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Blockchain as a Tool for Sustainability and Legality in the Timber Trade—A Study in the Context of the EUDR

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Abstract

Blockchain technology (BCT) is often discussed as digital support for timber traceability in the context of the EU Deforestation-Free Products Regulation (EUDR), which requires operators and traders to demonstrate legality, deforestation-free production, geolocation at the forest parcel level, and verifiable supply chain documentation from 30 December 2026, with an extended timeline for micro, small, and medium-sized enterprises (SMEs) until 30 June 2027. This study assesses where BCT can realistically add value in timber supply chains under operational forestry conditions and identifies the necessary technical, organizational, and legal prerequisites. A combination of a targeted literature review and empirical input from experts in the forestry and timber industry, including guided expert web-conferencing interviews ($n = 41$), an online survey ($n = 69$ completed responses), and a transdisciplinary workshop ($n = 18$) was utilized to obtain a comprehensive overview of industry perspectives. Qualitative data from interviews and workshop sessions were analyzed using structured qualitative content analysis, while survey data were evaluated using descriptive statistics. The expected benefits are associated with the introduction of tamper-proof timber harvesting practices and cross-organizational verification mechanisms. To address the discrepancy between biological uncertainty and digital rigidity, the study proposes a dynamic allocation model adapted from the energy sector that distinguishes between fixed and variable wood capacities to automate logistical planning via smart contracts. However, respondents emphasize that practical obstacles, such as limited digital maturity in forestry, fragmented data infrastructures across the supply chain, and unresolved issues of data sovereignty hinder the implementation of BCT. BCT alone is unable to resolve the problem of weak physical-digital identity continuity, a phenomenon widely known as the oracle problem; however, coupling the ledger with physical or biological anchors (e.g., photo-optical, automated inkjet marking identification) can re-establish this physical–digital continuity and thereby resolve the oracle problem. The results demonstrate that blockchain acts most plausibly as a supporting component within hybrid traceability architectures that prioritize event-based authentication, off-chain data processing where appropriate, and integration with existing certification systems. The study highlights the necessity of defining distinct organizational roles and responsibilities while integrating user-centric digital solutions tailored specifically to small and medium-sized enterprises (SMEs).



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conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.**Keywords:** timber supply chain; blockchain; traceability; forestry; EUDR

1. Introduction

Transparent timber supply chains are crucial for sustainable forest management and biodiversity protection. However, international timber flows remain susceptible to illegal logging, fraud, and information asymmetries. This environment is complicated by the diverse array of actors involved, varying cross-border regulatory systems, and the inherently fragmented structure of global supply chains [1–3]. To address these challenges, the European Union Deforestation Regulation (EUDR; Regulation (EU) 2023/1115) enforces strict due diligence and traceability mandates. These mandated disclosures include geolocated harvest plots, verifiable links to product origins, and robust evidence of compliance. Based on the officially adopted implementation schedule, the EUDR requirements apply from 30 December 2026 for large operators, whereas micro, small, and medium-sized enterprises (SMEs) are granted an extended timeline until 30 June 2027 [3–5]. Various identification and documentation approaches are already in use in forestry and timber logistics, including paint and hammer marks, barcodes, geolocation-based documentation, genetic analysis, RFID tagging, and laboratory verification [6]. These approaches address some aspects of traceability, but there are further limitations, especially in terms of interoperability between organizations, variable data quality, and variations in digital maturity within the operational forest environment. Additionally, there are concerns about data privacy and the protection of trade secrets [7,8].

In this context, the proposal of blockchain technology (BCT) as the basis for traceability is driven by the opportunity for cross-party verification across the entire timber supply chain [9,10]. However, it is important to understand that blockchain technology does not tackle issues related to data provenance or governance gaps. The system's effectiveness depends on the design decisions made. These include the events recorded, the data excluded from the blockchain, the actors validating entries, and how the system integrates with existing certification systems (e.g., PEFC and FSC) and GIS/IoT-enabled data collection. Without standardized data and coordinated governance, BCT risks making things more complex without achieving reliable improvements in transparency [11,12].

This study analyzes the potential of blockchain technology to add value to timber supply chains within the framework of European regulations, examining the technical, organizational, and legal requirements necessary for its implementation in the forestry sector [13]. To address these gaps and systematically incorporate insights from foresters and industry stakeholders, this study targets three interconnected research questions:

- RQ1: What are the operational potentials and socio-technical barriers of implementing BCT within timber supply chains under realistic forestry conditions?
- RQ2: How can BCT systematically interface with existing certification schemes and legal frameworks (specifically the EUDR) to ensure data integrity and mitigate the physical-digital oracle problem?
- RQ3: What socio-economic and governance prerequisites are required to ensure equitable and widespread technology adoption among fragmented forestry stakeholders?

Consequently, the focus of this work is on the operational feasibility of BCT in forestry and its suitability for the timber industry. Rather than viewing blockchain as a standalone, intrinsic solution, it is conceptualized as one component within a broader socio-technical system that encompasses physical identification technologies, standardized data schemas, governance rules, and regulatory integration. The core contribution consists of clarifying the conditions under which blockchain can credibly improve timber supply chain transparency under the EUDR, and identifying the practical requirements enabling an interoperable, practice-oriented implementation.

To substantiate the analysis of these adoption barriers, this study draws upon the Technology Acceptance Model (TAM) proposed by Davis [1]. TAM posits that the intention to adopt a new technology is primarily determined by two core factors: perceived usefulness (the extent to which a user believes the technology will enhance their job performance) and perceived ease of use (the degree to which the system is perceived as user-friendly) [14]. Within the forestry sector, which is characterized by highly heterogeneous digital maturity, this model offers a robust framework to distinguish between the regulatory necessity of blockchain (usefulness regarding EUDR compliance) and the operational friction of its field implementation (ease of use).

2. Materials and Methods

This study adopts a sequential mixed-methods research design (Figure 1) to evaluate the operational feasibility, constraints, and governance prerequisites of blockchain technology (BCT) for timber traceability under the EU Deforestation-Free Products Regulation (EUDR). To ensure a robust, triangulated analysis, quantitative trends derived from a broad industry-wide online survey were utilized to inform, contextualize, and refine the focus areas of a subsequent transdisciplinary, consensus-building expert workshop. This overarching empirical framework was structurally anchored by 41 in-depth, guideline-based expert interviews conducted across German-speaking Europe. By integrating qualitative depth with quantitative validation, this multi-stage approach systematically balances subjective stakeholder perspectives against broader industry indicators to derive scalable policy and technological recommendations.

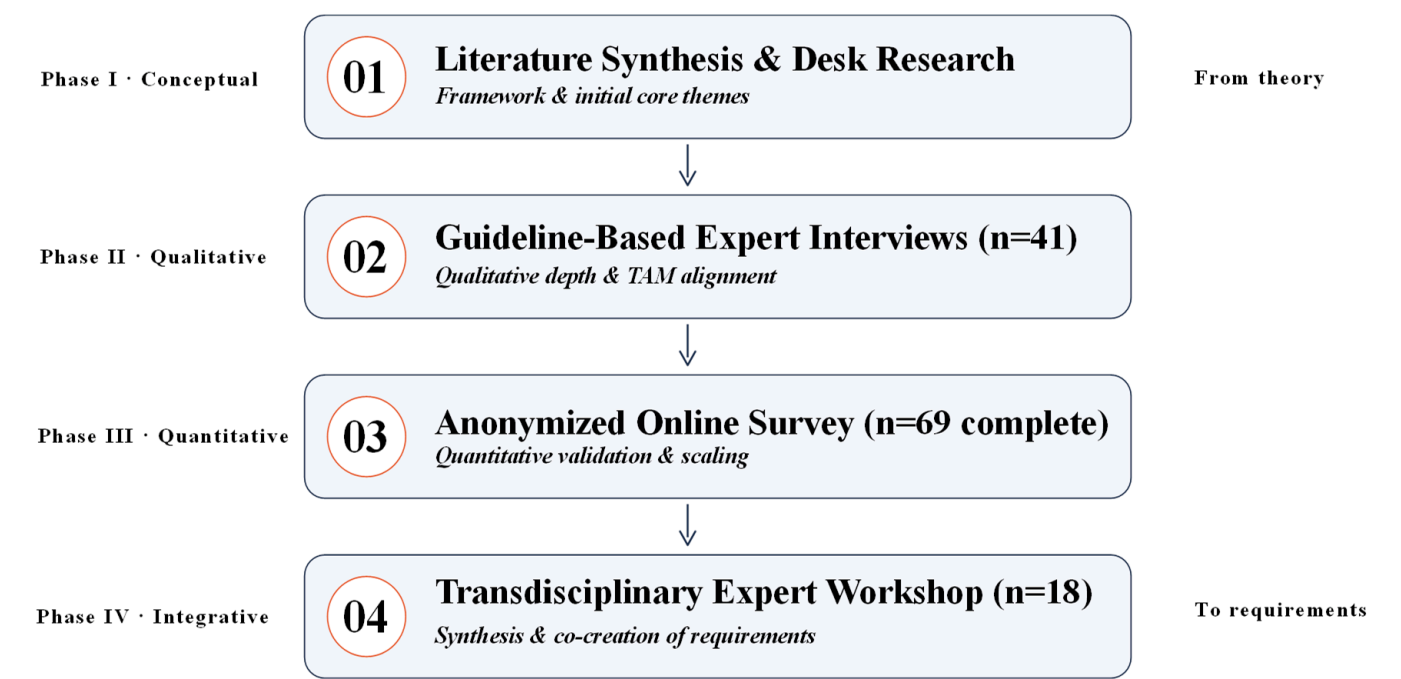


Figure 1. A four-phase mixed-methods design integrating qualitative depth, quantitative validation, and transdisciplinary synthesis.

2.1. Multi-Method Analysis and Ethical Data Governance

Building upon the conceptual foundation of a prior systematic literature review [13], this study employs an integrated multi-phase empirical framework. Each component was developed with a distinct functional objective to achieve comprehensive methodological triangulation:

1. Literature-Based Synthesis and Secondary Research: This initial stage established the core theoretical framework, mapped current technological capabilities, and identified critical research gaps regarding BCT applications in forestry logistics. The outputs directly informed the design of subsequent empirical instruments [15].
2. Guideline-Based Expert Interviews: This qualitative phase was designed to capture granular operational insights from key supply chain actors and identify localized practical hurdles to blockchain implementation across Germany, Austria, and Switzerland.
3. Anonymized Online Survey: This quantitative component served to validate the preliminary findings from the interview phase across a larger sample size and evaluate broader industry-wide consensus on the identified digital transformation trends.
4. Transdisciplinary Expert Workshop: This final collaborative phase enabled direct dialogue between cross-sectoral stakeholders, facilitating the co-creation of governance requirements and the collective synthesis of multi-perspective recommendations.

To systematically synthesize these components, the outputs of each phase served as direct analytical inputs for the next. Data collection and processing were governed by strict ethical standards and data ownership principles. No personal identifiers beyond necessary professional and organizational classifications were processed. All qualitative interactions were handled to preserve participant anonymity, informed consent was formally obtained from all respondents prior to data collection, and all data management protocols strictly complied with the European Union General Data Protection Regulation (GDPR).

2.2. Literature-Based Synthesis and Desk Research

A targeted literature review and secondary desk research were executed to systematically map contemporary scientific and grey literature concerning blockchain architectures, supply chain traceability, and digital forestry ecosystems. The screening process synthesized established domain reviews [6,15,16] to accomplish three primary goals: (i) characterize systemic challenges and architectural design choices in blockchain-supported tracking, (ii) define a baseline catalog of socio-technical prerequisites, and (iii) establish empirical core themes for subsequent field research.

The preliminary structural tools were designed through a multi-stage process based on these synthesis insights. Guideline items and survey prompts were drafted and iteratively refined within the research consortium using the digital collaboration platform Miro (miro.com). To ensure empirical standardization and enable future replication, these items were structured into formalized instruments (standardized interview guides and structured survey matrices) prior to deployment. This output provided an analytical anchor, ensuring that the empirical data collected in later stages could be directly triangulated against the state-of-the-art literature.

2.3. Guideline-Based Expert Interview and Qualitative Content Analysis

A purposive sampling approach was utilized to establish a candidate pool of 108 high-level experts and pivotal institutional actors within the central European timber value chain. Candidates were selected from the established professional networks and stakeholder databases of the participating research partners based on their direct operational engagement with timber logistics, certification, or EUDR compliance strategies. Out of this initial cohort, 41 experts self-selected to participate in the qualitative interview phase, ensuring a highly motivated sample with specialized technical and regulatory authority. This sample size was deemed methodologically sufficient as data saturation (thematic redundancy) was demonstrably achieved within the final iterations.

The interview cohort comprised 41 professionals stratified across seven distinct stakeholder categories to capture a comprehensive cross-section of the industry: forest owners ($n = 8$), foresters ($n = 5$), forest operating companies ($n = 2$), timber logistics providers ($n = 2$), timber processing and sawmill companies ($n = 6$), forest service firms ($n = 10$), and representatives from industry associations, research organizations, or scientific institutions ($n = 7$).

To maximize methodological transparency, data collection was standardized across a team of five trained researchers. The semi-structured interviews were conducted remotely via secure web-conferencing software or telephone, with selected sessions carried out in person. All sessions were audio-recorded and subsequently transcribed manually to ensure verbatim data precision. The total dataset encompassed interview durations ranging from 11 min to 1 h and 39 min, yielding a mean interview length of 43 min. To protect participant privacy, individual demographic identifiers such as exact age or specific corporate identities were fully omitted from the transcripts.

The qualitative text corpus was analyzed using Structured Qualitative Content Analysis [17]. This systematic, rule-guided framework combines deductive, theory-driven main categories derived from the literature with inductive, data-driven subcategories that emerged directly from the text. To minimize individual researcher bias and ensure analytical reliability, three independent researchers executed the multi-stage coding process; any coding discrepancies or boundary ambiguities were iteratively resolved through collaborative consensus-building discussions until a final, unified categorization was achieved. Coded segments were compiled into an aggregated coding dictionary and qualitatively ranked across five core thematic areas, structurally aligned with the constructs of the Technology Acceptance Model (TAM): (a) tracking mechanism and automated data capture, (b) economic and operational incentives, (c) legal and regulatory considerations, (d) forest certification integration, and (e) macro-level digital readiness.

2.4. Online Survey

To scale and statistically validate the qualitative insights gathered from the expert interviews, a quantitative online survey was deployed between 19 September and 23 October 2023. The survey items were designed to map onto the TAM constructs, operationalizing ‘perceived usefulness’ via regulatory compliance capabilities and ‘perceived ease of use’ via technological integration barriers. The survey was hosted securely on LimeSurvey (limesurvey.org) and utilized diversified item formats, including semantic differentials, Likert scales, ordinal rankings, and open-ended text fields.

Targeted recruitment utilized a multi-channel outreach strategy: the survey was formally promoted at two primary scientific venues: the Forstwissenschaftliche Tagung (FowiTa 2023) in Dresden, Germany, and the International Symposium on Forest Mechanization (FORMEC 2023) in Florence, Italy. This was supplemented by digital dissemination via institutional websites, professional social media channels, and 559 direct, targeted email invitations sent to industry stakeholders.

A total of 100 responses were logged, from which 69 fully completed questionnaires were secured. In alignment with established statistical protocols for exploratory survey research, partially completed responses were retained and analyzed up to the specific point of respondent dropout [18]. To prevent distortion, statistical analyses utilized pairwise deletion on an item-by-item basis for missing values, and no artificial data imputations were performed. Within the total sample, forest owners constituted the largest participating group (22%; $n = 22$), followed closely by foresters (20%; $n = 20$). The remaining sample consisted of research and academic staff (15%; $n = 15$), sawmill industry representatives (11%; $n = 11$), political delegates and association officers (8%; $n = 8$), logging contractors

(6%; $n = 6$), timber logistics operators (3%; $n = 3$), unclassified corporate entities (7%; $n = 7$), and miscellaneous stakeholders (8%; $n = 8$). Demographic age distribution was stratified as follows: <30 years (14%; $n = 14$), 30–49 years (41%; $n = 41$), 50–69 years (38%; $n = 38$), and >70 years (1%; $n = 1$). A marginal dropout rate of 5% was observed at the demographic classification section, while 1% of respondents elected not to disclose their age [18].

2.5. Expert Workshop

A transdisciplinary online expert workshop was convened on 2 November 2023, featuring $n = 18$ purposively selected participants. The core objective was to collectively evaluate the socio-technical impacts of digitalization within the forest-wood value chain, identify systemic innovation potentials, and co-design actionable operational recommendations. To capture a holistic view of the regulatory-operational interface, the panel blended high-level scientific expertise with field authority, drawing participants from academic institutions, private industry, public forestry administrations, and environmental non-governmental organizations (NGOs).

The collaborative session followed a consensus-building expert workshop with an iterative, two-stage co-creation and polling process around five core pillars: digitalization, sustainability, legal issues, certification frameworks, and tracking/tracing capabilities.

- Round 1 (Qualitative Co-Creation): Guided group discussions were conducted to gather qualitative perspectives on technological entry barriers and governance configurations. These collaborative inputs were captured in real time on a shared digital whiteboard (Miro), subsequently exported, and subjected to thematic matrix coding.
- Round 2 (Quantitative Evaluation): Participants anonymously evaluated the specific socio-technical potential and feasibility of BCT within each core pillar using digital polling software (Mentimeter.com) via a five-point Likert scale.

The quantitative workshop data were exported and evaluated using descriptive statistics, defining group consensus as an interquartile range of $IQR \leq 1.0$. Divergent positions and polarized rankings were intentionally preserved in the final analysis to transparently reflect conflicting stakeholder interests and structural asymmetries across the supply chain. Ultimately, the workshop functioned as an integrative layer of analysis, serving to validate, challenge, and contextualize the empirical datasets derived from the prior research phases. By systematically contrasting the qualitative depth of the individual interviews, the statistical breadth of the online survey, and the consensus-driven synthesis of the expert workshop, this integrated, multi-method methodology achieves a highly rigorous, triangulated assessment of blockchain readiness in the EUDR context.

3. Results

Based on the initial qualitative phase of the study, a comprehensive synthesis of core issues was executed to map stakeholder perceptions across five macro-thematic dimensions: digitalization, sustainability, legal issues, certification frameworks, and tracking and tracing capabilities. The five core themes extracted from the structured qualitative content analysis of the expert interviews are compiled and classified in Table 1. This thematic matrix served as the empirical foundation for operationalizing and scaling the subsequent items within the quantitative industry-wide online survey.

Table 1. Top 5 list of issues [15,16,18].

	Digitalization	Sustainability	Legal Issues	Certification	Tracking & Tracing
Core Topics and Empirical Synthesis	Structural demand for digital maturity to optimize supply chain sustainability and resource efficiency.	Dominance of economic sustainability metrics and financial feasibility interests among commercial actors.	Stricter due diligence and supply chain verification obligations driven by evolving regulatory mandates (e.g., EUDR).	Evaluation of carbon certificate markets as a viable long-term economic model for the forestry sector.	Yield optimization and supply chain loss reduction through continuous tracking and tracing protocols.
	Systemic operational hurdles concerning primary data collection and non-standardized software interfaces.	Addressing acute socio-economic constraints, including skilled labor shortages, through automated systems.	Critical requirement for standardized legal-technical frameworks and automated contract processing.	Enhanced certification accuracy and auditing efficiency enabled by real-time primary data availability.	Requirement that monetary and operational benefits of tracking systems remain proportionate to implementation costs.
	Variable penetration of digital data capture technologies in active field operations.	Emerging interest in digital platform architectures for forest ecosystem services (FES) and carbon compensation.	Regulatory friction regarding national calibration laws, standardized wood measurement protocols, and digital signatures.	Structural integration challenges within established certification frameworks (FSC/PEFC).	Coexistence of established tracking methods with a clear operational demand for secure, tamper-evident databases.
	Polarized stakeholder expectations regarding the absolute operational added value of blockchain deployments	Technical optimization of harvesting and logistics to achieve higher macro-level energy efficiency.	High priority placed on data confidentiality, antitrust compliance, and the protection of proprietary corporate records.	Market entry barriers driven by the absence of financial premiums for certified timber products.	Identification of a systemic data availability gap for carbon-accounting and provenance-verification applications.
	Pervasive deficits in baseline digital literacy and standardized cross-regional software programs	Ecological monitoring via digital forest inventories and continuous auditing of harvesting vs. reforestation rates.	Demand for state-backed incentives, clear regulatory boundaries, and public data infrastructure support.	Deployment of digital mobile logging applications containing integrated, verifiable certification credentials.	Operational exploration of advanced tracking models (e.g., genetic tracing, photo-optical log stack measurements).

3.1. Digitalization

Expert consensus strongly characterized advanced digital maturity as a non-negotiable socio-technical prerequisite for the operational deployment of blockchain-supported traceability architectures. However, empirical triangulation between the qualitative interviews and quantitative survey metrics revealed an asymmetric distribution of digital readiness across the central European forest-wood value chain, with analogue routines ('pen and paper') persisting in upstream forestry operations. This technological friction represents a critical operational constraint: the theoretical benefits of BCT, such as tamper-evident logging event registration and immutable cross-party verification, are strictly contingent upon the primary availability of high-fidelity digital data and standardized, interoperable machine-to-machine interfaces.

Quantitative survey data regarding the perceived usefulness of BCT reflected high polarization among industry actors. Within the structured qualitative coding of open-ended survey text fields, the subcategories 'Blockchain provides a distinct operational advantage' ($n = 15$) and 'Blockchain provides no discernible advantage' ($n = 14$) received statistically equivalent frequencies, underscoring divergent paradigm expectations within the sector (Table 2) [18].

To contextualize these qualitative statements, the survey included items on the current state of digitalization and its perceived effects. Respondents rated three items on a 1 ('very good') to 6 ('very bad') scale (Figure 2): Status Quo (Q1): Most stakeholders consider the current level of digitalization in their work environment as satisfactory ($\bar{x} = 3.27$; $n = 84$). Efficiency (Q2): Digitalization is seen as a significant driver of efficiency, receiving the most positive rating in this section $\bar{x} = 2.19$; $n = 80$). Feasibility (Q3): The feasibility of

implementing digital data capture processes with upstream and downstream partners is also rated as satisfactory with a tendency toward ‘good’ ($\bar{x} = 2.73$; $n = 79$). The fourth question (Q4) shifted the scale to measure intensity, where one represented ‘very low’ and 6 ‘very high’. Regarding the willingness to invest in necessary software, hardware, and data management, the companies showed a moderate to high tendency ($\bar{x} = 3.71$; $n = 69$).

Table 2. Qualitative Analysis of the topic of Digitalization [18].

Rank	Frequency (<i>n</i>)	Core Theme/Category
1	31	Demand for digitalization to increase sustainability and operational efficiency
2	20	Operational challenges in primary data acquisition and interface interoperability
3	15	Active field application of digital data collection protocols
4	15	Perception of blockchain as a distinct technological advantage
5	14	Perception of blockchain as providing no discernible advantage
6	14	Documented operational benefits of contemporary digital systems
7	11	Imperative for comprehensive standardization across software programs
8	9	Perception of baseline digitalization as critically low within specific sectors
9	8	Requirement for clear added-value creation through digital transformation
10	5	Operational necessity of public data availability and open access infrastructure

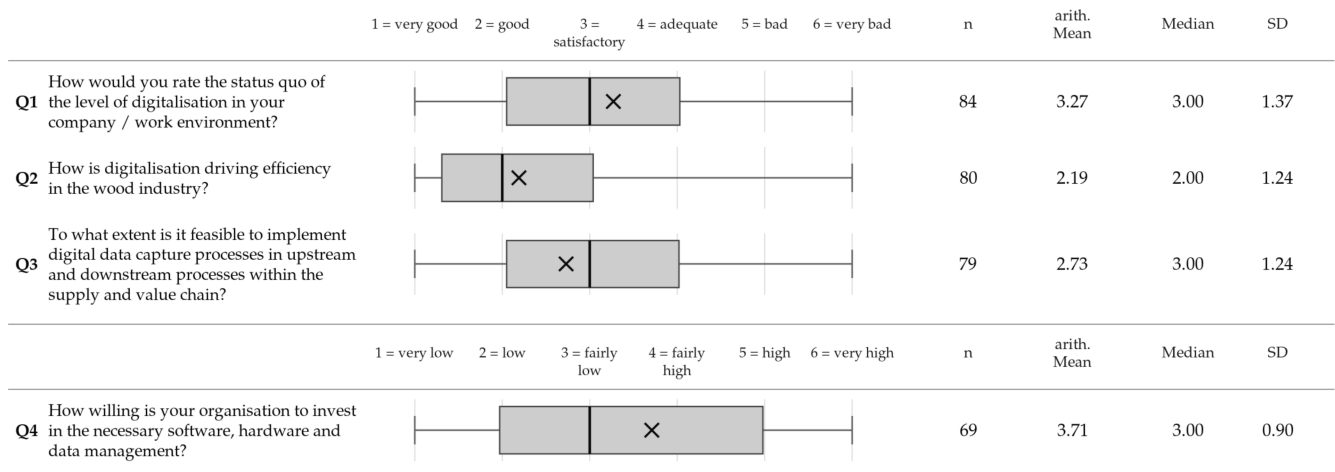


Figure 2. Results of questions on Digitalization (different scales).

3.2. Sustainability

Respondents evaluated the contemporary sustainability performance of the central European forestry sector across economic, environmental, and social dimensions using a standardized 5-point Likert scale (where 1 = ‘highly favorable’ and 5 = ‘highly unfavorable’) (Figure 3). Descriptive statistical analysis revealed an overall positive baseline assessment across all three pillars. The economic dimension was evaluated most favorably ($\bar{x} = 2.13$; $n = 78$), followed by the environmental ($\bar{x} = 2.22$; $n = 76$) and social dimension ($\bar{x} = 2.40$; $n = 78$). Several high scores (e.g., 5 in Q3) occurred across dimensions, indicating divergent views among respondents. Skill shortages and the extent to which digitalization can address them received a more moderate evaluation ($\bar{x} = 2.92$; $n = 77$), again reflecting variation in responses. Regarding ecosystem services, most respondents supported the idea of a platform spanning forest types, although no detailed design preferences were elicited in the survey. In the ranking task, the top priorities were water, fresh air, and CO₂ sink.

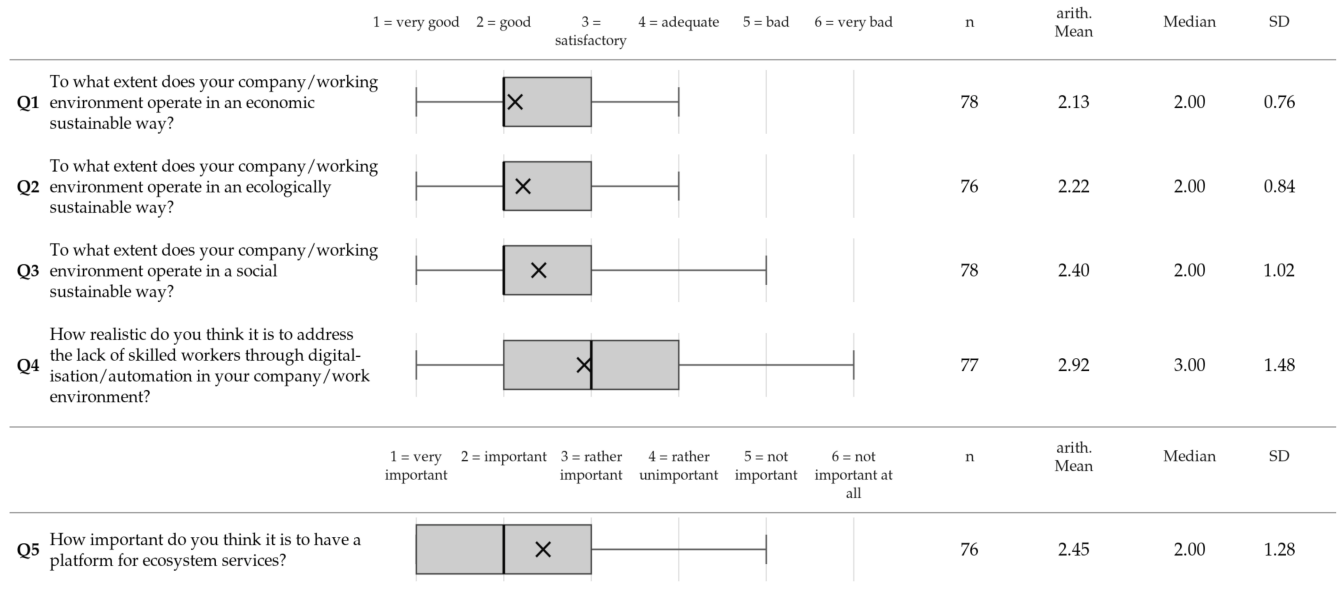


Figure 3. Results of questions on Sustainability (different scales).

To determine stakeholder priorities within such a platform, an ordinal ranking task was executed and evaluated via cumulative grade scores (where lower cumulative scores indicate higher priority). The protection and provisioning of water resources was identified as the highest stakeholder priority (cumulative rank score = 146), followed by fresh air provisioning (179) and the optimization of forests as carbon sequestration sinks (199; Table 3).

Table 3. Cumulative Ordinal Ranking of Forest Ecosystem Services (FES) for Platform Integration [18].

Rank	Ecosystem Service Dimension	Cumulative Score (Grades Totaled)
1	Water	146
2	Fresh air	179
3	CO ₂ sink	199
4	Habitat	232
5	Erosion control	264
6	Other	308
7	Recreation	324

A substantial divergence was observed regarding the operational integration of carbon footprint tracking and formalized life cycle assessments (LCAs). While a majority of 61% of the sample acknowledged the strategic macro-level significance of carbon metrics, 39% rejected their operational necessity. Qualitative interview records indicate that these reservations are primarily associated with the energy consumption profiles of continuous blockchain validation protocols and the potential administrative burden of auditing energy use across fragmented supply chain tiers.

3.3. Certification

Certification-related items produced mixed responses within the online survey. For the perceived relevance of certification for market access and product quality, responses were split: 35% indicated an effect on market access, whereas a similar share indicated no effect on product quality, and 27% reported uncertainty.

Further, respondents rated the economic importance of FSC/PEFC certification in Figure 4 as moderately important ($\bar{x} = 3.08$; $n = 66$). Views on dynamic forest inventories were mixed; pre-grading of roundwood was rated as comparatively informative ($\bar{x} = 3.12$; $n = 60$). Regional procurement and environmental measures received strong support ($\bar{x} = 2.76$; $n = 73$).

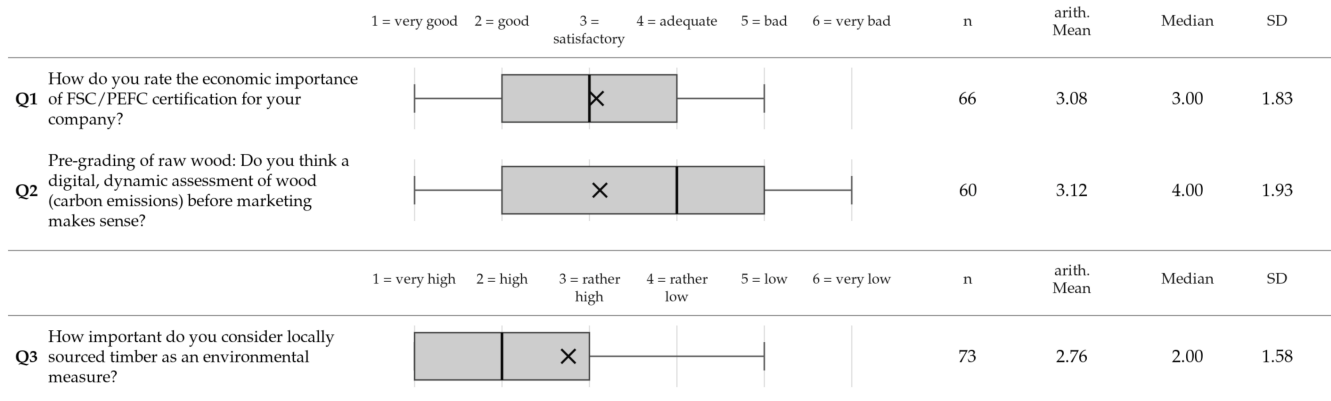


Figure 4. Results of question 1–3 on blockchain technology for certification (different scales).

By contrast, attitudes towards blockchain-supported CO₂ certificate trading were skeptical: 43% saw no value, 33% saw potential, and 21% were unsure. Consistent with this, only 19% reported having suitable data for carbon marketing, while 75% expressed uncertainty or indicated insufficient data. Together, these results point to a perceived data availability gap for carbon-related applications.

For seed traceability, responses were again divided: 35% did not see added value for their organization, 33% were unsure, and 28% saw added value. As this survey sample was dominated by forestry and timber stakeholders, application-specific relevance may differ for other actor groups (e.g., nurseries), which should be considered when interpreting these results.

3.4. Legal Regulations

Survey responses indicate uncertainty about whether legal regulation effectively promotes transparency in sustainable supply chains: 35% supported such regulation, 32% opposed it, and 32% were unsure. Respondents rated standards for timber purchasing as important (Figure 5). Confidentiality of business relationships and data protection were also rated as important ($\bar{x} = 1.82$; $n = 73$).

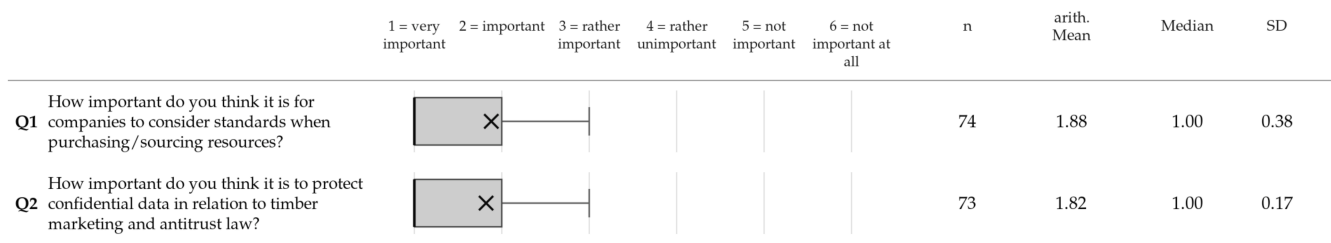


Figure 5. Results of question 1 and 2 on legal regulations.

When asked whether blockchain could improve transparency while supporting data protection, 51% indicated uncertainty, 34% indicated potential, and 11% considered it unsuitable. Similar patterns emerged for the suitability of blockchain for automated and legally secure contract processing: 60% were uncertain, 29% indicated suitability, and

11% indicated unsuitability. These distributions suggest that legal-technical use cases are perceived as plausible by a subset of respondents, but that uncertainty dominates, reflecting limited operational experience and unclear expectations regarding legal recognition of records and responsibilities.

3.5. Tracking & Tracing

Tracking and tracing are already used in practice, including within chain-of-custody certification schemes [19]. Respondents rated the need for traceability along the timber supply chain as relatively high ($\bar{x} = 3.27$; $n = 66$), with a wide dispersion across response categories (Figure 6). The perceived value of confidential traceability was similar ($\bar{x} = 3.24$; $n = 67$), while interest in new traceability methods was lower ($\bar{x} = 2.76$; $n = 66$). Respondents also expressed a need for a confidential and secure database along the supply chain ($\bar{x} = 2.94$; $n = 65$).

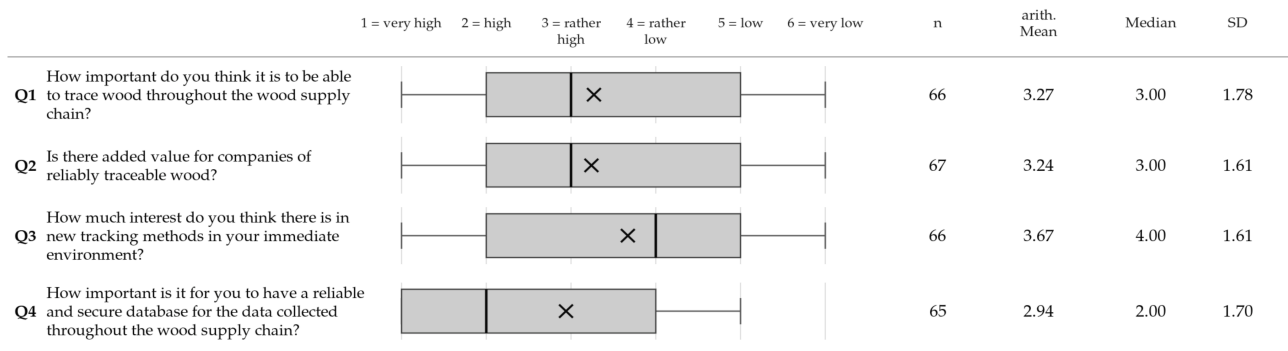


Figure 6. Answers to questions 1 to 4 on tracking & tracing.

When asked about transparency, almost half of respondents (49%) said they would welcome more transparency based on their work experience, while 23% did not, 25% were unsure, and 3% did not answer. Views on the economic benefits of tracking and tracing were similarly mixed: 31% expected financial gains, 32% did not, 33% were unsure, and 4% provided no response.

Regarding currently used tracking approaches, the most frequently reported were logical order with geodata ($n = 32$), color marks ($n = 31$), QR codes ($n = 18$), and photo-optical log stack measurement/documentation ($n = 17$), with multiple responses allowed (Table 4). Fingerprint and DNA analysis were reported rarely or not at all.

Table 4. Currently used tracking technologies (multiple responses allowed) [18].

Rank	Tracking Technology/Method (Multiple Responses Allowed)	Frequency (n)
1	Logical with geodata	32
2	Color	31
3	QR Codes	18
4	Photo-optical	17
5	Logical from machine data	13
6	Barcode	10
7	None	10
8	RFID chip	8
9	Punching/scoring	3
10	Other	2
11	Fingerprint	1
12	DNA analysis	0

On preferred proof of origin for digital traceability, respondents most frequently selected the forest stand ($n = 28$), followed by log stack ($n = 19$), single log ($n = 8$), and truck load ($n = 5$) (Table 5).

Table 5. Responses on preferred proof of origin for timber tracing [18].

Rank	Resolution Level for Digital Timber Traceability	Frequency (n)
1	Forest Stand	28
2	Log Stack	19
3	Single Log	8
4	Truck Load	5
5	No Answer	6
6	Other	3

Finally, the perceived potential of blockchain for wood origin certification was rated as satisfactory ($\bar{x} = 2.77$). In open responses, support was typically linked to improved documentation and verification, whereas reservations referred to investment requirements, operational complexity, and the need for reliable digital data capture.

4. Discussion

The implementation of blockchain technology (BCT) in forestry is not an isolated IT solution, but rather a complex socio-technical challenge. The empirical results illustrate that while this technology can function as a digital anchor of trust, its practical success is inextricably linked to the digital maturity of the entire supply chain, the operational constraints of the forest environment, and the evolving regulatory landscape.

To systematically evaluate the empirical findings, the five thematic dimensions identified during the expert consultations—sustainability, digitalization, certification, legal regulations, and tracking & tracing are synthesized and mapped directly onto the study’s three core research questions. Section 4.1 addresses RQ1 by merging the socio-technical challenges of digitalization with operational tracking and tracing barriers. Section 4.2 answers RQ2 by exploring the interfaces between regulatory EUDR mandates, existing certification schemes, and the physical-digital oracle problem. Finally, Section 4.3 addresses RQ3 by contextualizing stakeholder expectations regarding sustainability, long-term governance, and capacity allocation through the lens of the Technology Acceptance Model (TAM).

4.1. Operational Feasibility, Digital Maturity, and Socio-Technical Barriers (RQ1)

Regarding the practical field conditions of the forestry sector, the reluctance or willingness of stakeholders to adopt new digital tracking tools can be comprehensively explained by the Technology Acceptance Model (TAM) [14]. The empirical insights reveal a significant divergence between perceived usefulness and perceived ease of use. While the perceived usefulness of BCT is exceptionally high due to mounting regulatory pressure, its perceived ease of use is severely constrained by the sector’s traditional, analog field operations and heterogeneous infrastructure. Stakeholders predominantly view BCT as an additional cognitive and administrative burden rather than an operational optimization tool. This socio-technical friction is exacerbated by low digital maturity at the initial stages of the supply chain. Field operations in forestry regularly occur in remote areas lacking stable network connectivity, meaning rigid requirements for synchronous, real-time on-chain validation would inevitably result in severe logistical bottlenecks. Furthermore, the strategic value of BCT in realistic forestry environments lies less in unconditional transparency and more in providing compliance-relevant documentation through selective, verifiable evidence without compromising commercial confidentiality. In summary for RQ1, stakeholders perceive

BCT as potentially useful for securing data integrity and enabling shared verification, but its operational feasibility remains heavily conditioned by infrastructure deficits, analog workflows, and data privacy concerns. Disaggregating these attitudes by stakeholder role and baseline digital maturity helps locate the likely early adopters. The observed polarization was not uniform across the sample: actors at the industrial and institutional end of the value chain (sawmill and timber-processing companies, research and academic institutions, and certification or association bodies) combine comparatively high baseline digitalization with the strongest regulatory exposure under the EUDR, and therefore represent the most probable first movers. By contrast, the large and fragmented population of small private forest owners, whose operations still rely heavily on analog pen-and-paper workflows and who report the lowest digital maturity, constitute the principal adoption laggards. A rollout strategy should accordingly be tiered: pilots and interoperability standards can be seeded with digitally mature downstream and institutional actors, while smallholders are onboarded through cooperative data aggregators and user-centric, low-barrier mobile interfaces rather than through any requirement to operate ledger infrastructure directly. (These groupings are inferred qualitatively from the study's sample composition and the reported polarization; a formal cross-tabulation by role was beyond the present dataset.)

4.2. Regulatory Compliance, Certification Interfaces, and the Oracle Problem (RQ2)

In the context of European legal frameworks, stakeholders primarily evaluate BCT as a mechanism for ensuring data integrity under the strict mandates of the EU Deforestation Regulation (EUDR). Because the EUDR enforces maximum traceability down to geolocated harvest plots, it compels the industry to establish tamper-proof data chains. However, this study identifies the physical-digital 'oracle problem' (Garbage In, Garbage Out) as the most critical technical hurdle to ensuring this regulatory compliance [20]. While BCT mathematically guarantees data immutability after a transaction is recorded, it does not inherently protect against erroneous or fraudulent primary data captured at the forest plot level. This vulnerability reflects the classic 'Garbage In, Garbage Out' dilemma, as illustrated in the conceptual model of a Forest Anchored Blockchain (Figure 7).

Forest Anchored Blockchain

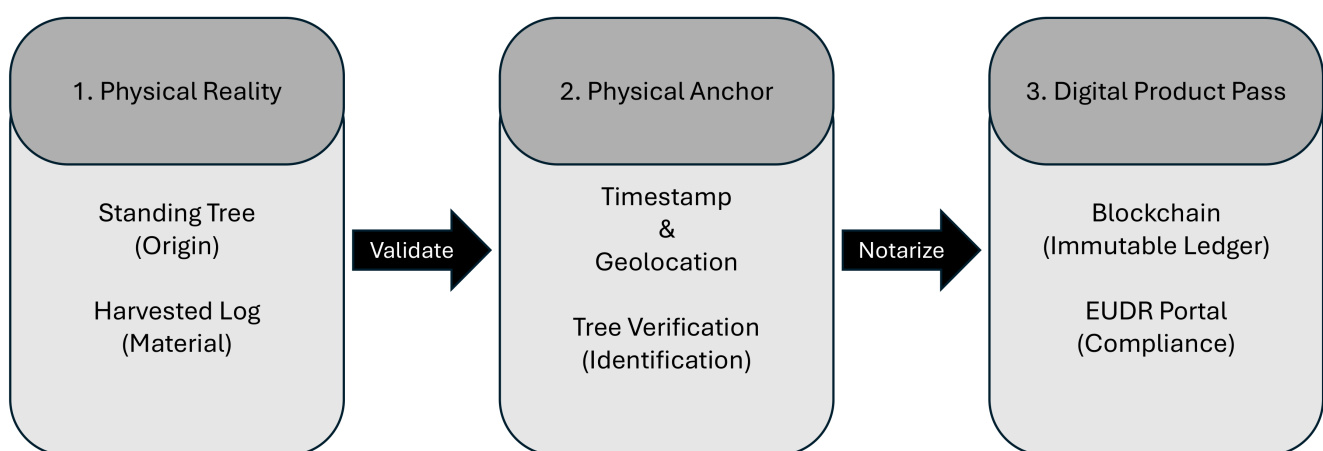


Figure 7. Conceptual model of a Forest Anchored Blockchain.

Consequently, digital transparency within a ledger remains incomplete without a reliable physical anchor. To mitigate the oracle problem, future blockchain implementations must be systematically linked with physical and biological verification methods, such as automated marking, ruggedized barcodes, RFID tagging, or genetic and laboratory analysis [6] to physically secure the link between the physical timber asset and its digital twin.

Notably, these physical anchors are currently the least used technologies in the surveyed practice: geodata-based logical ordering ($n = 32$) and color marks ($n = 31$) dominate, whereas RFID ($n = 8$), photo-optical measurement, fingerprinting ($n = 1$) and DNA analysis ($n = 0$) remain marginal (Table 4). This exposes a critical gap: the low-cost identifiers that stakeholders use establish logical order but do not cryptographically bind a physical asset to its digital record, whereas the anchoring technologies capable of resolving the oracle problem are precisely those with the lowest current adoption. Closing this gap is therefore less a question of technical availability than of adoption barriers such as cost and standardization and should be treated as a priority for future piloting rather than as established practice. A comparable physical-binding problem has been operationalized in the pharmaceutical sector through blockchain-and-IoT track-and-trace architectures.

Furthermore, to avoid creating isolated digital silos, BCT systems must establish seamless interoperability with existing third-party certification schemes (e.g., PEFC and FSC) and official regulatory registers. This requires the development of standardized APIs that communicate directly with the official EUDR information system, thereby eliminating administrative duplication and ensuring that cross-party verification is achieved without increasing technical fragmentation.

4.3. Socio-Economic Governance, Long-Term Lifecycles, and Capacity Models (RQ3)

Addressing the socio-economic and governance prerequisites for widespread adoption (RQ3) requires reconciling a fundamental temporal discrepancy: the conflict between biological rotation periods and digital lifecycles. In contrast to agriculture, where production cycles are measured in months [21], forestry operates across generations. While software standards, cryptographic algorithms, and hardware interfaces typically face obsolescence within a decade, forest data must remain accessible, immutable, and semantically readable for over half a century [22].

To cope with this timeline, a Forest Anchored Blockchain must fulfill dual functionality, operating simultaneously as an active transaction protocol and a generational long-term memory. A digital twin created at the seedling or planting stage today must remain securely readable by downstream processing systems many decades into the future, requiring architecture designs that prioritize long-term interoperability over short-term functional diversity.

Moreover, long-term biological production is regularly disrupted by short-term ecological crises, such as windthrows or bark beetle infestations, which demand the immediate processing of vast data volumes under adverse conditions. To maintain operational continuity during such calamities while ensuring ‘digital sustainability’, the deployment of a hybrid architecture approach is essential [23]. As conceptually detailed in the physical-digital continuity framework (Figure 8), operational data from GIS or IoT systems should be kept off-chain, utilizing the blockchain ledger selectively to notarize critical custody transfer points.

This layout enables asynchronous, offline-first data logging that can synchronize with the ledger once field crises subside. This approach also prevents energy-intensive consensus mechanisms (e.g., Proof-of-Work) in favor of energy-efficient alternatives like Proof-of-Stake (PoS) or private, permissioned architectures, ensuring the IT infrastructure does not counteract the ecological objectives of forest conservation [24].

Beyond the choice of consensus family, concrete deployment terms matter: this architecture favors a permissioned consortium topology rather than a public, open-membership network. Validating full nodes would be operated by a limited set of institutional stakeholders like certification bodies (FSC and PEFC), forest administrations, industry associations and larger sawmills, while forest owners and harvester crews interact through light clients and mobile applications that submit cryptographically signed transactions without hosting the ledger. Only a minimal, tamper-evident layer should reside on-chain: hashes of custody-transfer events, notarized proofs, token state and smart-contract logic, whereas high-volume operational data such as GIS geometries, IoT sensor streams and raw HPR/StanForD files remain off-chain, bound to the ledger by cryptographic reference. In such a permissioned setting, energy-intensive Proof-of-Work is neither necessary nor appropriate; Byzantine-fault-tolerant consensus (e.g., Practical Byzantine Fault Tolerance, PBFT) or Proof-of-Authority, in which known and accountable validators finalize blocks, delivers deterministic finality, low latency and negligible energy cost, with Proof-of-Stake as an option where a broader validator set is desirable (Figure 9). Emerging problem-solving consensus variants were also considered but remain immature for regulatory-grade custody tracking and are therefore not recommended in this setting.

Hybrid Architecture & Digital Sustainability

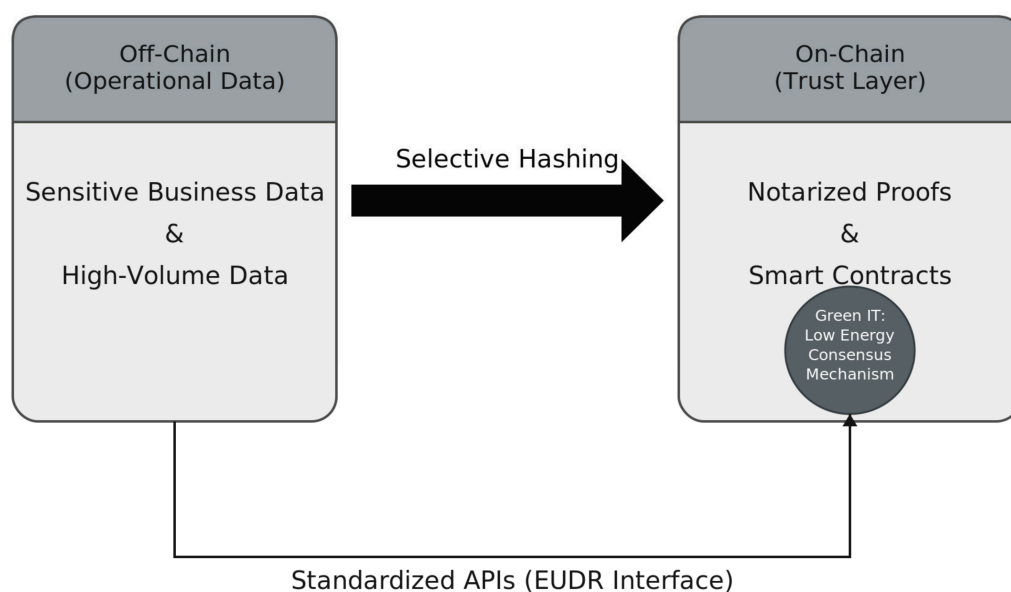


Figure 8. Concept of Physical-Digital Continuity.

From a socio-economic governance perspective, long-term network sustainability depends on equitable power distribution. Although BCT promises decentralization, a practical risk remains that large market players or central institutions may dictate protocols, creating new power asymmetries that marginalize small and medium-sized enterprises (SMEs). To prevent this, cooperative models (e.g., forestry cooperatives) must act as data aggregators to shield fragmented smallholders. Additionally, a sustainable business model must position BCT as an economic enabler rather than a compliance cost; linking traceability data to voluntary carbon markets or proof of ecosystem services provides a tangible commercial incentive [23].

The Forest-Anchored Blockchain: a hybrid traceability architecture

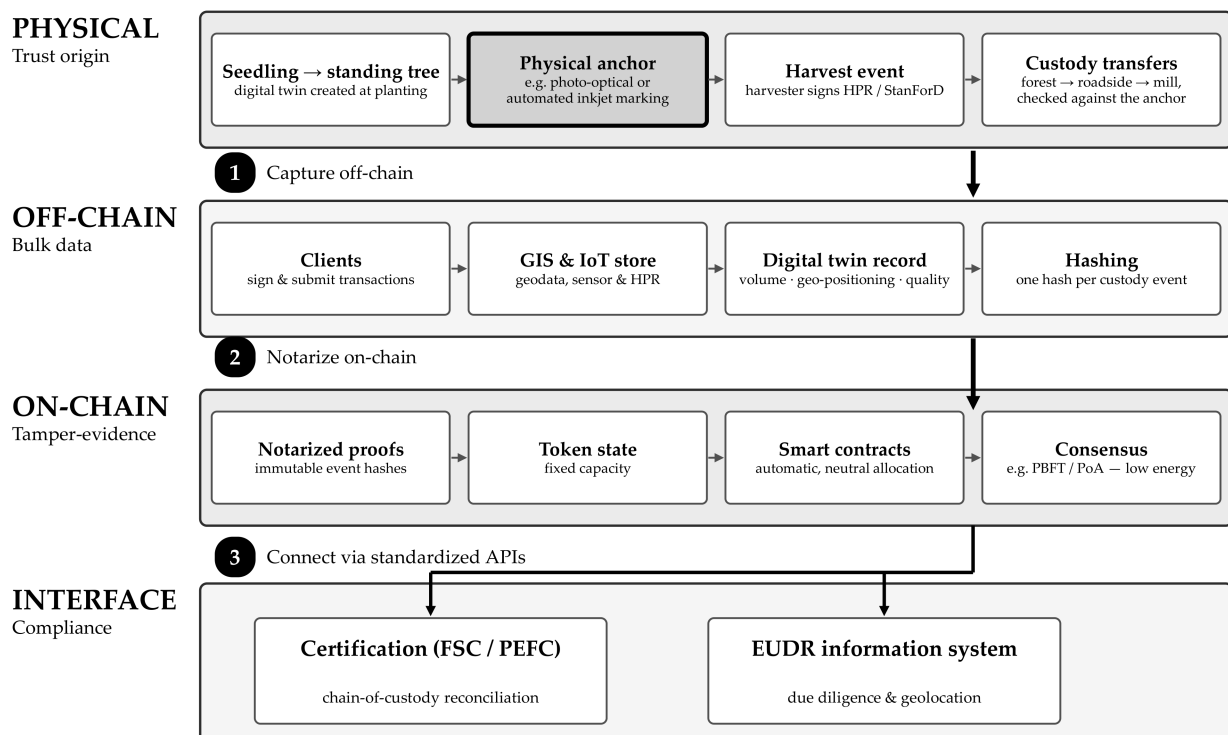


Figure 9. Architectural schematic of the forest-anchored blockchain and its data flows: physical anchoring, off-chain GIS/IoT storage, selective on-chain notarization with low-energy consensus, and certification/EUDR interfaces.

4.4. Technical Integration: Process Transfer from the Regulated Gas Sector

As a conceptual design proposal (rather than an empirically validated result) that illustrates how these hybrid architectures could operate under calamity conditions, the process logic of capacity ordering from the regulated gas energy sector can be transferred to wood logistics [25]. This model explicitly distinguishes between fixed capacities (planned annual harvests) and variable capacities (unplanned calamity volumes), directly addressing the discrepancy between biological unpredictability and digital rigidity. In this scenario, the forest enterprise acts as the upstream resource supplier and the sawmill as the downstream consumer, mirroring the relationship between transmission and distribution system operators (Table 6). Accordingly, this transfer scenario is presented as a hypothesis to be examined in a dedicated future pilot validation, not as a demonstrated outcome of the present study.

While this dynamic allocation model leverages smart contracts to automate logistical capacities, its real-world efficacy inherently depends on resolving the physical-digital oracle problem at the forest plot edge. If primary data collection is compromised, the downstream automated allocation logic fails. Consequently, this model does not assume standalone digital trust; rather, it must be strictly coupled with the robust physical tracking mechanisms discussed in Section 3.4 to secure the interface between physical timber assets and digital ledger tokens.

The technical implementation of this transfer scenario is operationalized across three core phases:

1. **Smart Contract as a Neutral Dispatcher:** The application's core is a smart contract that replicates the framework agreement's logic. Rather than a forester deciding manually which sawmill receives a particular stack of wood, the contract code exe-

cutes this decision automatically based on predefined qualities. The smart contract stores the entire order volume (e.g., 50,000 m³ spruce in quality B) and acts as an autonomous machine that manages the fulfillment status (e.g., 32,000/50,000 m³ delivered) in a tamper-proof manner, establishing a neutral, immutable protocol trusted by both parties.

2. **Tokenization of Variable Capacity:** As soon as an unforeseen amount of wood due to windbreak becomes available in the forest, the wood is converted into a digital asset (token). When the trees are further processed, the harvesting machine generates a standardized digital data record (HPR-file/StanForD) containing the important information: Volume, GPS coordinates, and quality/grade. The HPR-file is transmitted to the blockchain as a transaction and triggers the smart contract, that new variable capacity is available. The code compares this volume just in time with the open requirements of the sawmills. Conceptually, this tokenization of variable, capacity-bearing assets extends mechanisms already formalized for industrial product-lifecycle management, where a digital twin is instantiated at the earliest production stage and maintained as a generational, long-term record; it further draws on crypto-valuation approaches in which variable physical capacities are represented, priced and exchanged as tradable digital assets [26,27].
3. **Automated Allocation and Asset Transfer:** BCT creates real added value by enabling automated transactions without intermediary parties. If the quality of the new wood matches the open quota of Sawmill A, the volume is assigned to this contract. This entry activates the smart contract, indicating that new variable capacity is available. The volume is compared with the open requirements of the sawmills. This process takes only a few seconds, while the sawmill receives an automatic notification and can immediately plan logistics, such as transportation, without waiting for manual approval or an invoice. Finally, the process of wood distribution from a pull principle changes to an automated push principle. This eliminates the administrative costs that come up in the analog process, especially when dealing with calamities.

Table 6. Transfer of process logic from the gas sector to the forestry sector.

Process Component	Origin Scenario (Gas Sector)	Transfer Scenario (Forestry Sector)
Use Case	'Internal Ordering' of grid capacities	Annual framework agreement for roundwood
Upstream Actor	Transmission System Operator (TSO)	Forest Enterprise/Forest Owner (Resource Provider)
Downstream Actor	Distribution System Operator (DSO)	Sawmill/Timber Industry (Off taker)
Planned Resource	Fixed Capacity: Based on known historical data and fixed contracts.	Annual Cut: Based on forest management plans and long-term thinning schedules.
Unplanned Resource	Variable Entry Capacity: Dependent on physical load flows and temperature-dependent consumption.	Calamity & Variable Volumes: Dependent on storms, beetle infestation (forced cutting), or weather (accessibility).
Allocation Mechanism	Iterative Procedure: Step-by-step allocation as soon as variable capacities become technically available.	Dynamic Allocation: Immediate booking of log piles onto the contract as soon as they are digitally cleared by the harvester/forester.
Problem (Status Quo)	Media breaks via fax, email, and paper; time lag in coordination.	Manual 'notification of readiness': latency between harvest and logistical planning.
Solution (Technology)	Blockchain-based system for validation and capacity booking.	Smart Contracts for automated volume booking and asset transfer.
Objective	Non-discriminatory network access and transparency.	Transparent traceability (Chain of Custody) and efficient supply chain logistics.

4.5. Limitations of the Study

Despite the use of a robust, multi-method design in this study, certain limitations must be considered. First, the geographical focus of the expert pool is primarily on the DACH region and Central Europe. Therefore, the results reflect a specific level of regulatory and technological maturity; consequently, the findings may not directly apply to tropical timber environments characterized by different governance frameworks. Second, the recruitment process for the online survey introduced a potential digital selection bias, implying that stakeholders with a higher affinity for technology may be overrepresented compared to traditional, analog forest owners. Out of 559 direct email invitations, 69 completed responses were obtained, representing a net response rate of approximately 12.3%. While this sample constitutes a highly specialized and specific subset of stakeholders in the Central European forestry and timber sector, potential selection and non-response biases were rigorously mitigated by triangulating the quantitative survey data with deep qualitative insights from the expert interviews ($n = 41$) and the consensus-building workshop ($n = 18$). Third, while the qualitative content analysis followed strict protocols to ensure reliability [28], interpreting complex socio-technical concepts like trust and transparency remains inherently subjective and depends on respondents' individual experiences. Furthermore, even though the expert workshop utilized anonymous voting, the risk of groupthink in consensus-oriented formats cannot be entirely eliminated [29]. To validate and generalize these findings, future research should conduct large-scale quantitative studies across diverse international regulatory environments.

5. Outlook: Strategic Dimensions for Integrating BCT into Forestry

A substantial gap persists between the theoretical potential of blockchain technology (BCT) and its pragmatic scalability within the forestry sector. To bridge this divide and mitigate the systemic risk of 'garbage in, garbage out' inherent to distributed ledger technologies (DLT), future development must prioritize the cryptographic coupling of physical identification with digital tokenization. Digital supply chain transparency alone cannot eliminate the physical 'oracle problem' or prevent fraudulent declarations of timber provenance at the forest plot edge. Consequently, expanding toward a biologically and physically anchored BCT infrastructure, utilizing genetic tracing, radio-frequency identification (RFID), or photo-optical log measurement is imperative. This multi-layered validation framework shifts the sector's perception of BCT from a burdensome regulatory compliance cost into a strategic value driver. While contemporary timber markets offer limited price premiums for certified roundwood, BCT provides the foundational architecture required to effectively monetize non-timber forest ecosystem services (FES). By establishing tamper-proof, decentralized registries, BCT can streamline entry into voluntary carbon sequestration markets and facilitate automated biodiversity conservation payments [30].

This commercialization aligns with macro-level environmental frameworks, such as the EU Biodiversity Strategy (EUBDS) and the Nature Restoration Law (NRL) [31,32]. These regulatory instruments establish a clear roadmap for the formal implementation of nature credits, enabling forest owners to treat environmental data as an independent commodity, diversify revenue streams beyond traditional logging, and attract institutional green investments. However, operationalizing these systemic benefits requires coordinated regulatory action and technical standardization. To prevent the proliferation of fragmented, proprietary digital silos, policy efforts must enforce open-access, standardized application programming interfaces (APIs) and cross-regional data protocols. The long-term success of BCT is highly contingent upon its formal integration into European legal frameworks, specifically regarding the cross-border validity of digital signatures and the statutory recognition of smart contracts for automated due diligence. Furthermore, to lower entry barriers

for smallholder cooperatives, policymakers must introduce targeted socio-economic incentives, such as fiscal relief or streamlined audit pathways for regionally sourced, digitally verified timber assets. Finally, this technological transition demands a profound cultural paradigm shift to overcome historical mistrust among supply chain echelons. Currently, low baseline digitalization, typified by persistent ‘pen-and-paper’ workflows and acute skilled labor shortages, represents severe structural obstacles. True operational resilience will not be achieved through the isolated deployment of software architectures, but rather through industry-wide educational initiatives. These programs must equip the forestry workforce with the digital literacy required to manage hybrid, decentralized ledger systems. Ultimately, a corporate culture must be fostered where secure data sharing is perceived as a collective operational asset rather than a competitive exposure. Through this holistic integration, BCT can evolve from a reactionary compliance tool into the socio-technical backbone of a mature, transparent, and digitally sustainable bioeconomy.

6. Conclusions

The primary theoretical contribution of this study is the conceptualization of a biologically anchored blockchain, which systematically addresses the fundamental physical-to-digital vulnerability in supply chain tracking. The empirical results regarding system integration and technical synergies demonstrate that digital transparency alone is insufficient to mitigate the physical-digital ‘oracle problem’ or prevent fraudulent declarations of timber provenance. By cryptographically linking decentralized ledgers with physical and biological verification methods, the socio-technical integrity of a digital twin can be validated. This integrated architecture creates immediate practical synergies with established forest certification frameworks (e.g., FSC and PEFC), significantly enhancing automated auditing efficiency and data credibility. The transformative capacity of blockchain technology (BCT) as a mechanism for transparency and traceability in forest-wood value chains was evaluated under the pressure of escalating European regulatory mandates. While BCT offers a robust technical framework for immutable data orchestration, its practical deployment is strictly contingent upon a mature baseline digital and organizational infrastructure. Within the structural context of Central Europe, the forestry sector’s low digital maturity and persistent reliance on analog ‘pen-and-paper’ workflows create severe operational bottlenecks that constrain the perceived ease of use and usefulness of decentralized networks. Consequently, the transition to BCT must be conceptualized as a multi-stage process that begins with eliminating intra-organizational media breaks and establishing standardized digital machine interfaces across the localized supply chain. Regarding its regulatory utility, this research indicates that BCT can significantly reinforce the verifiability of supply chain documentation under the strict mandates of the EU Deforestation Regulation (EUDR). However, the technology cannot operate in a vacuum; its long-term viability depends on its integration into legally secured national frameworks and broader European environmental governance strategies, including the EU Biodiversity Strategy (EUBDS) and the Nature Restoration Law (NRL). The empirical data identified high initial capital expenditures, primarily driven by the financial burden of retrofitting legacy workflows, deploying tracking hardware, and managing fragmented institutional governance, as central barriers to adoption. Within the study area, these socio-technical obstacles can be effectively mitigated through targeted pilot implementations and formalized inter-organizational cooperatives, which serve to dismantle the deep-rooted competitive mistrust identified among supply chain echelons. For sustainable governance, future blockchain architectures must optimize long-term economic business models through equitable incentive alignment, particularly given the divergent transparency expectations among commercial actors. BCT should not be conceptualized merely as an administrative compliance cost, but rather as an economic

enabler of emerging markets. Linking digital traceability data to voluntary carbon markets, nature credits, and the formalized monetization of forest ecosystem services (FES) generates the commercial value necessary to foster self-sustaining networks. To ensure alignment with systemic digital sustainability goals, future research must rigorously evaluate blockchain architectural archetypes, explicitly prioritizing energy-efficient consensus mechanisms (such as Proof of Stake or Proof of Authority) over computationally intensive frameworks. Ultimately, embedding blockchain into the timber industry requires a systemic paradigm shift toward a mature, digitally integrated bioeconomy. Because these findings rest on DACH-region data with a recognized digital selection bias, the structural challenges, technical requirements, and transfer potentials identified here should be read as a hypothesis for future cross-jurisdictional research rather than as a directly transferable blueprint; whether the template extends to other EUDR-relevant commodities such as cattle, soy, palm oil, and coffee remains an open question for subsequent validation.

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Abbreviations

The following abbreviations are used in this manuscript:

API	Application Programming Interface
BCT	Blockchain Technology
CO ₂	Carbon Dioxide
DACH	Germany (D), Austria (A), Switzerland (CH)
DLT	Distributed Ledger Technology
DSO	Distribution System Operator
EUBDS	EU Biodiversity Strategy
EUDR	EU Deforestation Regulation
FES	Forest Ecosystem Services
FSC	Forest Stewardship Council
GIS	Geographic Information System
GPS	Global Positioning System
HPR	Harvester Production Record
IoT	Internet of Things
LCA	Life Cycle Assessment
M	Mean
n	Sample Size/Frequency
NRL	Nature Restoration Law
PEFC	Programme for the Endorsement of Forest Certification
PoA	Proof of Authority
PoS	Proof of Stake
QR	Quick Response (Code)
RFID	Radio-Frequency Identification

RQ	Research Question
SME	Small and Medium-sized Enterprises
StanForD	Standard for Forest Data and Communication
TAM	Technology Acceptance Model
TSO	Transmission System Operator

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