective implementation strategies (Kamble et al., 2020). In developing countries like India, BT adoption in ASC can address sustainability challenges by reducing intermediaries, lowering payment delays and shortening transaction times (Kamble et al., 2020). Integration of BT with IoT devices further enhances the smart agriculture ecosystem by automating data collection and reducing human error (Lin et al., 2018). IoT devices capture environmental and operational data automatically, which is recorded on the blockchain, ensuring a trusted, self-organized and open system involving all ecosystem participants, even if mutual trust is lacking (Lin et al., 2018). Additionally, smart contract scripts can automate warnings and assist authorities in timely problem resolution (Lin et al., 2018). In contrast, blockchain applications in forestry remain relatively recent and limited, with most developments emerging around 2022 and primarily focused on conceptual models for timber traceability and forest certification (He and Turner, 2022). This timeline clearly indicates that blockchain was introduced and operationalized in agriculture several years earlier than in forestry.

Blockchain is also being used to reform carbon credit markets by improving their transparency and accountability. Examples of such are Toucan protocol and Flowcarbon that tokenizes verified carbon credits into tradable digital assets like Etherium (https://toucan.earth/, https://www.flowcarbon.com/). Additionally, initiatives like KlimaDAO actively purchase and lock carbon credits in decentralized treasuries to reduce supply and increase market pressure for emission reductions (https://www.klimadao.finance/). Through voluntary carbon markets, BT can help bridge the funding gap for NbS. By improving transparency, accountability, interoperability and operational efficiency, blockchain offers a powerful tool to support financing for NbS (Döring, 2024).

1.2 Forensic forestry vs. forest governance: concepts, needs and technological innovation

Forest governance and forensic forestry are interrelated but distinct areas within the forest sector. Forest governance refers to the frameworks of rules, practices and institutions that determine how forest resources are managed, who benefits and how accountability is maintained (Agrawal et al., 2008). Good forest governance is characterized by principles like rule of law, transparency, stakeholder participation and accountability (FAO and PROFOR, 2011). For example, effective governance ensures clear legal rights to forest resources, robust enforcement against illegal activities and mechanisms for local involvement in management decisions. International frameworks, such as the Framework for Assessing and Monitoring Forest Governance (FAO and PROFOR, 2011), highlight three pillars: (1) policy, legal and institutional frameworks; (2) planning and decision-making processes; and (3) implementation, enforcement and compliance. Illegal logging and timber trafficking are major global issues, causing significant biodiversity loss, environmental degradation and economic harm. To combat these problems, the ability to accurately identify timber species and verify their geographic origin is essential for both law enforcement and sustainable forest management (Kleinschmit et al., 2016). Governments establish legal and policy instruments such as bans on unauthorized logging and harvest quotas that define permissible volumes, species and locations of extraction within a given period, to prevent overexploitation and promote sustainable management (FAO, 2022).

On the other hand, forensic forestry is a specialized field that applies forensic science and technical expertise to forest-related legal issues, often in the context of investigating crimes or resolving disputes (Latham, 2021; Grant and Chen, 2021). Forensic forestry includes the work of expert witnesses in court cases, such as testifying about timber theft, boundary issues or wildfire causes, as well as the use of scientific techniques to trace the origin of timber and detect illegal logging (Dormontt et al., 2015). Methods in forensic forestry are diverse, ranging from traditional approaches like visual identification and dendrochronology to modern analytical techniques. While traditional methods can be time-consuming and sometimes insufficient for precise species-level identification, modern approaches, especially those based on spectroscopy and molecular biology, are more rapid and accurate (Kannangara et al., 2020; Yadav et al., 2024).

At the international level, frameworks like the EU Timber Regulation (European Parliament and Council, 2010) and the Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan impose due-diligence obligations on timber importers and strengthen the traceability of legally sourced wood (Radosavljevic et al., 2023). Transparent record-keeping and prosecution mechanisms are essential to deter violations, while weak institutional capacity or corruption often enable undetected illegal logging (Dykstra et al., 2003; Baral and Vacik, 2018). Inclusive governance further depends on stakeholder participation, where community involvement enhances compliance and stewardship, as demonstrated by Nepal's community forestry programme (Baral and Vacik, 2018; Luintel et al., 2018). Transparency and anti-corruption measures, including traceable timber sales, trained enforcement personnel and financial auditing are critical given that illegal logging is frequently linked to organized crime and transnational trade networks (Greenberg et al., 2012). In this context, forensic forestry has become a technical extension of governance, strengthening verification and supply-chain transparency. Methods such as DNA barcoding, wood anatomy and stable isotope analysis provide scientific certainty regarding species and geographic origin, exposing mislabeled or fraudulent timber (Grant and Chen, 2021). Document authentication and digital forensics are increasingly relevant in regions with opaque supply chains, such as the WB6, where permit forgery and data manipulation remain common (Radosavljevic et al., 2023). BT introduces a paradigm shift in forest governance by addressing systemic weaknesses in record-keeping, verification and accountability. Through its immutability, blockchain ensures that once records, such as harvest permits, chain-of-custody certificates or DNA-based species identifications are uploaded, they cannot be altered without consensus, eliminating retrospective manipulation. Smart contracts can automate compliance verification by cross-checking harvest volumes against legal quotas or geographic boundaries, instantly flagging irregularities and enforcing sanctions (Stopfer et al., 2024). Consensus validation mechanisms distribute verification authority among multiple institutional nodes (e.g., forestry agencies, customs, laboratories), thereby reducing centralized control and corruption risks (Ibrahimy et al., 2024; Polcumpally et al., 2024). Digital identities assigned to forest actors, timber consignments and laboratory results ensure transparent provenance and traceability throughout the supply chain, linking biological verification with digital certification (Damaševičius and Maskeliūnas, 2025). Integrating blockchain with forensic forestry thus establishes a hybrid governance architecture where legal, biological and digital data interact seamlessly (Akbarfam et al., 2023; Damaševičius and Maskeliūnas, 2025). This fusion enhances trust among stakeholders, ensures algorithmic verification of legality and sustainability and enables real-time monitoring of timber flows from forest to market (Akbarfam et al., 2023; Damaševičius and Maskeliūnas, 2025). By embedding scientific traceability within an immutable digital ledger, blockchain has the potential to operationalize the core principles of good forest governance, transparency, accountability, participation and rule of law, thereby transforming enforcement efficiency and public trust in the forestry sector (Shibano et al., 2022; Stopfer et al., 2024).

In the WB6, forest governance institutions have been shaped by post-socialist transitions (World Bank, 2005). While countries like Albania, Bosnia and Herzegovina (BiH), Kosovo* (*references to Kosovo in this study are without prejudice to positions on status and are in accordance with United Nations Security Council Resolution 1,244 and the International Court of Justice Opinion on the Kosovo declaration of independence), Montenegro, North Macedonia and Serbia have restructured agencies to align with European norms and challenges, political interference and limited institutional capacity, persist (Regional Environmental Center for Central and Eastern Europe, 2010). For instance, Montenegro has struggled with a shortage of trained forestry professionals, affecting governance quality (UNECE, 2015). Decentralization has transferred some forest management responsibilities to local governments, but weak local capacity has sometimes led to increased illegal logging, as seen in Albania (Regional Environmental Center for Central and Eastern Europe, 2010; UNECE, 2015). Ongoing efforts to align WB6 institutions with EU requirements, such as EUTR (European Union Timber Regulation) due diligence systems are gradually improving governance, with Serbia, BiH and Montenegro identified as priority countries needing institutional strengthening to address illegal logging (Radosavljevic et al., 2023). International networks such as the Global Timber Tracking Network (GTTN) foster methodological standardization and data exchange across countries (Grant and Chen, 2021). Universities and training centers provide technical education, develop protocols and disseminate best practices (National Research Council, 2009). In the WB6 region, however, most capacity development depends on international partnerships, as local laboratories often lack the equipment and funding to perform advanced analyses. Samples are frequently sent abroad, slowing the development of regional self-reliance (Grant and Chen, 2021; USDA Forest Service, 2023). Blockchain-based credentialing and data-sharing platforms could support capacity building by ensuring secure access to verified analytical data, protocols and results for research and training purposes (Manoj et al., 2025). In the WB6 region, reforms are progressively incorporating advanced monitoring and verification tools (Radosavljevic et al., 2023). Embedding blockchain into these evolving frameworks could standardize digital chain-of-custody procedures, support smart contracts for automated compliance verification and reinforce judicial trust in digital evidence admissibility. Convergence of scientific verification and distributed ledger technology creates a resilient ecosystem where legality, authenticity and governance integrity become algorithmically secured, thereby reinforcing both national enforcement capacity and cross-border cooperation in combating illegal logging and timber trade (Batista et al., 2023; Liu and Zheng, 2024; Damaševičius and Maskeliūnas, 2025).

Although WB6 countries are reforming laws and aligning with EU regulations, implementation gaps remain due to limited resources, training and overlapping institutional responsibilities (Radosavljevic et al., 2023). There has been progress in regional cooperation, with joint efforts to share information, improve monitoring and involve civil society and media in exposing illegal practices (UNECE, 2015). However, advanced forensic methods for timber identification are rarely used due to financial and technical constraints. Most enforcement relies on traditional methods and the region lacks dedicated forensic labs or routine

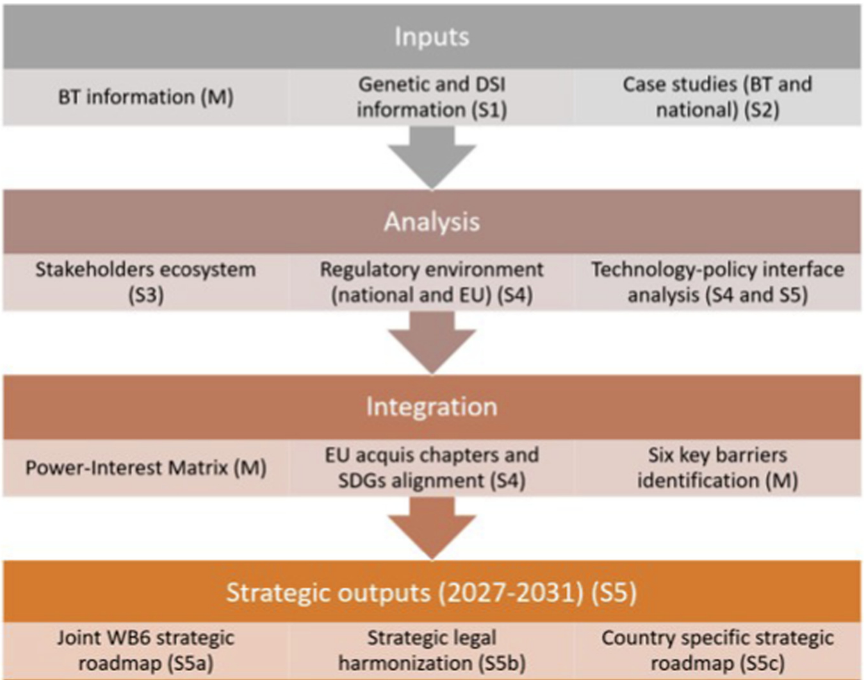

FIGURE 1
Structured methodological pipeline combining data inputs, multi-layered analysis and integrative assessments to derive strategic roadmaps for 2027–2031. M–can be found in the main manuscript.

DNA testing for timber (Grant and Chen, 2021). In the WB6, access to European markets is driving a practical link between governance and forensic forestry (Radosavljevic et al., 2023). Exporters aiming to sell wood to the EU are motivated to improve their supply chain transparency and even pre-test products to ensure legality, responding to EU regulations and the possibility of forensic checks. This market-driven pressure leads companies to voluntarily adopt better practices and forensic verification (Kim et al., 2024). When either component is weak, law enforcement loses transparency, consistency and deterrent power, allowing illegal activities to persist. Integrating BT can mitigate these weaknesses by creating immutable evidence trails, enabling automated compliance verification through smart contracts and providing real-time transparency across institutions, which collectively strengthens the integrity, consistency and responsiveness of forest law enforcement systems (He and Turner, 2022). As WB6 countries modernize their forest governance, adopting innovative approaches, including forensic science, will be vital for closing enforcement gaps and preventing the WB6 from becoming a conduit for illegal timber into EU supply chains (Radosavljevic et al., 2023).

2 Methodological framework

This study was conceived as a structured, multi-layered desk review that connects biological traceability potential (species and markers), real-use governance situations in the WB6 and the current digital/regulatory perimeter for blockchain and other distributed-ledger solutions (Figure 1). In contrast to generic technology reviews, the methodological logic here proceeds from what the region already has (genetic baselines, pilotable protected areas, identifiable stakeholders, existing digital-asset laws) towards what it can plausibly integrate (permissioned blockchain for FFG, cross-border verification, smart-contract–based compliance), using the five supplementary tables in main Supplementary Materials S1–S5 as operational inputs rather than illustrative annexes. The framework therefore aggregates:

1. Evidence on forest genetic resources (FGR) and marker systems for forensic forestry (Supplementary Table S1);
2. A purposive set of 13 forestry/agroforestry cases that display a governance or transparency need (Supplementary Table S2);
3. A consolidated stakeholder landscape for all six countries (Supplementary Table S3);
4. A jurisdiction-by-jurisdiction view of regulatory and supervisory readiness for digital assets, AML/CFT and trust services (Supplementary Table S4);
5. A 5-year strategic roadmap with joint, transboundary and country steps and risks and legal harmonization needs (2027–2031) (Supplementary Tables 5a–5c).

Together these layers enable an internally coherent assessment of feasibility, timing and institutional anchoring of blockchain in WB6 FFG.

2.1 Research design and desk-based approach

The research applies a qualitative, desk-based design relying exclusively on secondary sources to examine the feasibility and strategic conditions for integrating blockchain into FFG in Albania, Bosnia and Herzegovina, Kosovo*, Montenegro, North Macedonia and Serbia. A comprehensive integrative review was conducted for the period 2002–2025 to capture: (i) the emergence of blockchain/DLT in natural-resource governance across the Europe and globally; (ii) gaps, challenges and infrastructure potential for various BT integration in WB6 on national level vs. case studies; and (iii) the relatively maturing WB6 regulatory context for digital assets and trust services. Sources comprised peer-reviewed articles, FAO, UNECE and EU institutional reports, national laws and by-laws, white papers and grey but citable literature, accessed through Kobson, Google Scholar, Scopus, official government portals and verified open-access repositories to ensure traceability. Inclusion was limited to sources with direct relevance to forestry or agroforestry governance and blockchain-enabled traceability, while non-sectoral, duplicative or purely speculative materials were excluded. To reduce interpretive ambiguity on contested governance issues, a light critical appraisal was embedded by distinguishing the evidentiary nature of cited sources: binding legal and regulatory instruments were treated as normative baselines, peer-reviewed empirical studies as factual support and interpretive or grey literature as contextual input, with its non-binding character explicitly recognized. A total of 321 resources (references and webpages) were reviewed and analyzed: 149 peer-reviewed journal articles (original and review articles, with or without DOIs), 28 laws and by-laws (national and supranational, including EU legal instruments and related official acts), 32 international policy/agency documents (OECD and UN-system and affiliated bodies, including FAO, CBD and UNECE, as well as comparable international organizations), 112 other sources (reports, grey literature, theses, webpages and other non-indexed materials). A predefined keyword matrix guided the search, combining technological, governance and compliance terms: "timber traceability", "illegal logging", "blockchain forestry", "digital environmental governance", "forest genetic resources", "trust services/eIDAS" and "smart contracts for permits". Inclusion criteria prioritized documents that: (i) addressed forest management, environmental enforcement or digital transformation in at least one WB6 country or in EU accession contexts; (ii) referred to EU acquis chapters 9, 11, 12, 23, 24 and 27 to SDG targets 2, 8, 9, 11, 12, 13, 15 and 16; and (iii) contained either technical specifications relevant to permissioned blockchain (e.g., Hyperledger Fabric, Corda, Ethereum PoA/Besu, Sawtooth) or policy instruments relevant to those technologies.

To contextualize applicability, 13 forestry and agroforestry case studies were selected (Supplementary Table S2). Selection was purposive, not statistical: sites and value chains were taken where (a) ecosystem or production importance is high; (b) governance or transparency problems are documented or plausible (permits, concessions, non-wood forest products, community use); and (c) alignment with EU and multilateral obligations exists or is being built. These cases provided the empirical substrate for testing which blockchain patterns, tokenized permits, traceability ledgers, community monitoring, carbon/service tokenization fit which WB6 governance realities.

In parallel, a structured stakeholder mapping was carried out (Supplementary Table S3). Stakeholder examples were compiled from public websites, annual reports, project pages, national forestry and environment authorities, research and university sites and well-known environmental civil society organizations (CSOs) in the region. To preserve transparency and replicability, the mapping was kept at the level of stakeholder types rather than volatile company lists. Stakeholders were then positioned in a descriptive Power–Interest Matrix (PIM) according to (i) formal mandate or market leverage (ministries, inspectorates, state forest enterprises, customs, research institutes, certification/audit bodies, tech providers); and (ii) demonstrable or expected interest in digitalization and traceability. This allowed us to anticipate which actors can host validator nodes, which must be consulted for data-sharing and where resistance, capture or low capacity may slow blockchain uptake.

To strengthen methodological transparency and operational validity, the Power–Interest Matrix was derived from a structured, criteria-based scoring rubric grounded in governance and information-systems literature. Stakeholder positioning was determined using four analytically distinct variables: (i) legal authority, defined as the formal statutory mandate to issue, enforce, or adjudicate decisions relevant to forest governance; (ii) institutional and technical capacity, capturing organizational stability, digital readiness and ability to operate or supervise secure information systems; (iii) incentive alignment, reflecting the degree to which transparent, tamper-evident records support or constrain the stakeholder's organizational objectives; and (iv) governance risk exposure, representing vulnerability to political capture, conflicts of interest, or rent-seeking behavior. Each variable was scored on a standardized ordinal scale and aggregated without weighting to minimize subjective bias and preserve interpretability. For example, a national forestry authority typically exhibits high legal authority and moderate-to-high operational capacity, but variable incentive alignment, placing it in the high-power/high-interest quadrant and identifying it as a candidate validator-node host under a permissioned consortium. Validator-node governance is assumed to follow clearly defined rules, including admission based on statutory competence and technical certification, periodic audits and cross-validation rights among core public actors, conditional suspension or removal in cases of non-compliance and dispute resolution anchored in existing administrative or judicial procedures. This explicit linkage between stakeholder scoring, node-hosting roles and governance rules operationalizes the matrix and connects stakeholder analysis directly to a feasible consortium-based blockchain architecture.

A separate but connected technology-policy alignment analysis was run on the same corpus (2002–2025). It cross-referenced the technical requirements of blockchain-based forestry traceability (immutability, time-stamping, off-chain storage, digital identities, smart-contract execution) with EU and accession-relevant frameworks: the EU Deforestation Regulation (Regulation (EU) 2023/1115) (European Parliament and Council, 2023a), the Digital Decade Policy Programme, eIDAS and national trust-service laws, AML/CFT regimes that now all cover virtual-asset service providers, and, where present, comprehensive digital-asset acts (as in Serbia and Albania). This was necessary because, in the WB6, blockchain feasibility is conditioned as much by supervisory and evidentiary grounds as by technology itself. The analysis was strengthened by integrating the information from Supplementary Table S4 (Regulatory readiness), which sets out for every

WB6 jurisdiction the headline statute, competent supervisor, VASP (virtual-asset service provider)/licensing situation and specific observations for cross-border, permissioned pilots; this made it possible to distinguish anchor jurisdictions (Serbia, Albania) from those where blockchain should initially remain non-public, non-token-issuing and AML-focused (BiH, Kosovo*, North Macedonia, Montenegro).

The strategic roadmap in the S5 containing Supplementary Tables S5a–c was developed through a structured process that combines evidence synthesis, governance analysis and forward looking digital and forensic planning for the WB6. A focused review of scientific literature, national legal frameworks, enforcement practice and European Union regulatory requirements, including the European Union Deforestation Regulation, was carried out to identify the main constraints affecting forest traceability, digital readiness and cross border information exchange. Identified challenges were grouped into thematic clusters and assessed with respect to urgency, feasibility, scalability and alignment with European Union expectations.

Supplementary Tables S5a–c present (Supplementary Material) the shared regional challenges with their sets of solutions, risks and mitigation measures, the country specific strategic pathways for the period from 2027 to 2031 and the main legal and procedural harmonization requirements at national, regional and EU levels. Throughout the process, attention was given to the scientific requirements of FFG including the need to expand genetic and forensic capability such as Single Nucleotide Polymorphism and haplotype profiling for FGR. This methodology provides a concise, transparent and evidence-based foundation for the strategic roadmap.

Limitations of the study are also acknowledged. No primary data (interviews, surveys, Delphi) were collected, so tacit institutional practices, informal enforcement arrangements and political-economy constraints could only be inferred from secondary sources. Some country-level legal acts, especially in entity-level contexts in Bosnia and Herzegovina or in Albanian and Montenegrin implementation by-laws, may not have been available in English or Serbian at the time of screening. Findings must therefore be read as an evidence-informed analytical frame that enables, but does not replace, subsequent participatory, ministerial or inter-agency dialogue on concrete implementation.

The study pursues four objectives, updated in line with the expanded supplements:

1. To evaluate political, institutional and regulatory capacities of WB6 countries to adopt blockchain-based FFG and to identify legal/policy gaps.
2. To map systematically all stakeholder groups relevant for blockchain in forestry, public, research, private/market, civil society and international and to assess their influence and interest for future node governance, data validation and citizen monitoring.
3. To formulate country-specific and transboundary strategic recommendations and a 5-year, risk-sensitive roadmap (drawing on Supplementary Tables 5a–5c) for deploying permissioned blockchain in forestry, aligned with actual regulatory readiness shown in Supplementary Table S4.
4. To initiate a structured, regionally adapted dialogue on using blockchain to increase transparency, legality assurance and accountability in forest and agroforestry supply chains, including those that will fall under EUDR.

The analysis is restricted to WB6 accession countries and deliberately excludes Croatia and Slovenia, whose fully harmonized EU digital and environmental frameworks would mask the transition problems this paper intends to illuminate.

The outcome of collected data analysis is, among other, a three-tier integration model:

- Biological tier: what can actually be traced and with what resolution (from Supplementary Table S1);
- Spatial/governance tier: where such tracing or digital permitting makes sense (from Supplementary Table S2);
- Institutional/compliance tier: who can run/approve it and under which law (from Supplementary Tables S3, S4), plus when and with what risk (from Supplementary Tables 5a–5c).

Using timber legality and provenance as an illustrative target, traceability relies on linked evidence objects including harvest permits, transport events, and, where risk warrants, laboratory wood anatomy or genetic reports (Supplementary Tables S1, S2). Integrity-critical metadata (permit ID, species code, management unit, timestamp, document hash) are recorded on-chain, while full documents and analytical datasets remain off-chain within competent institutional systems. Validation follows legal mandate: forestry authorities validate permits, transport and customs authorities validate movement events and accredited laboratories validate analytical reports, with inspectorates providing oversight (Supplementary Tables S3–S5). This example demonstrates how the tiered model connects traceable assets, meaningful control points and legally competent validators.

This tiered model is the direct methodological basis for the strategic recommendations and the country roadmaps in Chapter 6 and the supplementary roadmap file (Supplementary Tables 5a-5c).

An interactive web map was developed in R (R Core Team, 2024) to visualize stakeholders, species-marker-blockchain relationships and 7 forestry related case studies across the WB6. Data were extracted from a structured Word document using the docxtractr package (Rudis and Muir, 2020) and cleaned in R with the dplyr, tidyr, and stringr packages (Wickham et al., 2024). Missing hierarchical entries (e.g., country, stakeholder group) were filled downward using tidyverse functions. Geographic coordinates for WB6 countries and selected protected areas were manually compiled and merged with the dataset. Two thematic layers were generated: (1) country-level stakeholder groups and actor examples and (2) grouped species-marker-BT entries. A third layer visualized national park case studies enriched with associated blockchain technologies, SDGs and EU acquis chapters. All layers were displayed using the leaflet and htmlwidgets packages (Vaidyanathan et al., 2023; Cheng et al., 2025), with color-coded markers, pop-ups and an interactive layer control. The final map was exported as a standalone HTML file and placed in the strategic-related Chapter (6) of this study in order to support its outputs.

2.2 Use of AI tools: objective and ethical considerations

AI tools were employed only as assistive infrastructure to manage volume, ensure terminological consistency and strengthen citation traceability; they were not used to generate original scientific claims.

- ChatGPT 5 was used to expand and refine keyword strings (e.g., combining "EUDR" with "permissioned blockchain" and "timber legality assurance"), to cluster policy and technology documents into coherent thematic groups and to harmonize terminology across sections. All AI-assisted outputs were checked against the original sources and retained only when they matched verifiable content.
- QuillBot was used to paraphrase and smooth sentences drawn from multiple institutional documents so that the narrative remained stylistically uniform and in line with scientific English.
- Rayyan supported systematic screening, de-duplication and eligibility checks for over 300 documents, improving reproducibility of the literature selection.
- Perplexity was added as a retrieval-based layer to cross-check AI-suggested references against citable primary sources, thereby reducing the risk of non-existent or unverifiable citations.

All AI usage followed three safeguards: (i) human-in-the-loop validation for every AI-generated or AI-reworded segment; (ii) no verbatim insertion of AI content without source confirmation; and (iii) full separation between AI-assisted processing (acceptable) and inferential/analytical reasoning (reserved for the authors). This preserves methodological integrity while allowing the study to cover a broad, fast-moving regulatory and technological field.

3 Blockchain in forestry

He and Turner (2022) found that the blockchain-based technologies globally are mainly developed or proposed in three areas of forestry: traceability of forest-based products, forest management and forest fire detection. It is not surprising that most research has focused on the use of blockchain technologies for improving the traceability of forest-based products, given that trade in illegally harvested timber is estimated to be worth between USD 51 and 152 billion annually worldwide (Düdder and Ross, 2017). In addition to global concerns, there are also alarming figures at the national level. For example, in 2018, illegal logging in Russia accounted for up to 16% of the total wood harvested (Lobovikov et al., 2021). In Peru, approximately 60% of the timber harvested in 2018 was sourced illegally (Cueva-Sanchez et al., 2020).

Forest carbon offset initiatives mitigate climate change by decreasing emissions and preserving forests, with their credits traded on carbon markets that offer financial incentives and foster sustainable development (de Beaufort, 2023). A recent study by Merlo et al. (2025) indicates that BT possesses considerable potential to enhance transparency, trust and efficiency in carbon markets by tackling verification and governance difficulties through its decentralized, immutable and automated characteristics. However, the same study also identifies key challenges such as scalability, energy consumption, regulatory uncertainty and interoperability, emphasizing the need for hybrid blockchain frameworks and regulatory integration to fully leverage blockchain for sustainable carbon markets. Furthermore, BT can enhance local communities by enabling direct market involvement and protecting property and community rights; however, these advantages are contingent upon established infrastructure and defined land tenure, underscoring the social factors essential to blockchain's efficacy in forestry carbon markets (Kotsialou et al., 2021). While the integration of BT into forestry-based carbon offset systems offers promising opportunities, these technological advancements are constrained by complex political and institutional challenges in the WB6 region (de Beaufort, 2023). Issues such as unclear carbon and land ownership rights, the ambiguous legal status of tokens, fragmented regulatory frameworks and jurisdictional overlaps, limited institutional capacity, governance weaknesses, corruption risks, as well as concerns over market design, distributional fairness and geopolitical dynamics, all influence the extent and effectiveness of blockchain integration in WB6 (Peterson St-Laurent et al., 2017; FAO, 2022; Redvers et al., 2025; Merlo et al., 2025; Gorain et al., 2025). Addressing the political dimensions of forest carbon governance remains essential for achieving equitable and effective outcomes. Various blockchain-based carbon projects face unresolved issues such as oversupply and limited buyer interest, which may have a significant effect on stakeholder participation (Round and Visseren-Hamakers, 2022). Nevertheless, the use of BT in conjunction with government incentives improves the trustworthiness and openness of forestry carbon sink (FCS) trading (Song and Wu, 2023). This, in turn, encourages more market engagement and long-term sustainability. Further improvements should focus on enhancing blockchain's efficiency, establishing clear regulatory, policy and political frameworks, addressing key carbon offset quality issues including carbon leakage and strengthening stakeholder engagement and technical capacity (Vilkov and Tian, 2023).

3.1 Forestry governance and BT

Forestry sectors globally are often plagued by issues of illegal logging, opaque chain-of-custody systems and weak enforcement capacity. In this context, blockchain offers a promising digital infrastructure to track timber harvesting, monitor land tenure and verify compliance with national and international laws (Stopfer et al., 2024; Damaševičius and Maskeliūnas, 2025). By recording each step in the forest product supply chain, from tree felling to end-user delivery blockchain enhances traceability and facilitates legal verification processes (Düdder and Ross, 2017; Ponnoju, 2022). This functionality aligns directly with due diligence requirements under frameworks such as the EU Timber Regulation and emerging deforestation regulations (European Commission, 2016; European Commission, 2024a). Through smart contract-enabled registries, payments in climate finance mechanisms can be automated based on independent verification of ecological outcomes, such as forest cover or carbon sequestration, recorded via satellite data and IoT devices (Sun R. et al., 2021). These features also make blockchain particularly valuable in forensic forestry, where evidentiary integrity is critical to prosecuting environmental crimes (Sravani et al., 2025).

Beyond regulatory compliance, blockchain supports participatory governance by enabling local communities to digitally register forest rights, monitor land-use decisions or vote on development projects through verifiable digital identities and traceable transactions (Willrich et al., 2019; George, 2025). This can help institutionalize inclusive governance frameworks and reinforce legal pluralism in contexts where statutory and customary land tenure coexist (George, 2025). Combined with IoT-enabled "smart forests," real-time ecological data can be securely integrated into adaptive management systems, supporting dynamic policy interventions and ecosystem service tracking (Lobovikov et al., 2021; Stopfer et al., 2024). Düdder and Ross (2017) emphasize blockchain's potential to digitize and secure the chain of custody (COC) in timber trade, reducing reliance on tamper-prone paper systems and ensuring due diligence in line with the EU Timber Regulation (Düdder and Ross, 2017). Lobovikov et al. (2021) present blockchain as a "killer of illegal wood," describing its role in creating tamper-proof, decentralized ledgers that enable real-time verification of timber legality and origin, thus marking the onset of Industrial Revolution 4.0 in forestry. Damaševičius and Maskeliūnas (2025) created a new system called QuantumForest that uses ideas from quantum physics to make BT for smart forestry faster, safer and less energy-intensive. Damašsevičius et al. (2024) further explore the integration of blockchain within the Forest 4.0 paradigm, a digitally driven forestry framework that applies Industry 4.0 technologies such as the IoT, artificial intelligence (AI) and big data analytics to monitor forest ecosystems, enhance decision-making, and automate smart contracts for carbon credit management and biodiversity conservation. Ponnoju (2022) provides an empirical industry case study, identifying blockchain as a promising but still maturing technology for verifying forestry compliance in wood furniture supply chains, while stressing the importance of feasibility assessments to overcome challenges such as cost, standardization and data privacy. Stopfer et al. (2024) demonstrate that blockchain can mitigate illegal logging and increase certification credibility by securely linking each transaction in the wood supply chain via smart contracts and hashing protocols, which reduce fraud and promote sustainability. Sun R. et al. (2021) explore blockchain's influence on FCS projects, revealing that it lowers operational costs, enhances data transparency and balances incentives for emission-controlled enterprises (ECEs) and forest farmers, especially through decentralized pricing and smart contracts. He and Turner (2022) focus on digital environmental governance, identifying blockchain as a potential tool to replace inefficient bureaucratic structures with distributed trust systems, especially in natural resource management. Vilkov and Tian (2019) discuss regulatory and legal challenges for blockchain adoption in global environmental contexts, underlining the need for harmonized governance frameworks to integrate blockchain within forestry regulation. Lastly, Beltrami et al. (2021) emphasizes the integration of blockchain into broader digital tools to support sustainability transitions, calling for its responsible governance to address ecological crises, especially when combined with AI and IoT in forest ecosystems.

Policy alignment plays a critical enabling role in the institutionalization of blockchain in forestry. Recent EU initiatives such as the Digital Product Passport and the proposed Deforestation Regulation mandate end-to-end supply chain traceability, thereby creating regulatory incentives for the adoption of blockchain and allied technologies (European Commission, 2024b). These initiatives also support the integration of blockchain into broader sustainability strategies under the European Green Deal and Industry 4.0, positioning it not only as a compliance mechanism but also as a foundational layer of digital environmental governance (European Commission, 2025).

3.1.1 Forestry governance, BT and wood traceability

In forestry, traceability means the ability to track and document the journey of wood from its source as a tree to its arrival at industrial processing facilities. This includes gathering both technical data, like production stages and spatial data, such as transport routes, linked to a unique identifier assigned to the timber (Kaulen et al., 2023). To implement traceability in the forest value chain, it is important to create a digital link between the raw material and technology systems, like DLTs or IoT platforms. These systems hold detailed information about the material and the processes it goes through in the supply chain (Kaulen et al., 2023). Traceability frameworks not only improve transparency but also increase the market value of timber by allowing for the identification and verification of legally sourced products. Essentially, a traceability system enables tracking in both directions, forward and backward, through all stages of harvesting, processing and distribution. This strengthens governance and accountability in forest product supply chains (Figorilli et al., 2018; Kaulen et al., 2023). By strengthening the credibility of legal and certified timber in global markets, traceability helps maintain trust in forest certification programs and supports responsible trade practices (Appelhanz et al., 2016). Additionally, traceability improves decision-making by providing reliable and verifiable data about the origin and movement of timber. This information is essential for enforcing conservation policies and managing forests sustainably (Appelhanz et al., 2016; He and Turner, 2022).

To ensure full traceability from the standing tree to end users, it is important to establish a tamper-proof link throughout the supply chain. Traditional methods often failed due to difficulties in identifying wood assortments during transport and processing (Stopfer et al., 2024). Current identification technologies in forestry fall into two main categories: active and passive systems. Active systems involve attaching tags or devices to the wood that can be read visually or through radio signals. These usually require a database and a reading device (Stopfer et al., 2024). Passive systems rely on the wood's own characteristics or collected data, using tools like cameras, scanners or chemical sampling to identify and track the timber. Both systems aim to improve traceability and reduce the risk of illegal logging (Stopfer et al., 2024). In the WB6 countries, log tracking and marking are commonly done using plastic tags and hammer stamping with identification marks or symbols. During manipulation and multiple transport vehicle changes of logs from the forest to the final buyer, such tags can easily fall off, leading to a loss of information about the origin of the timber and other details. As illustrated in Figures 2a,b, conventional tagging and documentation practices along the timber supply chain remain

FIGURE 2
(a) Bar code labels on logs indicating ownership in Serbia. Picture taken by: Aleksandar Markovic, 4 November 2020, Goč, Serbia, Samsung Galaxy A51 integrated camera. **(b)** A container loaded with oak logs prepared for overseas export at the private company's yard in Serbia. Picture taken by: Aleksandar Markovic, 20 March 2020, Mionica, Serbia, Samsung Galaxy A51 integrated camera.

highly vulnerable to manipulation and loss of information. The photographs from Serbian log yards clearly show that physical tags and hammer marks can easily be detached, replaced or become illegible during handling and transport, resulting in weak traceability links between harvest origin and export records. These visual examples reinforce the argument that integrating digital identifiers anchored in blockchain ledgers would provide a tamper-proof, verifiable chain of custody for each log and batch of processed wood.

Traditional traceability methods often fail due to difficulties in identifying specific wood assortments within the logistics chain (Stopfer et al., 2024). Another major issue is the overall complexity of traceability. The first challenge is to determine the legal origin of the timber, which requires thorough due diligence. The situation becomes more complicated when multiple transactions are merged into one or when a single trade is split into several smaller ones. In many cases, the document trail is insufficient, mainly due to the complexity and high cost of verifying records. This issue is comparable to money laundering, where tracing the original source of transactions is extremely difficult (Düdder and Ross, 2017). In Germany, there is a complex supply chain with many participants from different countries (Gallersdörfer and Matthes, 2019). The system uses smart contracts on the Ethereum blockchain to create a transparent supply chain with verified wood sources. It not only tracks log production but also follows other steps in the processing chain. This makes it possible to clearly determine the total volume of wood moving through the supply chain (Gallersdörfer and Matthes, 2019).

A study from China, used AKAZE technology to solve some of the problems found in traditional methods like QR (Quick Response) codes and RFID (Radio-Frequency Identification) tags (Sun Y. et al., 2021). The Wood Traceability System (WTS) is used to store information about wood products in factories. QR codes and RFID tags are placed on the surface of the wood to identify each product. Customers can scan the label to get basic information, such as the wood species, without sending samples to a lab (Sun Y. et al., 2021). AKAZE technology can recognize the unique texture of each wood piece, which makes it a good alternative to traditional image-based identification methods in blockchain-based wood traceability systems (Sun Y. et al., 2021).

Described technologies could be applied in WB6 countries to support trade in logs, sawn timber packed on pallets and individual furniture items. During trade and transport, wood products often change vehicles multiple times before reaching the final customer (Elias, 2024). With these technologies, buyers can verify whether any changes or repackaging occurred between the time of ordering and delivery. For example, this system can be used to check if the same logs selected for purchase were actually loaded into a container (Dormontt et al., 2015). It can also be used to verify palletized timber elements during transport or even individual pieces of furniture, ensuring that the delivered goods match what was originally promised (Dormontt et al., 2015; Elias, 2024). Figures 3a–d further demonstrate the traceability gap at the stage of international shipment and product consolidation. The images from Belgrade's Nelt terminal depict the trans-shipment of palletized and semi-finished wood products without visible digital or physical identifiers, exemplifying how provenance data are typically lost once products leave domestic custody. Their inclusion highlights precisely where blockchain-based tracking, supported by smart-contract verification and satellite-linked transport records, could ensure that legality, species identity and origin remain verifiable throughout the entire export process.

Figorilli et al. (2018) developed a blockchain-based system for electronic traceability in the wood supply chain. Their system uses

10.3389/fbloc.2026.1776900

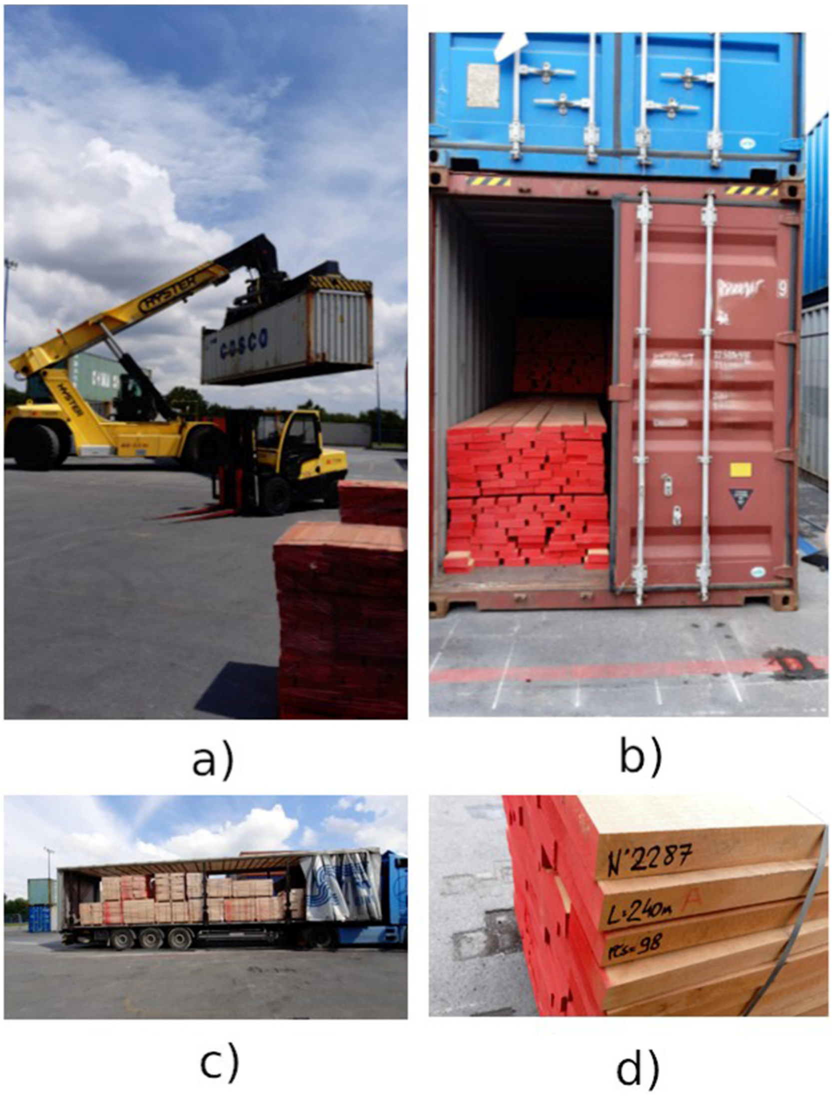

FIGURE 3
(a–d) Transshipment of pallets with semi-finished wood products, boards, from a truck into containers for overseas transport at the Nelt terminal in Belgrade. Photos taken by: Aleksandar Marković, 15 June 2020, Belgrade, Serbia, Samsung Galaxy A51 integrated camera.

RFID sensors and open-source technology. The full supply chain was simulated, from standing trees to the final product, passing through logging and sawmill processes. Various open-source IoT devices and tags were used and a custom app was created to support forest operations by collecting and storing key data (such as species, date, location and both dendrometric and commercial information) in a central database. Sheng and Wicha (2021) conducted a study on the use of BT in the teak supply chain in Thailand. They concluded that traceability systems, when combined with blockchain, could play an important role in the future by strengthening both the benefits and the legal verification of teak products. Komdeur and Ingenbleek (2021) from the Netherlands highlight the importance of proving the origin of wood products. They focus on how companies should make sure they buy wood from reliable and trusted sources. In the past two decades, the timber trade has increasingly emphasized certified legal timber to build buyer trust, especially in countries with reputational risks due to illegal logging (Komdeur and Ingenbleek, 2021). Technologies like blockchain can further strengthen trust, especially when combined with certification (Komdeur and Ingenbleek, 2021).

Research based on this approach could help reduce illegal logging and timber trade in the border areas of the WB6 countries. Such issues are common in regions near Kosovo*, where local forestry engineers often encounter sites of unauthorized tree cutting (Markus-Johansson et al., 2010).

Cueva-Sánchez et al. (2020) suggested using BT to help fight illegal logging in Peru by making transactions and records more transparent and secure. Their project aims to develop a cloud-based blockchain system that prevents both internal and external users from changing or tampering with records, including data on trees and certificates. The system includes both a web and a mobile application, which were used by national authorities and in forest-related operations (Cueva-Sánchez et al., 2020). In Sweden, a preliminary study has been done on using a blockchain-based traceability system to support legal compliance in the wood furniture supply chain. This study can serve as a starting point for future steps such as pilot projects, practical implementation and evaluating system performance (Ponnoju, 2022).

The Table 1 below presents case studies that have explored proposed applications of BT in forestry. Some of these studies also describe applications that are currently in experimental phases.

3.2 Blockchain-enabled data management, including digital sequence information (DSI) from woody plant species

The Figure 4 illustrates four main categories of data that can be stored in blockchain for forestry and genetic traceability:

- Qualitative data: descriptive information such as species identification, health assessments and legality verification used for monitoring biodiversity and compliance. Willrich et al. (2019) emphasized that a key initial step in implementing BT is the integration of forest inventory data into the blockchain database. National forest inventories represent a fundamental source of qualitative (and quantitative) data on forest conditions and dynamics, providing data on tree species, stand health, soil type, phytocoenoses and various other attributes (Chirici et al., 2012). Therefore, national forest inventories can support blockchain-based repositories, as shown by the AKAZE case study where a nonlinear diffusion filtering method captures wood texture and stores images for texture-based comparison across processing stages (Sun Y. et al., 2021).
- Quantitative data: measurable values including timber volumes, trade metrics and growth rates that support inventory management and supply-chain transparency. Tags in Figorilli et al. (2018) were linked to a database containing quantitative details such as standing tree marking date, GPS location, species, diameter at breast height (DBH) and qualitative classification. During the harvesting stage, a second RFID tag was attached to each log, recording additional data including cutting date, log length, mean diameter, wood quality categories and other relevant characteristics (Figorilli et al., 2018).
- Metadata: contextual records linking data to specific events or entities, including geolocation, timestamps, ownership history, permits and certification details, which provide traceability context. Munoz et al. (2021) introduced LogLog, a blockchain-based auditing system designed to support FSC (Forest Stewardship Council) certification compliance and ensure traceability of timber origin. Gallersdörfer and Matthes (2019) discussed the application of blockchain technologies and smart contracts for the digitization of transport information, enabling the tracking of container contents and ownership in land and maritime shipping. Cueva-Sánchez et al. (2020) discussed the use of data storage systems for tracking wood throughout the supply chain, including geolocation of trees and harvesting areas during the authorization stage. Additionally, their approach records images of each asset during different transformation phases, such as the standing tree, felled tree and sectioned logs. Mechik and von Hauff (2021) discussed a technology that facilitates the storage and monitoring of data across the entire timber supply chain, including harvesting licenses, compliance with authorized cutting volumes, transportation, export, storage, sales, fiscal payments, processing and delivery to the final consumer. Sheng and Wicha (2021) collected metadata including the owner's name, teak plantation identifier, teak profile, planting location and verification date.

All mentioned descriptors are fundamental for ensuring compliance with FAIR data principles, making data Findable, Accessible, Interoperable, and Reusable across research, policy frameworks and within used blockchain network. Properly curated metadata should also be aligned with international obligations under the Nagoya Protocol and the Commission on Genetic Resources for Food and Agriculture (CGRFA) discussions on digital benefit-sharing (CBD, 2011; FAO, 2023). Moreover, by embedding metadata into blockchain-based smart contracts, it becomes possible to secure immutable records of provenance, authorship and usage permissions, thereby strengthening transparency and trust in the management of DSI for woody plant species in the WB6 region.

Figure 5 illustrates an end-to-end traceability pipeline linking field samples to an immutable digital record. (1) Targeted plant material is collected from predefined tissues (e.g., leaves, cambium, seeds, etc.) under documented permits, with standardized metadata (species/taxon, geolocation, date, collector, voucher, chain-of-custody ID to ensure sample provenance). (2) DNA is isolated from the plant material using validated protocols; quality control metrics (e.g., A260/280, fragment integrity) and a laboratory accession/barcode are assigned, preserving the link to the original specimen and its metadata. (3) Targeted DSI, such as Single Nucleotide Polymorphism (SNP) panels, Simple Sequence Repeat (SSR) profiles, barcodes or chloroplast DNA (cpDNA) haplotypes, are generated and formatted (e.g., Fast Quality Format (FASTQ) and Variant Call Format (VCF) files, together with summary statistics), with cryptographic hash digests computed over raw and processed files to create tamper-evident fingerprints. (4) A blockchain-based repository records these hashes alongside core metadata, permissions and versioning through smart-contract logic; large files reside off-chain in secure storage, while on-chain entries provide an immutable audit trail, enforce access/benefit-sharing rules and guarantee end-to-end integrity and provenance, from targeted plant material, through isolated DNA and targeted DSI, to a permanently verifiable record suitable for certification, compliance and reproducible science.

- Digital Sequence Information (DSI) has emerged as a critical element in the evolving landscape of biodiversity management, forensic forestry and benefit-sharing systems. The term DSI, though still under debate for precise definition, generally refers to nucleotide sequence data (DNA and RNA), protein sequences and associated genomic, transcriptomic and metabolomic data (Hamilton et al., 2022). For the WB6 the integration of DSI derived from woody plant species into blockchain-based traceability and governance systems represents a timely and strategic opportunity to strengthen forest monitoring, combat illegal logging and enhance biodiversity value chains. The use of DSI in forensic forestry applications is increasingly gaining attraction globally due to its ability to provide species-level

TABLE 1 **Breakdown of blockchain based case studies in forestry, globally.**

Country	BT used	Purpose in forestry governance	Level of adoption	Source
Brazil	Ethereum, Hyperledger	Combat illegal logging, timber tracking and carbon credits	Pilot-level initiatives, especially focused in the Amazon region with NGO and tech collaborations	Corrêa Tavares et al. (2020) - forest credits; BVRio (2016) (BVRio's Responsible Timber Exchange trading platform)
China	Private blockchain systems	FCS projects for carbon trading and emission tracking	Advanced - actively implemented in national carbon sink policies and local pilot areas	Sun R. et al. (2021)
China-Gabon- DR Congo	Smart contracts and consensus algorithms (consortium blockchain)	Blockchain-based Timber Traceability System	Pilot-level initiatives for blockchain-based Timber Traceability System in International Trade of China with Gabon and DR Congo	Secretariat of the Global Green Supply Chains Initiative (2023)
Germany	Ethereum (public blockchain; smart contracts)	To ensure tamper-proof tracking of wood volumes and transparency in cross-border supply chains by recording transactions and volume data immutably on the blockchain	Pilot/Proof-of-Concept (PoC) – tested under controlled conditions with simulated datasets and prototype implementation; not yet at commercial or policy-level deployment	Gallersdörfer and Matthes (2019)
USA	Ethereum, Quorum	Timber legality assurance, data integrity in certification and supply chains	Moderate - state-led and industry-driven pilot projects	Arts et al. (2021)
Indonesia	Hyperledger Fabric	Transparency in timber certification (SVLK), reduction of illegal logging	Moderate to Advanced - embedded in legality verification systems	Susilawati and Kanowski (2022)
Ghana	Custom blockchain (pilot)	Digital wood tracking, forest permit verification	Pilot - supported by international development agencies	Bennet and van Hensbergen (2011)
Lithuania	Quantum Forest (custom)	Smart forestry and predictive ecosystem modeling	Experimental - academic-led prototypes in test environments	Damaševičius and Maskeliūnas (2024)
Thailand	Distributed ledger technology - Ethereum DApp	Smart Traceability System for Teak Supply Chain	Prototype Implementation	Sheng and Wicha (2021)
Italy	Distributed ledger technology in combination with Infotracing system is based on RFID	Electronic Open-Source Traceability of Wood	Prototype Implementation	Figorilli et al. (2018)
Peru	Hyperledger Fabric	Continuous registration of the forest activities and the authorization documents using a mobile application with data recording within blockchain	Experimental	Cueva-Sánchez et al. (2020)
Spain	No info	Traceability in the timber sector	Pilot	AKIS (2025) https://akisplataforma.es/en/node/100546
Spain	SaaS and online platform and QR-based digital passport	The digital platform based on BT for timber traceability control	Commercial - actively implemented	https://forest-chain.com/
Spain	Consensys Quorum and Smart Contacts	traceability to products derived from wood	Commercial - actively implemented	FORTRA Forest Traceability (by Agencia para la Modernización Tecnológica de Galicia https://alastria.io/en/fortra-forest-traceability-2/

(*Continued*)

 10.3389/fbloc.2026.1776900

TABLE 1 Continued

Country	BT used	Purpose in forestry governance	Level of adoption	Source
Europe-wide	Tokenization (blockchain-based technology platform and a crowdfunding mechanism)	Platform for tokenized investments in reforestation with satellite verification	Pilot	EKOFOLIO, 2019, https://cordis.europa.eu/project/id/876676/reporting
Worldwide/Forestry Stewardship Council (FSC)	FSC Trace	Supply chain integrity and traceability through BT	Beta version	https://fsc.org/en/fsctrace

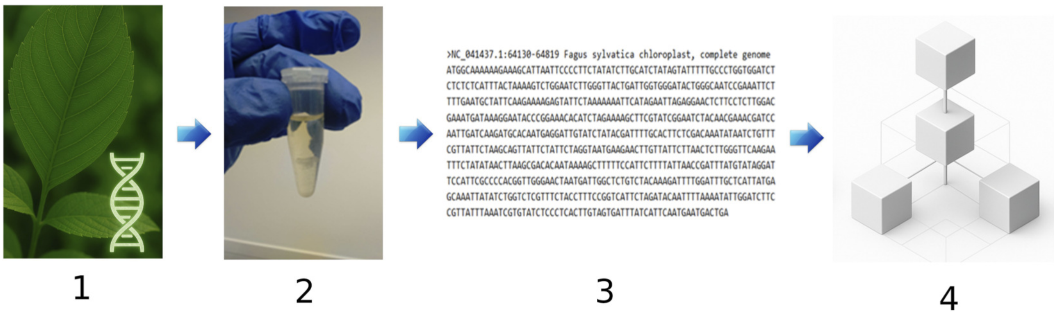

FIGURE 4
Blockchain-enabled workflow for forensic forestry: from plant material to secure DSI blockchain based storage. Numbers from 1-4 are explained in the text of the manuscript.

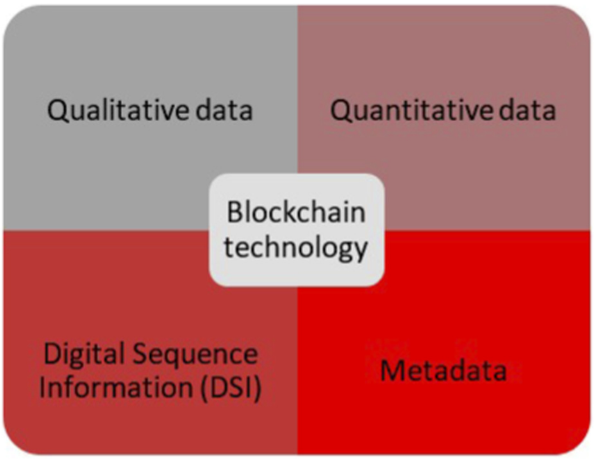

FIGURE 5
Data types stored in blockchain for forestry and genetic traceability.

identification, geographic origin assignment and genetic authentication of forest products (Heinemann et al., 2018). In the WB6 region, where forests such as those dominated by *Quercus robur*, *Fagus sylvatica*, *Picea abies* and *Pinus nigra*, represent both ecological and economic assets, DSI-based approaches can significantly improve the precision and legality of forest governance systems. However, while DSI is regularly submitted to public repositories such as the International Nucleotide Sequence Database Collaboration (INSDC), which includes GenBank, the European Nucleotide Archive (ENA) and the DNA Data Bank of Japan (DDBJ), traceability of data to country or source material remains limited. Only 16% of DSI entries are tagged with country-of-origin metadata and just 6% are explicitly linked to physical genetic resource repositories (CBD, 2020a). This highlights a crucial gap that the WB6 can address by ensuring that future submissions of woody plant sequences from the region include accurate metadata, thereby strengthening traceability foundations.

Integrating DSI into such blockchain-enabled systems could allow forest authorities in the WB6 to monitor the origin and movement of timber or reproductive materials in real time, authenticate the legality of exports and create enforceable links between genetic resources and digital permits (such as internationally recognized certificates of compliance under the Nagoya Protocol). These functionalities would be particularly valuable for WB6 countries given their increasing exposure to international biodiversity and wood markets, where demands for legal verification and traceability are growing (Radosavljević et al., 2021). Furthermore, the recent decision 15/9 under the Convention on Biological Diversity has established a multilateral framework for benefit-sharing from the use of DSI, calling for revenue-based contributions from commercial users and public-private partnerships to fund conservation efforts globally (CBD, 2024).

TABLE 2 Alignment of DSI groups with forensic forestry applications and blockchain governance opportunities in the WB6 region.

DSI group	Data type	Relevance in forensic forestry	Blockchain utility	Recommendation for WB6 forestry governance
Group 1	DNA, RNA sequences	High	Digital tagging, traceability	Mandatory tagging and open-source linking
Group 2	+ Protein sequences	High	Enhanced forensic resolution	Priority for enforcement agencies

The WB6 countries, as biodiversity-rich but economically transitioning nations, stand to benefit both as providers of DSI, especially from endemic and autochthonous forest species, and as recipients of support through global funds. By contributing high-quality, well-tagged sequence data and metadata from forest genetic resources into a blockchain-anchored system, these countries can strengthen their negotiating position within global access and benefit-sharing (ABS) mechanisms (Mhlanga, 2023; FAO, 2023).

From a technical standpoint, INSDC databases already provide Accession Numbers (ANs) and allow the inclusion of metadata fields like "/country" to enhance traceability (Rohden et al., 2020). However, these systems are primarily designed for open access and do not inherently support regulatory monitoring. A blockchain layer atop these open systems, anchored by hashed ANs and linked to metadata such as the IRCC (Internationally Recognized Certificate of Compliance), could close the traceability gap (CBD, 2020a). Such a system would enable WB6 countries to track not only who accesses their forest genetic data, but also for what purpose, when and under what contractual conditions. This is particularly important in combating unauthorized use of native genotypes in biotechnology, tree breeding or synthetic biology (Jacobs et al., 2023). Moreover, DSI has an emerging role in strengthening forest conservation planning in the WB6. Genomic data from trees can reveal patterns of genetic structure, gene flow and adaptive variation that are crucial for designing dynamic conservation units, particularly in light of climate change (Heinemann et al., 2018; CBD, 2020b). If incorporated into a blockchain system, such conservation units could be digitally registered, their genomic baselines archived and their monitoring outcomes transparently shared among stakeholders. In this way, blockchain and DSI can jointly operationalize the Kunming–Montreal Global Biodiversity Framework's Goal D and Target 19, which call for increased resource mobilization and transparent digital benefit-sharing (https://www.cbd.int/gbf/targets/19). Nonetheless, challenges persist. The operationalization of such systems in the WB6 will require policy harmonization across borders, technical training of forestry and customs personnel, institutional digital infrastructure and a legal framework that accommodates both open science principles and sovereign rights under the Nagoya Protocol. These challenges are surmountable with multilateral collaboration, especially given the strategic interest of the European Union and international donors in digital biodiversity governance in the region (Akpoviri et al., 2023; OECD, 2025a).

To guide implementation, the following Table 2 categorizes DSI types by their proximity to genetic resources, their applicability to forensic forestry and their alignment with blockchain functionality. DSI derived from woody plant species in the WB6 region represents not only a scientific asset but also a legal and economic resource. When paired with BT, DSI can enable a transformative approach to forest governance that is transparent, traceable and just. The region has both the biodiversity and the institutional momentum to lead in the piloting of blockchain-based ABS systems rooted in forest genetic data (Akpoviri et al., 2023; Kimura et al., 2023). As global CBD-led frameworks for benefit-sharing from the use of DSI are being operationalized (CBD, 2022) through a new multilateral mechanism and global fund, early engagement by the WB6 in linking DSI flows to transparent digital infrastructures (e.g., blockchain-based provenance and reporting) would allow the region to overcome existing ABS governance frictions, better safeguard native biodiversity assets and position itself in emerging bio-economy value chains (Ajates, 2023).

3.2.1 Potential integration of DSI from WB6 FGR into blockchain-enabled forensic forestry

WB6 harbors substantial standing genetic variation in dominant forest trees, yet research intensity and marker coverage are uneven across taxa and countries. The available genetic evidence for *Q. robur*, *F. sylvatica*, *P. abies*, *Picea omorika*, and Populus spp. is mapped together with evidentiary strengths for a permissioned blockchain architecture tailored to WB6 supply chains and institutional realities (see Supplementary Table S1 for the detailed species-marker-BT interface). Existing studies are concentrated in Serbia and Bosnia and Herzegovina, where nuclear and chloroplast markers for major taxa, *Q. robur*, *F. sylvatica*, *P. abies*, *P. omorika* and Populus spp., have generated critical baselines for genetic diversity, population structure and provenance testing (Ballian et al., 2010b; Ballian et al., 2012; Stojnić et al., 2019; Kesić et al., 2021). In *Q. robur*, nuclear Simple Sequence Repeats (nSSRs) reveal high within-population allelic richness and low among-population divergence in both Serbia and BiH (Ballian et al., 2010b; Trudić et al., 2021). Chloroplast Polymerase Chain Reaction - Restriction Fragment Length Polymorphism (PCR-RFLP) markers complement this picture: seven distinct maternal haplotypes span BiH and Serbia (reported as "Yugoslavia" in the original study), enabling lineage-level assignment of oak timber (Bordács et al., 2002). European beech (*F. sylvatica*) shows a similar partitioning of diversity. An isozyme survey from BiH attributed ~95% of total genetic variation to within-stand components and ~5% to among-stand structure (Ballian et al., 2012). For Norway spruce (*P. abies*), BiH nSSR data report expected heterozygosity of 0.61 (Han Pijesak)–0.68 (Kneževo) with Fst ≈ 0.026, indicating near-panmixia at the regional scale (Cvjetković et al., 2017). Serbia's EST-SSR natural population assessments corroborate similarly high diversity (Stojnić et al., 2019). Such homogeneity constrains fine-scale geo-assignment using nuclear loci but facilitates rapid species authentication and detection of non-local provenances. The endemic Serbian spruce (*P. omorika*) departs from this pattern. EST-SSR analyses across 14 Bosnian populations yielded He ≈ 0.45 and strong differentiation (Gst = 0.19), implying population-specific allele pools and high assignment power, critical for an IUCN-listed, conservation-sensitive taxon (Mataruga et al., 2020; Aleksić et al., 2022). In Populus spp., Serbian plantations have been genotyped with AFLP and SSRs, enabling robust clone discrimination and plantation monitoring (Orlović et al., 2009). To date, comparable datasets are not published for the remaining WB6 countries, underscoring a priority research gap.

Given these data asymmetries and the need to respect sensitive geolocations and commercial confidentiality-permissioned, modular blockchains are preferred so that governance mirrors institutional reality while preserving interoperability across WB6 supply chains (He and Turner, 2022). Hyperledger Fabric suits multi-stakeholder arrangements where forestry agencies, customs, inspectorates and industry operate on species-, region-, or workflow-specific channels (e.g., a "Serbian Spruce" channel), with membership services enforcing role-based access. Hyperledger Sawtooth, using a Proof-of-Elapsed-Time-style consensus, is appropriate for high-throughput, low-latency flows typical of plantation species (poplars; homogeneous spruce) (Corso, 2019). Corda excels when bilateral, privacy-preserving transactions dominate (e.g., fragmented cross-border oak and spruce trades). Where a small, trusted validator set is feasible, such as competent authorities across WB6 ministries and state/entity bodies in BiH, Ethereum-PoA/Besu enables smart-contract–based seed-lot certification and auditable permit workflows (He and Turner, 2022; Stopfer et al., 2024). BiH's complex administrative architecture (state level, Federation of BiH, Republika Srpska, cantons and Brčko District) necessitates validator distribution and channel partitioning aligned with legal competences. Population-sensitive datasets (e.g., *P. omorika*) should be confined to Fabric channels with granular permissions for conservation agencies and inspectorates, while cross-entity verification of consignments is enabled via shared read permissions or inter-channel proofs. This design accommodates fragmentation without sacrificing traceability integrity and reduces the risk of unlawful data exposure.

Coupling DNA forensics with blockchain directly supports compliance with the EU Timber Regulation (Regulation (EU) No 995/2010) and the EU Regulation on Deforestation-free Products (Regulation (EU) 2023/1115 (European Parliament and Council, 2023a), entering into application in 2025–2026) by furnishing immutable, science-based proof of origin (Radosavljevic et al., 2023; Regulation (EU) No 995/2010; Regulation (EU) 2023/1115) (European Parliament and Council, 2023a). Conservation outcomes improve because highly structured gene pools (e.g., *P. omorika*) become traceable to source populations, deterring illicit extraction (Aleksić and Geburek, 2010); commercial outcomes strengthen as Serbian poplar plantations demonstrate verifiable clone authenticity (Orlović et al., 2009). In oak supply chains, cpDNA-based maternal-lineage tracking deters laundering of Balkan oak into higher-value Central-European lots (Bordács et al., 2002; Ballian et al., 2010a; Ballian et al., 2010b). For fragmented, cross-border oak trade, Corda's notary service time-stamps provenance attestations while preserving counterparty privacy.

While Serbia and BiH provide substantial baselines (nuclear SSRs for Q. robur; isozymes for *F. sylvatica*; SSRs/EST-SSRs for *P. abies* and *P. omorika*; AFLP/SSRs for Populus spp.), comparable datasets are lacking for other WB6 countries (see Supplementary Table S1 for more information). Priority actions include harmonized nuclear and chloroplast marker panels for oaks and beeches across borders; expansion of *P. abies* reference sets to improve non-local provenance detection; and coordinated sampling of Populus clones used commercially. These steps will elevate assignment power where currently limited and enable uniform, cross-border smart-contract thresholds.

3.3 Integration of blockchain with other technologies in FFG: augmented reality (Ar), artificial intelligence (AI), machine learning, internet of things (IoT) and geospatial sensing and data driven technologies (GSDDT)

Recent work demonstrates that blockchain can function as a forensic integrity layer for data-driven decision systems, securing analytical outputs rather than generating them. In a Smart Agriculture 5.0 framework, reinforcement-learning-optimized predictions were immutably anchored to a blockchain ledger, ensuring verifiable timestamps, integrity and auditability of results at the moment of generation (Jagan Mohan et al., 2026). The system achieved a mean absolute error of 12.5% in multicropping loss estimation while enabling fully traceable, tamper-resistant records of predictive outputs and transactions.

Molinaro and Orzes (2022) examine the wood supply chain end-to-end, from forest management to finished products, and outline steps for its digital transformation via Industry 4.0. They identify blockchain, augmented reality (Ar) and robotic automation as key enablers of end-to-end data capture, sharing and analysis to support better decisions at every stage.

For Albania, Bosnia and Herzegovina and Kosovo*, there are currently no documented case studies or implemented blockchain-related projects in agriculture, forestry or nature-based solutions. However, it is worth mentioning that in September 2025, The GrowHub Limited signed a Memorandum of Understanding with the Government of the Republic of Srpska (an entity within Bosnia and Herzegovina) to establish innovative blockchain-based traceability approaches to support forestry conservation and reforestation within the framework of ESG (Environmental, Social, and Governance) initiatives (The GrowHub Limited, 2025). Nonetheless, no recorded case studies or concrete results from this application have been reported so far. In 2021, Montenegro recorded its first documented sale of a farm asset for cryptocurrency when a cow was purchased with bitcoin on the 'Seljak.me' peer-to-peer platform (European Bank for Reconstruction and Development, 2021). The transaction highlighted the emerging potential of digital payment methods in agriculture, although it did not involve broader blockchain applications beyond the use of cryptocurrency.

The integration of blockchain with AI-enabled GSDDT is beginning to reshape governance and financing models for long-lived, tree-based systems. Two recent Serbian initiatives, Treesury's hazelnut tokenization and The Walnut Fund's walnut-plantation tokens, illustrate both the promise and the growing pains of this convergence in a real regulatory setting. Treesury (Serbia) issued a regulated digital token to finance the establishment and management of modern hazelnut orchards. The offering is conducted under Serbia's Digital Assets Law (https://www.nbs.rs/en/ciljevi-i-funkcije/nadzor-nad-finansijskim-institucijama/digital-imo/) with a white paper approved by the Serbian Securities Commission (https://www.sec.gov.rs/index.php/en/). Substantively, Treasury's token is not economically tied to an individual tree; rather, returns are pooled across orchards financed by the raise (with detailed formulas for variable interest over a 40-year horizon). That design spreads idiosyncratic horticultural risks while keeping the on-chain instrument simple (https://hazelnut.treesury.com/rs/). The Walnut Fund is operated by The Walnut Enterprise DOO (Croatia) and develops walnut plantations in Serbia. In 2024 it launched a pilot Initial Token Offering tied to the Rekovac plantation, following approval of its white paper by the Serbian Securities Commission. The offering sold 1,854 of 4,400 tokens in the initial window (raising ~11.1 million RSD), with subsequent communications describing continued token availability (The Walnut Fund, 2024a). Public materials present the token as a blockchain-secured claim linked to plantation economics; the project also accepts cryptocurrency payments via its platform. While the firm emphasizes sustainable, mechanized orchard management, it provides less details than Treesury on concrete integration of remote sensing, drones or AI in day-to-day governance and investor reporting. In effect, the blockchain component is clear and regulated, whereas the geospatial/AI layer, though highly compatible with the model, is not yet fully elaborated in publicly available documentation (https://thewalnutfund.com/walnut-plantations-about-the-walnut-fund/). Although both examples are private agroforestry models rather than classical public-forest management, they sit at the forest–agriculture interface and are directly relevant to "tree governance" questions: long asset lifecycles, spatially explicit risks, ecosystem-service co-benefits and the need for transparent stewardship over decades. The Treesury model (Republic of Albania, 2008), in particular, demonstrates how regulated tokenization can be tied to geospatial/AI monitoring, insurance and codified decision rules to create a traceable, investor-facing governance framework (Treesury, 2024) The Walnut Fund's regulated token pilot suggests that standardized, supervised digital instruments can gain traction for tree assets in Serbia, with room to deepen the geospatial/AI layer in future iterations. Together, these cases indicate that the most credible models will be those that embed machine-verifiable sensing and analytics directly into on-chain reporting and rights, operate under securities-grade disclosure regimes and design for multi-decadal climate uncertainty through risk pooling, adaptive management and insurance (The Walnut Fund, 2024b).

4 Results

4.1 Comparative analysis of digital and crypto-asset frameworks across the WB6

This section reviews the primary legal bases for digital-asset and crypto-asset activities in the WB6 and their relevance for cross-border, permissioned blockchain initiatives in (agro)forestry (see Supplementary Material S4). The comparison focuses on four main aspects:

1. The existence and scope of a dedicated statute;
2. The supervisory architecture;
3. The licensing or registration status of VASPs;
4. Regulatory constraints affecting non-speculative, enterprise-grade' DLT deployments, such as issuance of credentials or tokens, custody of cryptographic keys and compliance of on-/off-ramp operations.

Across all WB6 jurisdictions, virtual-asset activities and VASP operations are governed under AML/CFT frameworks, which provide a workable compliance perimeter for permissioned, enterprise blockchain systems that do not rely on public tokens or mining. In practice, customer-due-diligence, record-keeping and transaction-monitoring duties apply under each country's AML law, for instance:

- Republic of Serbia. Law on the Prevention of Money Laundering and Terrorist Financing (Official Gazette of the Republic of Serbia, Nos. 113/2017, 91/2019, 153/2020);
- Republic of North Macedonia. Law on the Prevention of Money Laundering and Financing of Terrorism, as amended by the 2024 transfer-controls act (Official Gazette of the Republic of North Macedonia, Nos. 120/2018, 275/2024) (Republic of North Macedonia, 2024);
- Bosnia and Herzegovina. Law on the Prevention of Money Laundering and Financing of Terrorist Activities (Official Gazette of Bosnia and Herzegovina, No. 13/2024) (Bosnia and Herzegovina, 2024);
- Montenegro. Law on the Prevention of Money Laundering and Terrorist Financing (Official Gazette of Montenegro, Nos. 033/2023, 067/2025) (Montenegro, 2025);
- Republic of Kosovo*. Law No. 05/L-096 on the Prevention of Money Laundering and Combating Terrorist Financing (Official Gazette of the Republic of Kosovo, No. 13/2016);
- Republic of Albania. Law No. 9917/2008 on the Prevention of Money Laundering and Terrorist Financing, as amended and aligned with the EU acquis (Official Journal of the Republic of Albania) (Republic of Albania, 2008).

Parallel frameworks on trust services and electronic identification, modelled on the EU eIDAS Regulation (Regulation (EU) No 910/2014) (European Parliament and Council, 2014), exist in all six jurisdictions, enabling qualified electronic signatures, seals and trusted time stamps so that digitally signed forest permits, transport manifests and custody records can have evidentiary value across borders. The relevant statutes include:

- Law on Electronic Document, Electronic Identification and Trust Services in Electronic Business (Official Gazette of the Republic of Serbia, Nos. 94/2017, 52/2021) (Government of Serbia, 2017; Republic of Serbia, 2021);
- Law on Electronic Documents, Electronic Identification and Trust Services (Official Gazette of the Republic of North Macedonia, Nos. 101/2019, 275/2019) (Government of North Macedonia, 2021);

- Law No. 08/L-022 on Electronic Identification and Trust Services in Electronic Transactions (Official Gazette of the Republic of Kosovo*, No. 11/2021, entered into force 7 January 2022);
- Law on Electronic Identification and Electronic Signature (Official Gazette of Montenegro, Nos. 31/2017, 72/2019);
- Law on Electronic Signature (Official Gazette of Bosnia and Herzegovina, No. 91/2006) (Bosnia and Herzegovina, 2006);
- Law No. 107/2015 on Electronic Identification and Trusted Services (Official Journal of the Republic of Albania) (Albania, 2015).

Regional trade-facilitation mechanisms also support digital interoperability: the Additional Protocol No. 5 to the Central European Free Trade Agreement (CEFTA Secretariat, 2017) and the SEED/SEED+ customs data-exchange platforms (World Customs Organization, 2024; WCO/CEFTA, 2025) establish electronic cooperation channels that blockchain-anchored attestations and verifiable credentials can integrate with.

The depth of statutory coverage varies across WB6. Serbia and Albania have enacted comprehensive product-and-services laws regulating issuance, secondary trading and custodial services:

- Law on Digital Assets [Zakon o digitalnoj imovini] (Official Gazette of the Republic of Serbia, No. 153/2020) (Government of the Republic of Serbia, 2020);
- Law No. 66/2020 "On Financial Markets Based on Distributed Ledger Technology (DLT)" (Official Journal of the Republic of Albania, Albania, 2020).

In contrast, Montenegro, North Macedonia and Bosnia and Herzegovina rely mainly on AML-based coverage of virtual-asset activities and VASPs. Product-law issues such as the legal classification of tokens, public-offer discipline or disclosure obligations remain fragmented or implicit under general law. A partial exception exists in Republika Srpska, where virtual-currency services are recognized under the Law on the Securities Market (Official Gazette of Republika Srpska, Nos. 92/2006, 63/2022) (Republika Srpska, 2022).

Kosovo* represents an outlier. Following an energy-security decree temporarily banning crypto-mining (Government of the Republic of Kosovo, 2022, January 4, Decision on Emergency Energy Measures Introducing a Temporary Ban on Crypto-Mining Operations), the Central Bank announced a phased regulatory approach culminating in the Regulation on the Licensing of Crypto-Asset Service Operators (Exchange Services) (issued 29 August 2025 under Law No. 08/L-295 on Crypto-Assets [Central Bank of the Republic of Kosovo, 2025]).

Licensing and authorization models differ across the region: Serbia and Albania operate full licensing regimes; Montenegro, North Macedonia and Bosnia and Herzegovina apply registration or notification models under their AML perimeters; and Kosovo* has not yet implemented a complete licensing system. Institutional fragmentation is most pronounced in Bosnia and Herzegovina, where state-level AML enforcement and entity-level securities supervision must be coordinated for cross-entity blockchain deployments.

For regional, permissioned blockchain networks supporting (agro)forestry traceability, functions that require explicit product-law authorization, such as issuance and custodial services, should be anchored in Serbia or Albania. Operators in Montenegro, North Macedonia, and Bosnia and Herzegovina can engage under their AML-based compliance perimeters (e.g., Know Your Customer (KYC) legal process, key custody, audit trails). In Kosovo*, pilot projects should remain token-neutral and non-mining, focusing on credential-based traceability and verifiable presentations rather than token offerings.

Across all six jurisdictions, records with legal effect should employ qualified electronic signatures or seals and trusted time stamps under national trust-services legislation. Governance frameworks must also designate a clear data controller under the General Data Protection Regulation (GDPR) for off-chain personal and geolocation data, ensuring that only cryptographic commitments are stored on-chain (Commission Nationale de l'Informatique et des Libertés [CNIL], 2018; EPRS/STOA, 2019). These legal foundations enable integration with CEFTA/SEED+ data-exchange channels and align the regional compliance architecture with due-diligence obligations under the EU Deforestation Regulation (2023/1115).

4.2 Country case studies: pilot opportunities for blockchain-enabled FFG in the WB6

Thirteen WB6 case studies are presented in order to diagnose institutional constraints, characterize governance practices and assess the feasibility of blockchain in forest, agroforestry and protected-area governance. The sample comprises seven forestry cases and six agroforestry cases, allocated as two per country across the WB6, with one planned exception: Serbia hosts three cases - two forestry and one agroforestry - justified by its pronounced north–south agroecological gradient and associated management heterogeneity. Serbia also represents a particularly strong pilot environment because recent WB6-wide analyses show that GSDDTs, including UAV- and satellite-based monitoring, are already being applied across (agro)forestry systems, creating standardized, geo-referenced evidence layers that can be anchored on-chain as immutable audit trails. This makes Serbian cases especially suitable for testing permissioned blockchain workflows for permit logging, intervention verification and ecosystem-service accountability under real-world data conditions (Trudić et al., 2025). Case selection was purposive to maximize geographic representativeness, ecological diversity and variability in governance challenges, covering mountainous forests, hilly landscapes and lowland agricultural–agroforestry mosaics. This design enables robust within- and cross-country comparison under differing ecological and policy contexts while maintaining a consistent analytical framework, thereby supporting rigorous inference on blockchain's adaptability, effectiveness and scalability across heterogeneous WB6 conditions.

4.2.1 Albania

Prespa National Park in Albania, established in 1999, forms part of the transboundary Prespa-Ohrid ecoregion shared with Greece and North Macedonia. It is managed by the National Agency for

Protected Areas (NAPA). The Park faces challenges related to fragmented governance, limited coordination between institutions and local stakeholders and insufficient transparency in resource allocation (Shumka et al., 2014). The Albanian part of the Prespa National Park is under significant ecological stress from combined anthropogenic pressures like overgrazing and livestock pressure, unsustainable fodder harvesting, illegal wood cutting and unsupervised harvest of non-timber forest products. These activities have led to degradation of pastures and fragile alpine zones, forest cover loss and long-term habitat fragmentation (Grazhdani et al., 2010). Unfortunately, local annual wood demand, approximately 13,000 m^3 far exceeds forest growth capacity 0.35–2.2 m^3/ha/year which leads to further forest exploitation, threatening biodiversity and forest regeneration (Grazhdani, 2013). Environmental conservation is possible by further enforcement of anti-logging regulations and enhanced cooperation with Greek and Macedonian park authorities (Grazhdani et al., 2010). Blockchain technologies could support the creation of secure, tamper-proof records of management decisions and resource-use agreements through smart contracts. This would enhance trust among communities and funding institutions (FAO, 2020).

Traditional agroforestry is widespread in Albania's rural areas, where smallholders often combine trees, crops and livestock on the same land (Bojović et al., 2024). Olive groves are commonly interplanted with other fruit trees and even vines, creating multipurpose farm plots that yield olives, fruits, fuelwood and fodder (Bojović et al., 2024). Genetic research of Dervishi et al. (2021) reveals that olive is one of Albania's oldest and most significant cultivated tree species, with numerous native cultivars (like Kalinjot and Kokërrmadh Berati) and oleasters preserved through centuries. Key challenges include land fragmentation and low farmer awareness of agroforestry's long-term benefits (Bojović et al., 2024). Olive farming in Albania is characterized by an average farm size of approximately 1.2 ha. When coupled with excessive land fragmentation, limited investment, inadequate infrastructure and insufficient storage capacity, this structural context poses significant challenges to the sustainability, efficiency and modernization of olive production systems (Shahini, 2024). In the olive oil sector, a lack of supply chain transparency has led to issues like adulteration and mislabeling (for example, oils being falsely sold as "extra virgin"), undermining trust and farmer incomes (Ledger Insights, 2020).

BT can help tackle these issues by introducing transparent, tamper-proof tracking of agricultural products. For instance, a blockchain-based system could record each batch of olive oil from grove to bottle, guaranteeing the origin and quality. This approach is already used by a Spanish olive oil cooperative that leverages blockchain to ensure authenticity and combat fraud in olive oil labeling (Ledger Insights, 2020). By giving consumers a secure record of an Albanian olive oil's journey (e.g., via QR code on the bottle), farmers could fetch better prices for genuine extra-virgin products. Moreover, smart contracts could automate fair payments to small olive farmers, even in a fragmented landholding scenario, ensuring they receive a larger share of profits when their high-quality, blockchain-verified oil reaches international markets (Vitaskos et al., 2024; Staffolani et al., 2025).

4.2.2 Bosnia and Herzegovina

Sutjeska National Park in Bosnia and Herzegovina, established in 1962, is the country's oldest park and includes the Perućica primeval forest. It is under the jurisdiction of the Ministry of Trade and Tourism of Republika Srpska. The Park suffers from institutional fragmentation, weak transparency in the concession system and limited involvement of local communities (Porej and Matić, 2009). Although officially protected, Sutjeska National Park is increasingly threatened by a range of anthropogenic pressures that challenge its long-term ecological sustainability. Scientific attention to protected areas remains limited, largely due to the assumption that their legal status ensures adequate conservation; however, the situation in Sutjeska demonstrates that this assumption often does not reflect reality (Miljević et al., 2016). The Park has experienced a 4.9% reduction in natural vegetation cover, primarily driven by logging, expansion of tourism infrastructure, construction of secondary housing and localized agricultural activities (Hrelja, 2019). These challenges highlight the gap between legal protection and effective ecological stewardship, underlining the urgent need for integrated, science-based management approaches to ensure the sustainable future of Sutjeska National Park. Blockchain-based systems could ensure real-time tracking and verification of logging and tourism permits, thereby increasing institutional accountability and reducing opportunities for mismanagement (Stopfer et al., 2024; Abbas, 2024; Baydeniz, 2024).

In BiH, agroforestry has traditionally taken the form of silvopastoral systems - grazing livestock under tree cover in the rugged uplands (Bojović et al., 2024). Many rural communities (especially around the Dinaric Alps) still raise sheep or cattle on semi-natural grasslands dotted with oak and pine, blending farming with forestry (Bojović et al., 2024). Silvopastoral systems, integrating trees with livestock, provide environmental benefits such as soil conservation, biodiversity enhancement, carbon sequestration and fire risk reduction, while improving drought resilience. Economically, they can increase farm profitability through timber production, though challenges include long payback periods and risks in native forest management (Ghaffariyan, 2025). The sub-Mediterranean karst landscapes of southern BiH, though harsh, have supported these agrosilvopastoral practices for generations, providing firewood, forage and some tree crops in tandem (Bojović et al., 2024). This traditional approach is valued for maintaining biodiversity and sustaining livelihoods on marginal lands. The karst highlands present major challenges: thin soils and rocky terrain make conventional agriculture difficult (Bojović et al., 2024). Decades of land degradation and rural depopulation have led to patches of "karst desertification," where overgrazing and erosion leave the land barren. Modern agroforestry in BiH is still in its infancy, there is no national agroforestry association and institutional support is minimal (Bojović et al., 2024). Farmers lack incentives and resources to rehabilitate degraded pastures with tree planting. Restoring these areas (for example, by planting drought-tolerant fruit trees alongside fodder crops) has been suggested as a strategy for ecological and economic revival (Bojović et al., 2024), but financing and coordination remain hurdles. The IUCN (2021) report highlights the potential of nature-based solutions in BiH, emphasizing how agroforestry can contribute to climate change mitigation by enhancing carbon sequestration, biodiversity and ecosystem services. It underscores the importance of implementing agroforestry within existing land-use and agricultural systems to maximize environmental benefits and support sustainable land management (Kapović Solomun, 2022).

BT can incentivize and streamline landscape restoration in BiH's karst regions. One idea is to integrate blockchain-based carbon credit systems for silvopastoral projects. As trees are reintroduced on grazing lands, carbon sequestration credits could be earned and recorded on a blockchain ledger, guaranteeing transparency and trust for investors and communities. In fact, over 60% of new carbon-credit platforms now use blockchain to transparently track forestry and agriculture credits (Farmonaut, 2025; CarbonCredits, 2025). By tokenizing the environmental services of silvopastures (like carbon capture or biodiversity conservation), small farming communities could directly access global green funds (Chalkias et al., 2024; Boonrat et al., 2025). Smart contracts could automatically pay farmers or cooperatives when independent sensors or satellite data (linked to the blockchain) confirm that new trees have survived and grown (Pranto et al., 2021). This would help overcome the funding gap by rewarding Bosnian farmers for sustainable land management, all while providing verifiable proof of environmental impact to donors and buyers. Additionally, blockchain-led supply chain tracing can boost market value for silvopastoral products (like organic lamb or cheese from these regions) by confirming their origin and sustainable farming methods, thereby connecting BiH's mountain farmers to eco-conscious consumers with greater trust (Yao and Zhang, 2022; Lv et al., 2023).

4.2.3 Kosovo*

Sharr Mountain, located across Kosovo*, North Macedonia and Albania, is a prominent natural region with considerable ecological and economic significance. It was initially designated in 1986 and reaffirmed in 2012, contains significant endemic biodiversity and supports traditional pastoralist livelihoods. Encompassing roughly 1,600 km^2, the massif is distinguished by its high peaks, expansive alpine pastures, glacial lakes and exceptional biodiversity, including numerous endemic and protected species (Mustafa et al., 2018). Its varied geomorphology and climate contribute to abundant water resources and rich vegetation, creating favorable conditions for animal husbandry and mountain tourism. Although the region holds substantial potential, its natural resources remain largely untapped, highlighting the need for sustainable utilization and development efforts (Mustafi et al., 2023). Sharr Mountains National Park (SMNP) in Kosovo* faces a range of complex management challenges, primarily due to fragmented institutional authority, limited community engagement and ineffective policy enforcement (Jupolli, 2010). The Park is jointly managed by three entities: the Park Directorate in Prizren (under the Ministry of Environment and Spatial Planning), a Serbian-affiliated Park Directorate in Shterpce and the Kosovo* Forest Agency which creates overlapping mandates and confusion about responsibilities. This lack of clarity has weakened governance and allowed environmentally harmful practices to persist (Republic of Kosovo*, Ministry of Environment and Spatial Planning, 2015). Although laws promote public participation, local communities are largely excluded from meaningful decision-making, often restricted to minimal consultation. Their access to essential forest resources like fuelwood and medicinal plants has been curtailed, increasing economic hardship and resistance to conservation efforts (Jupolli, 2010; AMMK, 2015). Additionally, corruption, political instability and poor coordination among institutions further undermine park management. Communities around the park depend heavily on agriculture and natural resource-based income, but face obstacles such as limited market access, land rights issues and inadequate financial support (Jupolli, 2010). The absence of a unified management plan and weak communication between authorities and residents have fostered distrust, hindering prospects for sustainable and inclusive park governance. As a result, both conservation goals and community development opportunities remain underrealized (Jupolli, 2010). Key governance challenges include disputed land tenure, illegal logging, a pervasive informal economy and unreliable environmental data (Jupolli, 2010; AMMK, 2015). Blockchain's decentralized nature offers potential for participatory monitoring systems that allow local communities to track forest resource flows, enhancing transparency and ownership (Kosovo* Environmental Protection Agency, 2021).

In Kosovo*'s western municipalities, chestnut forests form the basis of a locally important agroforestry system. Roughly 3,500 ha of sweet chestnut (*Castanea sativa*) woodlands are managed for multiple outputs, notably edible chestnut nuts (Tahiri, 2018). Villagers traditionally harvest these forests for chestnuts (about 2,500 tons annually) (Tahiri, 2018), which are sold as a seasonal delicacy and used in flours and confections. These chestnut groves also support grazing and beekeeping; farmers often pasture livestock beneath the trees and place beehives to produce chestnut honey, making the most of this forest-farm mosaic (Tahiri, 2018; Slow Food Foundation for Biodiversity, 2025). Recent initiatives have recognized chestnut value chains as a development opportunity, helping locals rehabilitate aging chestnut stands and improve nut processing for market (CNVP Kosovo, 2020).

BT could significantly improve the chestnut value chain by connecting small producers directly to buyers and certifying product authenticity. Using a blockchain-based platform, cooperatives of chestnut gatherers could record each step, from forest collection, sorting, to packaging, on an immutable ledger (Kamilaris et al., 2019; Menanno et al., 2023). This would let overseas buyers verify that a packet of chestnuts or jar of honey indeed came from sustainable Kosovo*'s forest plots. Moreover, blockchain smart contracts can help farmers bypass excessive intermediaries. With a transparent digital marketplace, chestnut farmers could sell their crops directly to international retailers or processors, with the blockchain automatically handling payments once delivery is confirmed (Kamilaris et al., 2019; dos Santos et al., 2021; Menanno et al., 2023). Nevertheless, a blockchain-enhanced supply chain could help revitalize Kosovo*'s chestnut agroforestry by assuring quality, facilitating fair trade and attracting investments (for example, through tokenized contributions to plant new chestnut trees, which backers can monitor via blockchain records) (dos Santos et al., 2021).

4.2.4 Montenegro

Biogradska Gora National Park in Montenegro, one of the last three European primeval forests, is managed by the national public enterprise for protected areas. Although central governance is well established, the park faces increasing tourism pressure and lacks digital tools for visitor control and biodiversity monitoring (Janković et al., 2017). Mixed forests in Biogradska Gora National Park, composed of beech, sycamore, ash and elm, show higher species richness, productivity and biodiversity compared to pure beech stands, with up to 58 plant species and timber volumes exceeding 800–1,300 m^3/ha. These forests benefit from better litter decomposition and lower soil acidity, contributing to greater ecological and structural complexity. However, without appropriate silvicultural management, especially in early development, light-demanding species struggle to compete with the dominant beech due to limited regeneration under closed canopies. While unmanaged forests preserve biodiversity and support rare species, active management, such as creating canopy gaps, is essential for maintaining species diversity and optimizing productivity in mixed stands. Uncontrolled tourism negatively impacts National Park habitat integrity, accumulation of solid waste and frequent disturbance to native wildlife (Mileusnić-Škrtić et al., 2024). Illegal logging contributes to forest degradation, soil erosion and the fragmentation of sensitive ecosystems. Additionally, unauthorized construction of structures built without environmental regulation further disrupts the ecological balance by fragmenting forest habitats. Collectively, these anthropogenic pressures accelerate habitat loss, reduce biodiversity and threaten the park's ecological stability (Ranković, 2023). Blockchain solutions could include tokenized entrance permits and automated licensing processes to ensure transparency in revenue collection and ecological impact mitigation (IUCN, 2021).

Montenegro boasts extensive forests (nearly 60% of its land) (Bojović et al., 2024) and a rich variety of medicinal and nectar-producing plants, which together create ideal conditions for forest-based apiculture. Many Montenegrin farmers are small-scale beekeepers who place hives in or near wild forests and mountain meadows, allowing bees to forage on lime trees, chestnut blossoms, sage and other native flora. This practice is a form of agroforestry that leverages forests for honey production, yielding specialty honeys noted for their quality. Researchers have highlighted Montenegrin apiculture and the biodiversity of honey plants as a key potential for agroforestry development in the country (Bojović et al., 2024). Despite its promise, the honey sector in Montenegro (as in many countries) faces challenges of scale and trust. Production is fragmented among many small beekeepers, making consistent quality control and marketing difficult. Perhaps most significantly, honey fraud is a global problem, even in the EU, an estimated 14% of honey on the market is adulterated or mislabeled (Intertek, 2024). Climate change and environmental pollution threaten floral resources for bees, adding pressure on yield consistency. Montenegrin beekeepers need better access to markets and assurance that their authentic product can be distinguished from counterfeits (Vukašinović-Pešić et al., 2020).

Blockchain traceability can greatly enhance the credibility and market value of Montenegrin forest honey. By recording every step "from hive to jar" on a blockchain, consumers and regulators can verify that a given batch of honey is pure and originates from Montenegro's designated apiaries. For example, the HoneyTrace platform launched in 2024 uses blockchain to securely verify beekeeper identities, log lab test results and track honey batches through the supply chain (Intertek, 2024). A similar system could be adopted by Montenegrin cooperatives: each jar of honey would carry a QR code linked to an immutable record showing where and when it was harvested and that it passed authenticity tests. This level of transparency builds consumer trust and can help Montenegrin honey command premium prices by ensuring transparency and authenticity across the supply chain (Intertek, 2024). Furthermore, blockchain smart contracts could facilitate micro-insurance or subsidy payouts to beekeepers (for example, automatically releasing funds if hive losses or climate extremes are documented), helping them cope with environmental challenges (Madhwal et al., 2023).

4.2.5 North Macedonia

North Macedonia's Mavrovo National Park, the largest in the country and established in 1949, is marked by tension between conservation goals and large-scale infrastructure projects, particularly hydropower plants (The Center for Environmental Research and Information, 2015). Mavrovo National Park in North Macedonia harbors a rich diversity of forest ecosystems shaped by a combination of geological, climatic and human influences (Aleksova et al., 2025). Some forests display virgin characteristics, including old-growth stands of beech, fir and chestnut, highlighting their high conservation importance. Natural forest regeneration is occurring in abandoned pastures, where Macedonian pine, juniper and various shrub thickets are spreading in response to declining grazing pressure (Acevski and Simovski, 2011). Additionally, erosion-control plantations of native conifers have been established near settlements. Altogether, the park's forest ecosystems illustrate a dynamic interplay between natural processes and anthropogenic legacy, emphasizing the importance of ongoing ecological monitoring and protection (Acevski and Simovski, 2011). Institutional shortcomings such as poor law enforcement, corruption in natural resource management and opaque decision-making processes persist. The use of blockchain could improve the traceability of concessions and enable open verification of environmental impact assessments, strengthening public oversight (Bhatt and Emdad, 2025).

North Macedonia has a diverse agricultural landscape, including extensive vineyards and fruit orchards that could be enhanced with agroforestry techniques. Traditional small orchards of apricots, plums or walnuts sometimes have vegetable plots or pastures underneath the trees. While these combinations exist, there is significant untapped potential to systematically introduce windbreak trees around fields or nitrogen-fixing shrubs among rows to improve microclimate and yields. Overall, North Macedonia's mix of hilly terrain and fertile valleys provides opportunities for agroforestry (like shelterbelts to protect against erosion in windy plains, or mixed orchards in mountain villages) that are only beginning to be realized (Stefanova et al., 2012; Bojović et al., 2024). Macedonian farmers share many of the region's general challenges: land holdings are highly fragmented and adopting new practices can be difficult on many small, scattered plots (FAO, 2024). Climatic stresses (hot, dry summers and variable rainfall) put vineyards and orchards at risk, requiring better resilience measures. Traditional certification systems (paper labels, appellations, etc.) help but can be undermined by fraud or error. This lack of full transparency in the supply chain can reduce the premium that quality Macedonian products (like single-origin wines or organic fruits) could fetch (Martinovska-Stojcheska, 2024).

The blockchain-based traceability system could document every stage of wine and fruit production, boosting both export credibility and domestic consumer trust (Malisic et al., 2023). For example, a winery could use blockchain to record details from vineyard to bottle: grape variety, vineyard GPS location, harvest date, fermentation batch data, all stored on a decentralized ledger. This would enable buyers to scan a QR code on a bottle of Macedonian wine and instantly verify its provenance and journey, an approach already being used to combat counterfeit wines in other countries (Marr, 2025). By securely recording and verifying the authenticity of each bottle (Marr, 2025), blockchain helps protect the reputation of regional winemakers and assures consumers they are getting a genuine product. The same principle can apply to high-quality fruit: for instance, a shipment of organic Macedonian apples could be tracked on blockchain from orchard to retailer, so retailers and end-consumers can see proof of the apples' farm of origin and organic certification (Morais et al., 2024). By adopting these tools, North Macedonia can enhance the global image of its wines and fruits, ensure farmers are rewarded for quality through transparent pricing and overcome the trust gap caused by fragmented supply chains (SWG Regional Rural Development Standing Working Group, 2023).

4.2.6 Serbia

Tara National Park is located in the western region of Serbia, covering the majority of Mount Tara and Zvijezda. It was established in 1981 and is characterized by a relatively advanced model of integrated forest and tourism management under the public enterprise "National Park Tara", in cooperation with state forestry and local authorities. The mountain's distinctive natural characteristics and remoteness have facilitated the emergence of many plant and animal species, including a notable proportion of endemic and relict species. A significant characteristic of NP Tara is its forest ecosystems, which encompass about 78.8% (Brankov et al., 2017). Due to its unique characteristics, Tara NP is designated as an Important Plant and Bird Area (IPA and IBA), a Prime Butterfly Area (PBA) and a site of Areas of Special Conservation Interest (ASCI) within the EMERALD network (Brankov et al., 2022).

Despite its protected status, this national park encounters multiple challenges, such as illegal logging, poaching, unregulated/unsustainable tourism, infrastructure expansion, climate change, invasive species, etc. These challenges jeopardize its rich biodiversity, including the endemic Serbian spruce (*P. omorika*), which underscores the necessity for sustainable management and enhanced governance in addressing these concerns (Matović et al., 2025). Alongside the Law on National Parks in Serbia, the Tara National Park Management Plan for the Period 2020–2029 constitutes the core legal framework regulating the conservation, use and management of protected areas, while considering the necessities of the inhabitants of the area (JP Nacionalni park Tara, 2020).

Blockchain platforms could facilitate transparent documentation of forest parcel status, legal harvesting and permitting procedures (FAO, 2020). Implementing blockchain in Tara National Park could effectively mitigate its significant issues, based upon careful integration and consideration of indigenous stakeholders. It may further enhance transparency, accountability and efficiency in all aspects of national park management (e.g., logging regulation). Furthermore, integrated watershed management (IWM) practices (Vasić et al., 2024) might be considered for sustainable management of these and other national parks. Integration of blockchain-related technologies within IWM practices could be a significant addition for enhanced management by securing data integrity and transparency as well as improved stakeholder coordination.

Fruška Gora National Park, located in the Vojvodina region of Northern Serbia, represents a significant ecological and tourism asset, distinguished by its extensive forest ecosystems and international protection status as an IPA (Ristić et al., 2024). Encompassing over 26,000 ha, with 23,000 ha under forest cover, the park hosts a rich diversity of flora and fauna, including many rare and endangered species. As a mosaic of forest, steppe and meadow habitats, Fruška Gora supports over 1,500 plant species and serves as a vital habitat for protected bird and mammal species. The park's natural wealth and biodiversity offer unique opportunities for nature-based tourism (NbT), including hiking, wildlife observation, scientific tourism and community engagement (Ristić et al., 2024). Negative human influences on Fruška Gora National Park have led to significant ecological degradation, particularly of its forest ecosystems. The most critical impact stems from past unsustainable forest exploitation, including widespread clear-cutting, which resulted in over 80% of the forest being of coppice origin (Šušić et al., 2022). This led to a loss of structural and species diversity, reduction of large and mature trees, increased prevalence of fast-growing and competitive species like silver lime (*Tilia argentea*) and suppression of slower-growing, ecologically valuable species such as beech (*F. sylvatica*). Forest management policies, historically focused on commercial timber production, have compounded these problems by prioritizing short-term economic gain over long-term ecological sustainability. Degraded forest stands, particularly those under lower protection levels, now exhibit lower biodiversity, diminished soil quality, sparse herbaceous layers and reduced canopy cover (Trifunov et al., 2013). These changes decrease the park's capacity to provide valuable ecosystem services, including both timber and non-timber products and push the ecosystem closer to critical thresholds, beyond which recovery becomes uncertain or highly costly. Unfortunately, repeated human disturbances have eroded both the ecological integrity and economic potential of the park's forests (Trifunov et al., 2013).

Serbia's northern province of Vojvodina is a vast agricultural plain where shelterbelt windbreaks are a hallmark agroforestry practice. With over 75% of Vojvodina's land under cultivation, rows of planted trees (often poplar, oak or acacia) are used to shield crops from strong winds (Bojović et al., 2024). These windbreaks, sometimes stretching for kilometers along field boundaries, are the most common agroforestry system in the region (Bojović et al., 2024). The influence of agroforestry systems on adjacent agricultural crops is well documented and largely determined by factors such as tree size, windbreak condition and the extent of planted areas. Windbreaks exert a positive effect on nearby crops, with vegetation index analyses consistently showing higher values in zones closest to the shelterbelts compared to the remainder of the field (Višacki et al., 2024). This type of remotely sensed, plot-level evidence is already being operationalized in Serbia through large-scale digital agriculture and agroforestry initiatives, where UAV- and satellite-based monitoring is combined with field interventions to support sustainable crop production and ecosystem service delivery (Trudić et al., 2025). Such data streams provide a practical foundation for blockchain-based verification of agroforestry practices, including shelterbelt maintenance, biological interventions and compliance with sustainability standards. Additionally, Serbia has traditional silvopastoral systems in its river floodplains: along the Danube, Sava and Tisa rivers, farmers graze cattle and sheep in seasonally flooded oak forests (Bojović et al., 2024). This practice, one of the country's oldest forms of agroforestry, yields meat and dairy while maintaining forest cover. Together, windbreak planting and floodplain grazing illustrate Serbia's blend of introduced and natural agroforestry in support of its large agriculture sector. Key challenges for Serbian agroforestry include maintenance and modernization of these systems. Many windbreaks were established decades ago; some have been removed to gain arable land, despite the cost to soil health (Ristić et al., 2021). This has left parts of Vojvodina highly susceptible to wind erosion, a serious issue as topsoil can blow away without protection. Re-establishing and managing shelterbelts require coordination among neighboring farms and upfront investment, which are not always forthcoming. There are also agronomic challenges: in certain areas, high soil salinity impedes tree growth, so finding salt-tolerant tree species that can thrive and even provide fodder is essential (Bojović et al., 2024). In floodplain silvopastures, balancing timber production with grazing rights can be difficult under current regulations. Finally, farmers lack direct incentives or financial rewards for the ecosystem services these agroforestry systems provide (like climate mitigation and soil conservation), which can lead to neglect or removal of tree belts over time (Forest Restoration, 2025; Institute for Nature Conservation of the Province of Vojvodina, 2018).

BT could help reinvigorate Serbia's agroforestry by monetizing its environmental benefits and improving cooperative management. One approach is to integrate blockchain-based reward systems for ecosystem services: for example, a farmer who plants or regenerates windbreak trees could earn tokenized carbon credits or green certificates once satellite imagery (linked via blockchain) verifies the trees' growth (Weninger et al., 2021; CIFOR-ICRAF, 2022; Sustainability Directory, 2025a). This is becoming a global trend, as blockchain's transparency and immutability are ideal for tracking such credits (Farmonaut, 2025). In practice, Serbian authorities or environmental markets could issue smart-contract-based payments to groups of farmers when a windbreak reaches a certain survival rate or when soil erosion in the area drops, with all data open and verifiable (Saraji and Borowczak, 2021). Blockchain could also facilitate group governance: neighboring landowners could form a smart contract that manages a shared shelterbelt, automatically handling cost-sharing for planting or pruning and distributing any profits from timber harvested. Additionally, supply chain transparency via blockchain can add value to products from these systems, for instance, a "climate-friendly" wheat or corn grown under protected conditions could be tagged on a blockchain, allowing buyers to pay a premium knowing it came from fields protected by sustainable windbreaks (Weninger et al., 2021). Overall, blockchain tools would introduce both accountability and incentive, encouraging Serbian farmers to maintain windbreaks and silvopastoral areas.

The results presented in Supplementary Material S2 demonstrate the potential, rather than the current reality, of blockchain integration into (agro)forestry systems across the WB6. What emerges is a clear thematic divide: in countries like Albania and North Macedonia, blockchain is envisioned as a mechanism to strengthen supply-chain transparency and product authenticity, especially in olive oil and wine, sectors plagued by adulteration and mislabeling. In contrast, Bosnia and Herzegovina and Serbia are positioned as testing grounds for blockchain-enabled environmental service monetization, where carbon credits, erosion control and collective windbreak management could be tokenized to provide incentives for sustainable land management. Montenegro and Kosovo* present hybrid cases where blockchain could both elevate niche, high-quality products (forest honey, chestnuts) to premium export status and simultaneously build systems of automated payments or insurance for smallholders. These possibilities illustrate that blockchain is being conceptualized not merely as a technological upgrade, but as a policy-aligned tool bridging ecological conservation with economic resilience. The EU acquis references in Supplementary Table S2 suggest a forward-looking harmonization pathway: compliance with food traceability, geographical indication schemes or EUDR could be accelerated by adopting blockchain, positioning WB6 producers for integration into EU markets. However, the analysis also exposes systemic risks. Integrating blockchain requires digital literacy, infrastructure and institutional readiness, all of which remain uneven across the region. Thus, while blockchain promises to resolve long-standing trust deficits between farmers and markets, citizens and institutions, its feasibility hinges on broader capacity-building, equitable access and governance reforms. In this sense, blockchain integration into (agro)forestry in the WB6 is best understood as an opportunity space, contingent upon aligning local realities with transnational policy and technological frameworks.

4.3 Stakeholder landscape analysis in WB6 region for blockchain adoption in FFG

The possible stakeholders for blockchain integration into FFG in the WB6, as mapped in Supplementary Table S3, reflect both the structural complexity and the opportunities for reform. Universities, forestry faculties and reference laboratories would be critical in providing the scientific basis for blockchain-linked wood anatomy and DNA fingerprinting (Dormontt et al., 2015), ensuring that digital ledgers are backed by verifiable forensic evidence. Civil society actors, such as environmental NGOs and watchdog groups, would benefit from tamper-proof grievance tracking and authenticated citizen-science submissions, enhancing transparency and community oversight (Chalkias et al., 2024). Private actors, including ICT firms, timber processors, cooperatives and carbon-market intermediaries, stand to gain from end-to-end traceability and transparent measurement, reporting and verification systems

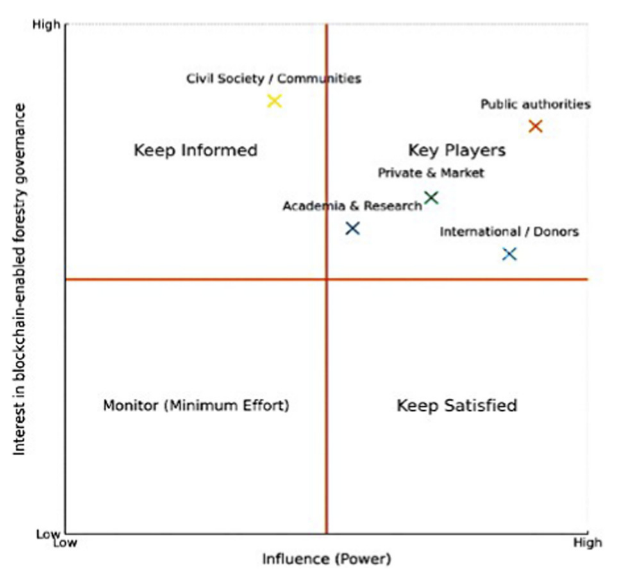

FIGURE 6
Descriptive stakeholder Power–Interest Matrix (PIM) for blockchain-enabled FFG in the WB6 based on stakeholders mapping exercise (Supplementary Material S3).

(MRV), particularly as EU due diligence requirements tighten (He and Turner, 2022). Public authorities, such as forestry ministries, agencies and national park directorates, could employ permissioned ledgers to reconcile standing-to-stump inventories, cutting permits and transport licenses, thereby addressing long-standing enforcement deficits (Corrêa Tavares et al., 2020).

At the regional and international level, organizations such as FAO, GIZ, World Bank, EU Delegations and FSC/PEFC auditors are likely to push for blockchain-enabled verification as part of conditional funding, certification and results-based disbursement. The diversity of interests suggests that blockchain could serve as a bridging mechanism: aligning scientific rigor with market incentives and grassroots monitoring with policy enforcement. However, its integration would require negotiation of access rights and governance structures to avoid excluding smallholders or community bodies from decision-making (Stopfer et al., 2024). Stakeholders with vested interests in maintaining opaque practices, such as segments of concessionaires or politically tied forestry enterprises, may resist such reforms, indicating that uptake will not be uniform. The capacity of academic institutions and NGOs to engage with blockchain will also vary, with stronger nodes in Serbia and Albania compared to more fragile ecosystems in Kosovo* or Montenegro. The stakeholder map highlights that blockchain is unlikely to be adopted as a stand-alone tool, but rather as part of a negotiated ecosystem of actors who bring different mandates, capacities and interests into the forensic forestry domain.

The PIM (Figure 6) operationalizes power and interest as normalized composites derived from legal mandate, budget and enforcement capacity, procurement/standard-setting authority, network centrality, EU-acquis alignment, dedicated resources, prior digital pilots and revealed participation. Public authorities occupy the high-power/high-interest quadrant, consistent with statutory control of permits, inspections, transport documentation and sanctions. Private and market actors are positioned at relatively high power and interest because certification, supply-chain traceability, forest reproductive material provenance and carbon-market MRV confer structural leverage and direct incentives. MRV denotes the formal system for quantifying and disclosing forest-carbon stocks and flows, with uncertainty, under standardized protocols and independent third-party audits; in a blockchain context, MRV artefacts (sensor and remote-sensing series, sampling notes, model versions) are hashed and time-stamped to secure provenance and auditability. International and donor organizations exhibit high power with programme-contingent interest, civil society shows high interest but lower formal power and academia lies mid-range on both axes as a methodological and data-stewardship enabler, yielding a governance configuration dominated by public authority and market leverage.

5 Discussion and implications

5.1 Barriers for blockchain integration in WB6 FFG

Despite its transformative potential, the large-scale deployment of blockchain remains subject to key constraints. These include energy-intensive consensus models such as PoW, limited transaction throughput and the absence of global standards for interoperability and smart contract legality (Buonocore et al., 2022). Moreover, cryptographic innovations such as zero-knowledge proofs and homomorphic encryption offer new avenues for reconciling transparency with data privacy, especially under the regulatory frameworks of jurisdictions such as the European Union's GDPR (Buonocore et al., 2022). While abovementioned case studies examples illustrate blockchain's potential for enhancing traceability and regulatory enforcement in the (agro)forestry sector, they also reveal substantial barriers to blockchain adoption in forestry governance in the WB6 countries. High upfront costs for equipment and training, limited access to stable internet infrastructure and lack of legal recognition for blockchain-generated evidence can restrict its applicability, particularly among smallholders or communities in remote regions. As such, hybrid governance models that combine traditional oversight with blockchain transparency may offer a more pragmatic path forward (Vilkov and Tian, 2019). Blockchain is a complex and costly technology, especially due to the high energy use of cryptocurrency mining (Laimon et al., 2025). Authorities or large companies may also resist adoption because blockchain increases transparency, which might not serve their interests (Akter et al., 2024).

5.1.1 Inadequate legal capacities and regulatory framework

This is a key constraint for blockchain implementation. Most WB6 countries lack comprehensive legal frameworks regulating the use of digital assets and cryptocurrencies in international trade, thereby limiting the applicability of blockchain systems that depend on token-based transactions (Odorovic et al., 2020).

5.1.2 Lack of technological infrastructure

Technological infrastructure across the WB6 is also inadequate for widespread blockchain adoption in forestry governance. Several reports indicate persistent weaknesses in e-government systems, underinvestment in digital public services and delays in digital transformation processes across the region (Balkan Investigative Reporting Network (BIRN), 2024; BIRN, 2025). Public institutions often lack the IT infrastructure and expertise needed to implement and maintain blockchain-based solutions. Moreover, low public trust in digital systems, coupled with high levels of perceived corruption, creates resistance to the adoption of technologies that promote transparency and accountability (BIRN, 2025). Serbia represents a partial exception within the WB6. It has adopted a regulatory framework that recognizes digital assets and permits their use under specific conditions (Law on Digital Assets (Official Gazette 153/2020)).

5.1.3 Energy consumption

Another critical barrier lies in the energy profile of the region. Most WB6 countries rely heavily on fossil fuels, with over 60% of electricity generation derived from coal and other non-renewable sources (Energy Community, 2021; OECD, 2025b). The deployment of energy-intensive blockchain systems, particularly those based on PoW consensus, would place further strain on national energy systems that are already outdated and in need of modernization. Limited investments in renewable energy and smart-grid infrastructure exacerbate this challenge (OSTP, 2022; Laimon et al., 2025). Thus, in the near term, the implementation of energy-efficient blockchain solutions, particularly those using PoS or other low-energy consensus mechanisms, should be prioritized and aligned with national energy and climate strategies (European Environment Agency, 2020).

5.1.4 Digital skills gap across key stakeholders

This landscape presents another significant constraint. Across the WB6, there is a pronounced digital skills gap, with limited participation in upskilling programs and inadequate access to advanced IT education. Very few training programs address emerging technologies such as blockchain and even fewer are tailored to the forestry or natural resource sectors (ETF, 2024; OECD, 2024a). Although initiatives such as the Regional Skills Partnership and European Digital Innovation Hubs (EDIHs) aim to improve digital competencies, specialized blockchain expertise remains rare (Angelis and da Silva, 2019).

5.1.5 Sustainable financing

Most (agro)forestry enterprises in the region lack both the financial resources and institutional capacity to recruit or retain dedicated blockchain specialists (European Training Foundation, 2025; SMARTLABOR Initiative Centre for Public Policy Research, 2025). Instead, they often depend on public–private partnerships, EU-funded technical assistance or innovation hubs to access the necessary skills and technological tools. Collaborations with universities and participation in EU-backed training and internship programs may gradually build in-house capacities for digital transformation (Regional Cooperation Council, 2025a; Regional Cooperation Council, 2025b; Balkan Insight, 2024).

5.1.6 Social/cultural constraint

Enduring public distrust in institutions and certification systems reduces willingness to accept blockchain records as legitimate evidence in forensic timber cases, particularly where enforcement has been politicized (SGS, 2020; Kaulen et al., 2023; Sustainability Directory, 2025b). Entrenched informal timber-market norms and cash-based transactions create cultural resistance to end-to-end traceability that could expose side payments or unlicensed harvesting. Multilingual, multi-layer governance (state/entity/municipal) and contested identities make shared data standards and consortium-run nodes politically sensitive, slowing alignment across agencies and across borders (OECD, 2022). Limited awareness of ABS and DSI obligations and fears of surveillance or job loss among rangers and smallholders, discourage on-chain disclosure unless offset by clear incentives, training and safeguards (Adler Miserendino et al., 2022).

The above analysis highlights that implementing blockchain for forest governance in the WB6 is not merely a technical endeavor but tightly interwoven with policy frameworks. On one hand, policy drivers are pushing for enhanced transparency and legality in the forestry sector, exemplified by the EUTR and its successor, the EU Deforestation Regulation. These legal instruments require robust verification of timber origin and compliance with sustainability criteria. Blockchain offers a technological means to meet these requirements by providing an immutable audit trail of timber from forest to market (Nectar Labs, 2024).

To further strengthen the technology–policy alignment, a concise threat-model perspective is incorporated, reflecting evidentiary admissibility as a first-order design constraint. In permissioned blockchain deployments for forest governance, key risks include private-key custody and rotation for validator and issuer identities, insider manipulation of records prior to anchoring, potential collusion among validator nodes, and the integrity and auditability of smart-contract components, particularly where permits or permissions are tokenized. These risks are mitigated through role-based identity management aligned with eIDAS trust-service principles, periodic key rotation and revocation procedures, multi-validator consensus with audit logging, and restricted, formally reviewed smart-contract logic. For forensic evidence, the evidence-to-ledger chain follows a clear sequence: laboratory reports (e.g., wood anatomy or genetic analyses) are generated and signed within accredited institutional systems, cryptographically hashed, and time-stamped on-chain, while full reports remain off-chain under the control of designated data controllers in line with GDPR. This approach preserves evidentiary integrity, enables independent verification, and ensures compliance with EUDR, AML/CFT and data-protection requirements.

Beyond legality, blockchain integration supports broader governance reforms. The EU acquis Chapter 27 on Environment mandates WB6 countries to build effective monitoring and reporting systems for forests and biodiversity. By design, blockchain ledgers enhance data integrity and transparency, thus serving as a tool to implement these policy obligations (Bartoszek, 2021). The technology–policy nexus is also evident in the EU's digital transformation agenda, which, although not a formal acquis chapter, guides accession countries toward developing e-governance and interoperable data systems aligned with the European Interoperability Framework and the Digital Decade Policy Programme 2030. Within this policy context, blockchain-based registries for forest permits, concessions or carbon credits could be developed to enhance transparency, traceability and administrative efficiency in line with EU digital governance standards (European Commission, 2017; European Commission, 2020; European Parliament and Council, 2022).

In this way, the policy goals (e.g., curbing illegal deforestation, improving public access to environmental information) find a novel ally in BT, which can automate trust and traceability in a manner previously not possible (Trackgood, 2023). However, it must be emphasized that technology alone cannot solve governance issues, it must operate within a supportive legal context. The absence of explicit recognition for blockchain records in national laws (as noted, most WB6 states except Serbia lack comprehensive DLT legislation (OECD, 2024a)) could hinder the admissibility and official use of blockchain evidence. Therefore, legal reforms (e.g., adapting definitions of official records, accepting digital ledgers in court or administrative procedures) are a crucial prerequisite to fully realize the policy-technology alignment (OECD, 2024a; OECD, 2024b). The institutional dimension underpins all others: without capable and coordinated institutions, even the best technology will not achieve its potential in forest governance. The WB6 context is characterized by fragmented institutional arrangements; forestry responsibilities are often split among environmental ministries, agriculture/rural development agencies, and decentralized forest enterprises, with limited data-sharing between them (Radosavljevic et al., 2023). This siloing is exacerbated at the regional level: until recently, there were few formal mechanisms for cross-border cooperation on forests. The case of the Prespa Park, a transboundary protected area managed jointly by Albania, North Macedonia and Greece, shows both the challenges and progress in regional institutional cooperation (Catsadorakis et al., 2022; Roussos et al., 2025). It took over two decades to move from a political declaration to establishing a functional interstate management committee, due to historical mistrust and lack of "institutional tradition" in cooperation (European Green Belt Association, 2022). Once set up, however, these structures provide a platform for harmonizing practices and sharing data (European Green Belt Association, 2022). Blockchain solutions could greatly benefit from such platforms: a distributed ledger of timber permits or biodiversity data could be co-managed by multiple national authorities, but this requires trust and interoperability agreements among those authorities. Institution-building is therefore critical, regional bodies (e.g., the WB6 Chamber Investment Forum's data hubs, or the RCC's biodiversity monitoring initiative (Price, 2024)) need to include blockchain literacy and data standards in their agendas.

Adopting blockchain in forest governance can serve the dual purpose of advancing EU accession requirements and accelerating progress toward the SDGs. The mapping of EU acquis chapters in previously mentioned 13 case studies (see Supplementary Table S2) illustrates this synergy. For instance, Chapter 27 (Environment) obligations include establishing robust systems for tracking timber legality and protecting biodiversity, implementing a blockchain-based timber tracking system directly contributes to those obligations by improving due diligence and reporting (thus helping meet EU benchmarks on illegal logging reduction) (Trackgood, 2023). At the same time, this promotes SDG targets under Goal 15 (Life on Land), such as SDG 15.2 on sustainable forest management and 15.5 on curbing biodiversity loss. A transparent ledger of forest resource use can help identify and halt unsustainable practices, thereby aligning with global conservation targets. Similarly, Chapter 11 (Agriculture and Rural Development) in the EU acquis emphasizes sustainable rural livelihoods and community-based resource management. Blockchain-enabled traceability can elevate rural products (e.g., certified timber or non-timber forest products) in global markets, supporting SDG 8.9 and 12.b which call for sustainable tourism and local culture-based products. For example, communities in BiH or Serbia producing artisanal wood crafts could use blockchain to certify the wood's legal origin, making their products more attractive to ecotourists and ethically conscious consumers (Kshetri, 2018). This not only drives rural income (contributing to SDG 1 and 8) but also incentivizes communities to uphold sustainable harvesting practices, reinforcing SDG 15. The social/cultural facilitators like NGO outreach and community forestry groups play a key role here, by raising awareness and organizing local stakeholders, they ensure that the technology is embraced and used to its full potential. Cases from the region show that when local people see tangible benefits (e.g., premium prices for traceable, certified products or donor funding for blockchain pilots that involve community co-management), their willingness to participate increases, thus building a culture of transparency and sustainability from the ground up (REFORD and CNVP Foundation, 2017; FSC, 2025). It is worth noting that EU acquis Chapter 9 (Financial Services) and the emerging digital finance regulations also become relevant when considering innovative funding models for forestry via blockchain. For example, smart contracts could automate payments for ecosystem services or carbon credits, an area which intersects with SDG 13 (Climate Action) and SDG 15 (Life on Land). This can improve accountability and reduce leakage of funds, directly contributing to SDG target 15.a (mobilizing resources for conservation) by ensuring that earmarked funds reach their intended purpose in a traceable way (Price, 2024). By adhering to EU standards on financial transparency and anti-money laundering even in these blockchain-based transactions, WB6 countries would simultaneously fulfill acquis chapters on finance and governance (Chapters 9 and 24) and SDG 16 (building effective, accountable institutions).

5.2 Security, ethics and further legal implications of possible blockchain based FFG in WB6

Blockchain is not prohibited by EU data-protection law, but deployments must strictly meet GDPR principles of lawfulness, minimization, storage limitation and privacy by design/by default, with clear role allocation between controllers and processors (Regulation (EU) 2016/679 [GDPR], Arts. 5, 25–26 (European Parliament and Council, 2016); Recital 26). In practice, personal and geolocation data should remain off-chain while only cryptographic proofs are anchored on-chain (CNIL, 2018). For cross-border personal-data flows, organizations rely on GDPR transfer tools, most commonly the European Commission's Standard Contractual Clauses, together with a transfer-risk assessment (Commission Implementing Decision (EU) 2021/914 (European Commission, 2021); Regulation (EU) 2016/679, Art. 46 (European Parliament and Council, 2016)). The EU Data Act introduces essential requirements for smart contracts used to execute data-sharing agreements, including access control, robustness and a "safe termination/reset" facility (Regulation (EU) 2023/2854, Art. 36 (European Parliament and Council, 2023b)).

For records with legal effect, qualified e-signatures, e-seals and time-stamps under eIDAS (as amended in 2024) provide the trusted-services basis for evidentiary value across borders (Regulation (EU) 910/2014, as amended by Regulation (EU) 2024/1183) (European Parliament and Council, 2024).

Most WB6 states have GDPR-aligned personal-data regimes (Serbia 2018/2019; North Macedonia 2020/2021; Kosovo* 2019; Montenegro 2018/2023), while Albania adopted a new GDPR-aligned law (No. 124/2024) that entered into force in January 2025 (DLA Piper, 2025; KPMG, 2025). Forestry blockchains must therefore minimize personal data on-chain, keep identities off-chain and use hashes/pseudonyms with clear controller/processor allocation. European guidance (CNIL, 2018; EPRS/STOA, 2019) recommends selecting a governance model that designates a controller (e.g., a consortium SPV) and using off-chain storage with on-chain proofs to facilitate erasure/correction rights. These are workable design constraints for WB6 pilots that anticipate EU oversight (Serbia DP Law, 2018; Albania Law 124/2024, 2024; EPRS/STOA, 2019).

In the WB6 context, a permissioned blockchain can strengthen the integrity and auditability of forest-governance records, but security and ethics have to be designed in from the start. Reviews of forestry use cases note that the field remains immature and complex, so real-world impact depends less on the ledger choice and more on identity, data quality and accountability across actors (He and Turner, 2022). A first security concern is the physical–digital link. QR codes and RFID tags are fast and cheap for mills and yards, yet they are vulnerable to copying or label swapping. Texture-based "biometrics" mitigate that risk. The AKAZE method captures feature key points from wood's anisotropic surface; the descriptors are hashed and referenced on-chain so that, at delivery, a fresh photo can be matched against the original capture to confirm identity. This two-step "upload → verify" workflow directly addresses weaknesses of label-only systems and has been demonstrated for wood traceability (Sun Y. et al., 2021; He and Turner, 2022; Stopfer et al., 2024). A second concern is process and volume integrity. Prototypes in the literature implement smart contracts that reconcile produced and processed volumes at each custody transfer and block the next step when balances or documents do not match. Systems such as LogLog and related Ethereum/Hyperledger designs make discrepancies visible as consignments change hands, packaging or transport modes, useful where logs, pallets and finished pieces travel through multiple operators (He and Turner, 2022; Stopfer et al., 2024). Route integrity during transport can also be enforced: GPS-constrained delivery with automatic flagging of deviations has been discussed in anti-illegal logging contexts and complements contract checks (Lobovikov et al., 2021).

On the cybersecurity side, good practice is conservative: hardware-backed keys, change-controlled smart-contract code and a hybrid storage pattern in which only minimal metadata and cryptographic commitments are on-chain while permits, photos and lab reports remain off-chain behind access controls (He and Turner, 2022; Damašsevičius et al., 2024; Stopfer et al., 2024). In permissioned frameworks, private data collections or similar mechanisms allow sensitive commercial information to be shared only with the entitled consortium members, while auditors and authorities still get a verifiable hash trail (Linux Foundation, 2023).

Privacy and data ethics require the same discipline. Hashing does not automatically anonymize personal data; in practice, many hashes are pseudonymous. For governance records that may include precise plot coordinates, personal identifiers or business-sensitive documents, the ethical baseline is: keep personal/precise location data off-chain, record only proofs/commitments on-chain, define clear controller roles and retention and use selective disclosure when showing evidence to third parties (He and Turner, 2022; Ponnoju, 2022). This also helps reconcile immutability with obligations to correct or delete data in underlying systems.

Inclusion and fairness matter as much as cryptography. Traceability and compliance systems can shift costs to smallholders and small and medium enterprises (SMEs) if onboarding and capture protocols are too heavy. The literature recommends phased roll-outs, shared tooling (devices, training) and simple capture routines so that smaller actors can participate on fair terms, otherwise transparency becomes exclusionary (Ponnoju, 2022; He and Turner, 2022). Where projects touch community rights or customary use, applying FPIC-style engagement and publishing only aggregated (not precise) public maps reduce unintended harms (Lobovikov et al., 2021).

Finally, environmental proportionality is part of ethics. For public-interest governance and industrial consortia, permissioned Byzantine Fault Tolerance or other lightweight consensus mechanisms are preferable to energy-intensive designs; reviews and architecture papers in forestry point this direction, aligning digital infrastructure with sustainability goals (He and Turner, 2022; Damašsevičius et al., 2024; Stopfer et al., 2024).

Building regionally interoperable blockchain solutions for (agro) forestry governance in the WB6 is not a purely technical exercise; it sits at the intersection of EU-driven market rules, regional trade facilitation instruments and domestic e-ID/trust-services and data-protection laws. In practice, legal feasibility in the WB6 hinges on three pillars: (i) alignment with the EUDR and its Information System; (ii) the ability to issue, sign and verify cross-border electronic records under eIDAS-style trust-services laws; and (iii) data-protection compliance for on-chain/off-chain personal and supply-chain data. For any WB6 exporter placing timber or wood-based products on the EU market, the EUDR provides the immediate policy pull for verifiable traceability. The European Commission launched the EUDR Information System (the registry for Due Diligence Statements) on 4 December 2024, enabling operators to submit and manage statements digitally (European Commission, 2024a). The WB6 economies participate in CEFTA Additional Protocol 5 (AP5) on Trade Facilitation, which requires data exchange among customs authorities and the use of risk-management and interoperability measures; the region's SEED/SEED+ platforms operationalize these exchanges (CEFTA Secretariat, 2024; World Customs Organization, 2024; WCO/

CEFTA, 2025). A forestry blockchain layer can therefore be designed to produce verifiable credentials and event logs (harvest, transport, export) that are legally consumable by customs/market-surveillance systems and, where feasible, synchronized with CEFTA data exchange routines. This lowers cross-border frictions for log consignments and finished wood products, while preserving agency-level controls (CEFTA Secretariat, 2024; World Customs Organization, 2024). All WB6 jurisdictions have enacted frameworks for electronic identification and trust services inspired by the EU eIDAS Regulation, albeit with varying maturity.

The EU's European Blockchain Services Infrastructure (EBSI) and its Verifiable Credentials framework provide architectural patterns for cross-border credential exchange (issuers–holders–verifiers) that WB6 pilots can mirror for timber legality, due-diligence evidence and operator identity. Where WB6 administrations converge on EBSI-compatible schemas (e.g., Legal Entity Credentials, transport permits), private operators can reuse wallets/VCs across borders and, eventually, towards the EUDR Information System or customs. This aligns with the Common Regional Market (CRM 2025–2028) agenda on digital interoperability (EBSI, 2025a; EBSI, 2025b; Regional Cooperation Council, 2025a; Regional Cooperation Council, 2025b; European Commission, 2023a; European Commission, 2023b). However, in practice the network for exchanging information on timber legality is primarily managed by public entities, exhibiting robust internal connections while lacking strong ties with non-state stakeholders, such as private forest owners and the scientific community (Radosavljevic et al., 2025).

A minimal, legally robust architecture for a WB6 "Forest Legality VC" could be as follows: (1) issuers (licensed harvesters, mills, transporters) and authorities (forest inspectorates, customs) are registered as trust-anchored entities; (2) each critical step (harvest permit, load manifest, customs exit/entry) produces a digitally signed record off-chain, anchored on-chain with a hash and qualified timestamp; (3) the exporter generates an EUDR-ready due-diligence bundle as a Verifiable Presentation referencing these credentials; (4) importers/authorities verify signatures and timestamps against national trust lists and consortium registries; (5) optional synchronization of event metadata with CEFTA SEED+ interfaces to streamline border procedures. This approach meets EUDR timelines, leverages existing WB6 trust-service laws, and contains GDPR risk through off-chain storage and selective disclosure (European Commission, 2024a; CNIL, 2018).

Finally, it is worth noting that the technical feasibility of high-granularity wood traceability has been demonstrated in recent literature (e.g., image/texture-based identification and supply-chain anchoring) and can be combined with the legal stack above to create verifiable, low-friction cross-border flows in the WB6 context (Sun R. et al., 2021; He and Turner, 2022; Stopfer et al., 2024).

5.3 Comparative analysis of institutional feasibility to integrate blockchain in FFG across the WB6

Table 3 provides an overview of national engagement for blockchain-enabled forest governance in the WB6, encompassing institutional indicators, legal frameworks, forensic capacity and market/regional drivers. According to this overview, the legal basis for evidence-grade digital traceability is already in place across the WB6 where every country has enacted eIDAS-style laws on electronic identification and trust services, allowing qualified e-signatures, seals, and trusted timestamps on harvest, transport and export records. This provides the core infrastructure for permissioned blockchain pilots that anchor cryptographic proofs, while personal data remain off-chain under domestic data-protection regimes. In parallel, the EU Deforestation Regulation's Information System, launched as the registry of due-diligence statements, creates an immediate compliance target and the region's SEED/SEED+ customs data-exchange stack under lowers the integration barrier for cross-border verification of digitally signed events. At the same time, descriptive readiness is constrained less by legal enablers than by enforcement depth and monitoring realism: illegal logging remains a documented challenge in Albania, Serbia and elsewhere, with fragmentation, coordination deficits and skills shortages undermining deterrence and evidential quality. Forensics is the critical bottleneck: there is no publicly documented, national-level timber DNA/isotope laboratory capacity in the WB6 and global reviews show that origin-verification reference data are still sparse compared with species identification, which limits the feasibility of routine forensic proof-of-origin unless cases are outsourced to foreign labs or backed by complementary methods such as wood anatomy and NIR/MS chemistry. In strict terms, Serbia is legally best positioned for early permissioned pilots due to the combination of a mature trust-services law and a digital-assets statute that enables code-based execution, but its enforcement credibility still hinges on addressing corruption risks and improving controls in private forests; North Macedonia, Kosovo* and Montenegro have serviceable legal baselines yet need to build staffed enforcement and monitoring capacity; Bosnia and Herzegovina and Albania face the steepest climb from legal feasibility to operational assurance due to fragmentation and persistent illegal logging pressures.

6 Strategic roadmap and technological recommendations

The integration of blockchain technologies into forestry governance across the WB6 represents both a technological and institutional transformation, requiring carefully sequenced action rather than a uniform regional rollout. Findings presented throughout this study demonstrate that while digital infrastructures and legal frameworks are progressively evolving, their maturity varies considerably among WB6 countries. Consequently, implementation should proceed through phased, country-specific pathways that reflect local governance realities, institutional digitalization levels and readiness for cross-border interoperability.

The interactive WB6 map (https://mehdibentargem.github.io/Interactive-Map-representing-S1-S2-S3/) integrates layered information from Supplementary Table S1 (species–marker–blockchain interfaces), Supplementary Table S2 (only 7 forestry related case studies which could be geolocated) and Supplementary Table S3 (complete stakeholder

TABLE 3 National readiness for blockchain-enabled forest governance in the WB6.

Country	Institutional and enforcement signals affecting blockchain uptake	Legal/Trust-services and data-protection baselines	Forensic and monitoring capacity baseline	Market and regional drivers relevant to blockchain traceability	Overall descriptive readiness*
Albania	Decentralization moved most forest management to municipalities, but enforcement remains uneven; illegal logging persists despite a national moratorium, reflecting capacity and coordination deficits (Kacani and Perri, 2019)	eIDAS-style trust-services in place (Law No. 107/2015 on electronic identification and trust services; Law No. 9880/2008 on e-signature (Government of Albania, 2017); (Law No. 107/2015, 2015)	No publicly documented dedicated timber DNA/isotope labs; monitoring relies primarily on traditional inspections; scientific wood testing is *ad hoc* and typically externalized (NEPCon, 2017)	EUDR Information System operational as the registry of due-diligence statements; SEED/SEED+ enables cross-border customs data exchange in WB6 (European Commission, 2024c)	Moderate-Low (legal rails present; institutional enforcement capacity remains the key constraint)
Bosnia and Herzegovina	Fragmented governance and weak inter-agency cooperation hamper high-level corruption enforcement; forestry oversight capacity is uneven across entities (European Commission, 2024c)	Electronic signatures recognized (Official Gazette 91/06), with national trust-infrastructure (IDDEEA) and related by-laws (Agency for Identification Documents, Registers and Data Exchange of Bosnia and Herzegovina (Agency for Identification Documents, Registers and Data Exchange of Bosnia and Herzegovina, 2025)	No dedicated timber forensics capacity documented; routine DNA/isotope origin testing not institutionalized; reliance on conventional inspections (NEPCon, 2017)	Same regional drivers: EUDR due-diligence registry and data exchange (SEED/SEED+) (European Commission, 2024c)	Moderate-Low (legal base exists; fragmentation and oversight challenges depress readiness)
Kosovo*	Enforcement capacity remains constrained; illegal logging reported in multiple forms, indicating the need for specialist training and tighter controls (Duri, 2021)	Law No. 08/L-022 (2021) on electronic identification and trust services, with secondary acts; EU eIDAS transposition noted in EU interoperability reporting (Government of Kosovo, 2021)	No public evidence of in-country timber DNA/isotope labs; reliance on traditional inspections and external laboratories when advanced analyses are needed (NEPCon, 2017)	EUDR Information System and CEFTA/AP5 interoperability creates immediate incentives to issue verifiable, signed records (European Commission, 2023a)	Moderate (sound trust-services law; practical enforcement/forensics capacities need strengthening)
Montenegro	Skills shortages and low attractiveness of forestry professions reduce enforcement depth; governance improvements repeatedly called for by regional fora (United Nations Economic Commission for Europe, 2015)	Law on Electronic Identification and Electronic Signature (2017, amended 2019) establishes qualified trust services; official government documentation available (Government of Montenegro, 2019)	No dedicated timber forensics labs documented; advanced testing infrequent and project-based; routine monitoring remains conventional (NEPCon, 2017)	Same regional drivers: EUDR due-diligence registry; SEED/SEED+ customs data exchange (European Commission, 2024c)	Moderate (legal rails are serviceable; human capacity and specialist forensics are the bottlenecks)

(*Continued*)

TABLE 3 Continued

Country	Institutional and enforcement signals affecting blockchain uptake	Legal/Trust-services and data-protection baselines	Forensic and monitoring capacity baseline	Market and regional drivers relevant to blockchain traceability	Overall descriptive readiness*
North Macedonia	Ongoing alignment with EU norms; persistent implementation gaps typical of the region, with repeated calls to strengthen action against illegal logging (United Nations Economic Commission for Europe, 2015)	Law on Electronic Documents, Electronic Identification and Trust Services (2019; amended 2021), aligned with eIDAS (Official Gazette of the Republic of North Macedonia, Nos. 101/2019, 275/2019) (Government of North Macedonia, 2021)	No publicly documented national timber DNA/ isotope facilities; monitoring relies on conventional inspections and *ad hoc* lab support where available (Low et al., 2022)	EUDR due-diligence registry and SEED and provide a ready data-exchange backbone (European Commission, 2023b)	Moderate (good legal enablers; readiness hinges on resourcing enforcement and monitoring systems)
Serbia	Illegal logging remains an enforcement concern (notably in private forests); investigative journalism and international reporting point to organized practices and corruption risks that erode deterrence (Sunjka, 2021)	Law on Electronic Documents, Electronic Identification and Trust Services (OG 94/2017; 52/ 2021) (Government of Serbia, 2017) and Law on Digital Assets (2020) provide mature rails for qualified e-signatures and code-based execution (Official Gazette 153/2020)	No dedicated timber forensic pipeline institutionalized; origin testing capacity must be sourced externally; conventional inspections prevail (NEPCon, 2017)	EUDR due-diligence registry and (SEED/SEED+) create clear incentives for verifiable, cross-border event logs (European Commission, 2024c)	Moderate-High (legally best-positioned for permissioned pilots; enforcement/forensics upgrades remain essential)

*Qualitative judgement integrating the cited legal/institutional signals with the paper's region-wide capacity findings.

landscape) visualizing how species-specific forensic potential, case-study geographies and institutional actors intersect spatially across the region (Rudis and Muir, 2020; Vaidyanathan et al., 2023; R Core Team, 2024; Wickham et al., 2024; Cheng et al., 2025). Its purpose is to provide a unified geospatial decision-support tool that reveals where blockchain-enabled FFG is most feasible, by displaying country-specific genetic traceability potential, governance needs and stakeholder roles.

Between 2027 and 2031, the region's collective objective should be to establish a trusted, permissioned and energy-efficient blockchain ecosystem that strengthens transparency, accountability and legality assurance within forest-based value chains. This process must begin with harmonized metadata standards and legal recognition of digital ledgers, followed by the deployment of pilot systems within forestry agencies and protected-area administrations and culminate in the integration of blockchain-anchored evidence into EUDR and SEED+ customs frameworks. Countries possessing more advanced e-governance and data infrastructures, particularly Serbia and Albania, are positioned to lead early pilots, while Montenegro, North Macedonia, and Kosovo* should initially prioritize institutional capacity building, metadata harmonization and stakeholder engagement. Bosnia and Herzegovina, given its multilevel governance structure, will require a dual-entity coordination model linking forestry agencies under a single interoperability protocol. Regionally, the establishment of a WB6 Blockchain Forest Legality Consortium under the auspices of CEFTA or RCC could ensure common standards, shared learning and pooled technical resources.

Although structural readiness across the WB6 remains low, owing to fragmented data architectures, uneven digital literacy, weak forensic capacity and limited cross-border interoperability, the region is far from homogeneous. Serbia and Albania constitute partial positive deviations: both have adopted comprehensive digital-asset legislation (Supplementary Table S4) and maintain more consolidated institutional and technical ecosystems (Supplementary Tables S2, S3). Consequently, regional readiness limitations coexist with national-level regulatory and organizational maturity in these two countries, enabling them to function as anchor jurisdictions for early permissioned-blockchain pilots. This distinction reconciles the generalized regional constraints with the country-specific opportunities identified in this study.

The 5-year strategic roadmap (S5) operationalizes these conclusions through a stepwise sequence of actions for each country from 2027 to 2031 and joint strategic framework. It identifies, for every year, the targeted challenge, the intended resolutions, the principal risks affecting implementation and the corresponding mitigation measures. Collectively, these pathways reveal a progressive convergence toward interoperable blockchain systems capable of supporting national forestry databases, digital permits, genetic-traceability ledgers and cross-border verification protocols. The roadmaps also highlight recurrent regional risks, most notably regulatory uncertainty, low digital literacy, potential resistance from market actors benefiting from opacity, funding discontinuities and pairs each with pragmatic mitigation strategies such as targeted training, legislative clarification, phased onboarding and alignment with EU accession and various financing instruments.

Selecting blockchain technologies suited to forestry governance and forensic verification in the WB6 region requires balancing security, interoperability, scalability and energy efficiency against legal and institutional feasibility. Considering administrative structures, data sensitivity and current levels of digital maturity, permissioned (private or consortium) frameworks are the most appropriate. They allow verified governmental, academic and private stakeholders to act as trusted nodes while maintaining confidentiality of sensitive forestry and genetic information.

For national-level (monocountry) systems, three technologies stand out:

- Hyperledger Fabric, optimal for forest-permit registries, concession monitoring and transport licenses owing to its modular design, detailed access control and low energy demand. Serbia, Albania, and Montenegro can deploy Fabric within forestry agencies or national-park directorates.
- Corda (R3), suited to forensic forestry and DSI validation where privacy and selective data disclosure are critical, especially relevant for Bosnia and Herzegovina and North Macedonia.
- Private Ethereum (PoA), appropriate for seed-lot, nursery or timber-batch certification that requires smart-contract automation and integration with IoT or satellite oracles, offering transparency to external buyers under strict energy and governance control.

For cross-border interoperability, the recommended architecture combines:

- Hyperledger Fabric consortium channels connecting national nodes through a regional "WB6 Forest Legality Channel", ensuring traceability of timber flows and mutual recognition of legality certificates among CEFTA members.
- EBSI-linked Verifiable Credentials, enabling proof-of-origin exchange with EU customs and EUDR databases.
- Corda interoperability gateways, allowing confidential cross-border exchange of forensic or genetic data without exposing underlying sequences, in full alignment with Nagoya-Protocol and CGRFA principles.

7 Conclusion

Hyperledger Fabric and Private Ethereum (Po A) provide robust foundations for national deployment, while Corda and EBSI-compatible frameworks ensure regional and international scalability. This layered approach combines the transparency and auditability required for legality assurance with the confidentiality essential for forensic forestry and DSI governance, thereby delivering a secure, interoperable and sustainable digital backbone for the WB6 forest sector.

Recent evidence confirms that blockchain's principal contribution to data-intensive governance systems lies in preserving the integrity, traceability, and auditability of analytical outputs, rather than in improving analytical accuracy itself. In a Smart Agriculture 5.0 framework, reinforcement-learning-derived predictions were immutably anchored to a blockchain ledger, enabling tamper-resistant storage, verifiable timestamps and automated execution of predefined rules through smart contracts (Jagan Mohan et al., 2026). Although demonstrated in an agricultural context, this architecture is directly transferable to forensic forestry governance, where genetic, isotopic, anatomical, and remote-sensing analyses generate scientifically robust evidence that is often weakened by institutional fragmentation and limited cross-border trust. By securing forensic outputs at the point of creation, blockchain-enabled systems can enhance evidentiary continuity and regulatory credibility in forest legality verification and deforestation-free supply-chain frameworks (Jagan Mohan et al., 2026).

Implementing the actions outlined in Supplementary Tables 5a-5c and adopting the above technological configuration will enable the WB6 region to transition from isolated pilot initiatives to a coherent, verifiable governance framework. In doing so, it will strengthen compliance with EU acquis Chapter 27 (Environment), foster the uptake of FAIR data principles for forest genetic and spatial datasets, and contribute directly to SDG 8.3 (Inclusive and sustainable economic growth), SDG 13.2 (Climate action integration) and SDG 15.2 (Sustainable forest management) targets in particular. The concluding vision is one of digital integrity and institutional trust: a region where transparent, blockchain-anchored forestry data enhance environmental governance and elevate the WB6 as a credible, interoperable partner in Europe's climate-neutral and bio-economy transition.

This study demonstrates that blockchain ledger integrity cannot compensate for weak or incomplete origin-verification baselines; without credible, reference-grade forensic data, traceability systems remain administratively useful but legally fragile. Consequently, staged regional laboratory partnerships, shared genetic and isotopic reference libraries and systematic method triangulation emerge as prerequisite investments for achieving judicially admissible, blockchain-enabled FFG in the WB6.

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Conflict of interest

Author TZ was employed by ETIK.AI.

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Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. AI tools were used solely as assistive infrastructure to manage document volume, ensure terminological consistency, and strengthen citation traceability, and were not employed to generate original scientific claims. ChatGPT-5 supported the expansion and refinement of keyword strings, thematic clustering of policy and technology documents, and harmonization of terminology; QuillBot was used to paraphrase and smooth text from institutional sources to maintain stylistic consistency; Rayyan facilitated systematic screening, de-duplication, and eligibility assessment of over 300 documents; and Perplexity was used as a retrieval-based layer to cross-check AI-suggested references against citable primary sources. All AI-assisted outputs were subject to human-in-the-loop validation, no AI-generated text was included without source verification, and analytical and inferential reasoning remained exclusively the responsibility of the authors, thereby preserving methodological integrity while enabling coverage of a broad and rapidly evolving field.

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Glossary

ABS	Access and benefit-sharing
AI	Artificial intelligence
AML	Anti-money laundering
ANs	Accession Numbers
AR	Augmented reality
ASCI	Areas of Special Conservation Interest
ASC	Agricultural supply chain
BiH	Bosnia and Herzegovina
BT	Blockchain technologies
CFT	Countering the financing of terrorism
CGRFA	Commission on Genetic Resources for Food and Agriculture
COC	Chain of custody
cpDNA	Chloroplast DNA
CSOs	Civil society organizations
DBH	Diameter at breast height
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DDBJ	DNA Data Bank of Japan
DLT	Distributed ledger technologies
DSI	Digital Sequence Information
EBSI	European Blockchain Services Infrastructure
ECEs	Emission-controlled enterprises
EDIHs	European Digital Innovation Hubs
ENA	European Nucleotide Archive
EUDR	EU Deforestation-Free Regulation
EUTR	European Union Timber Regulation
EVM	Ethereum Virtual Machine
FASTQ	Fast Quality Format
FCS	Forestry carbon sink
FFG	Forest governance and forensic
FGR	Forest genetic resources
FLEGT	Forest Law Enforcement, Governance and Trade
FSC	Forest Stewardship Council
GDPR	General Data Protection Regulation
GSDDT	Geospatial Sensing and Data-Driven Technologies
GTTN	Global Timber Tracking Network
IBA	Important Bird Area
INSDC	International Nucleotide Sequence Database Collaboration
IPA	Important Plant Area
IPFS	InterPlanetary File System
IRCC	Internationally Recognized Certificate of Compliance
ISM	Interpretive Structural Modeling
IoT	Internet of Things
IWM	Integrated watershed management
MRV	Measurement, reporting and verification systems
NbS	Nature-based solutions
NbT	Nature-based tourism
NFT	Non-Fungible Tokens
nSSRs	Nuclear Simple Sequence Repeats
NAPA	National Agency for Protected Areas
PBA	Prime Butterfly Area
PCR-RFLP	Polymerase Chain Reaction–Restriction Fragment Length Polymorphism
PIM	Power–Interest Matrix
PoA	Proof of Authority
PoET	Proof of Elapsed Time
PoS	Proof of Stake
PoW	Proof of Work
QR	Quick Response
RFID	Radio-Frequency Identification
SDGs	Sustainable Development Goals
SMEs	Small and medium enterprises
SMNP	Sharr Mountains National Park
SNP	Single Nucleotide Polymorphism
SSR	Simple Sequence Repeat
UAV	Unmanned Aerial Vehicle
VASP	Virtual-asset service provider
VCF	Variant Call Format
WB6	Western Balkans 6 region
WTS	Wood Traceability System