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Research Article

Blockchain-powered traceability in the wine industry: Enhancing transparency and consumer trust

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ABSTRACT

This study presents a blockchain-based traceability system designed to enhance transparency, combat counterfeiting, and strengthen consumer trust within the wine industry. The proposed solution employs a private MultiChain blockchain using a Proof of Authority (PoA) consensus mechanism to ensure data integrity, immutability, and accountability across the supply chain. Smart contracts are integrated to automate critical processes such as product registration, quality verification, and ownership transfers, while QR codes allow consumers to access the complete lifecycle history of each wine bottle. The system was developed and evaluated following the Design Science Research Methodology (DSRM) and tested in a real-world wine supply chain in the Douro Valley, Portugal. Results demonstrate substantial improvements in traceability, regulatory compliance, and operational efficiency, including a 75 % reduction in regulatory audit time and significantly higher consumer trust scores in a controlled field survey ($n = 372$). This research contributes a replicable and scalable framework for decentralized product identity management in agrifood supply chains, offering actionable insights for industry stakeholders and enriching the theoretical discourse on blockchain-enabled transparency in agriculture.

1. Introduction

The wine industry faces significant challenges in ensuring product authenticity, regulatory compliance, and consumer trust due to complex global supply chains and the prevalence of counterfeiting, particularly in the luxury market [1]. Traditional traceability systems, reliant on centralised databases or physical identifiers such as barcodes, are prone to tampering, lack real-time tracking, and fail to provide transparent provenance data [2]. These limitations undermine consumer confidence and increase the risk of fraud, with global wine fraud estimated to cost the industry billions annually [3]. Blockchain technology offers a transformative solution by providing a decentralised, immutable, and transparent ledger for supply chain data, yet its application in the wine industry remains underexplored.

This study addresses this gap by proposing a blockchain-based traceability system using a private MultiChain platform with Proof of Authority (PoA) consensus. The system integrates smart contracts, QR codes, and Internet of Things (IoT) oracles to ensure data integrity, automate processes, and empower consumers with verifiable product

information. The research question guiding this study is: How can a blockchain-based system using PoA consensus ensure secure product identity and traceability in the wine supply chain? Through Design Science Research Methodology (DSRM), a prototype was designed, implemented, and evaluated in a real-world wine supply chain, demonstrating its efficacy in enhancing transparency, reducing fraud, and aligning with EU and FDA global standards.

The contributions of this study are twofold. Firstly, it provides a practical framework for wine producers to implement blockchain-based traceability, improving operational efficiency and regulatory compliance. Secondly, it advances the theoretical understanding of decentralised systems in agricultural supply chains, addressing gaps in existing literature on scalable blockchain applications.

The integration of blockchain technology into the wine industry's supply chain offers a transformative approach to traceability, ensuring data integrity, immutability, and transparency across all stages of production and distribution [3,4]. This innovative system leverages a private blockchain platform, such as MultiChain, to meticulously control participant access, restricting validation rights to trusted entities such as

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wine producers, bulk distributors, and packers, fostering a secure and reliable environment for transaction verification [1]. Smart contracts play a pivotal role in automating critical processes, including quality verification and ownership transfers, thereby streamlining operations and reducing the potential for human error or fraudulent activities. Data integrity and security are paramount, achieved through the implementation of cryptographic hashing, which ensures the immutability of recorded data, preventing unauthorised alterations or tampering [3]. Public-private key pairs are employed to authenticate each participant within the blockchain network, guaranteeing the legitimacy of transactions and data contributions [1]. Pre-distributed common secret keys add an additional layer of protection for sensitive business information, safeguarding confidentiality and preventing unauthorised access to critical data [5].

The operational workflow of this blockchain-based traceability system begins with the generation of a unique identifier for each bottle of wine, typically in the form of a QR code, which serves as a digital gateway to the comprehensive blockchain records associated with that specific product [3]. Throughout the supply chain, detailed information is meticulously logged at every stage, capturing crucial data points such as vineyard information, production methods, quality control measures, and distribution details, creating a comprehensive and auditable history for each bottle of wine. Miners, acting as trusted validators within the private blockchain network, play a crucial role in verifying the accuracy and legitimacy of these records before they are permanently appended to the blockchain, ensuring the integrity and reliability of the data.

This transparent system empowers consumers with unprecedented access to detailed product information, fostering trust and confidence in the authenticity and quality of the wine they purchase. By scanning the QR code on a wine bottle, buyers can effortlessly access the product's full history, tracing its journey from the vineyard to the point of sale, providing assurance and combating counterfeiting. This capability is particularly important in the luxury goods market, where demonstrating the authenticity and provenance of products like bottled wine is critical [1]. The ability to retrace the entire supply chain through a simple QR code scan enhances consumer trust and provides a competitive edge for producers who prioritise transparency [3].

The implementation of blockchain technology not only prevents wine fraud but also improves operational efficiency and regulatory compliance, aligning with global traceability standards set by organisations such as the EU and FDA. Furthermore, the system facilitates compliance with organic and biodynamic certifications by providing a transparent record of sustainable practices throughout the production process. The traceability system guarantees data integrity and provenance, immutability, and transparency of data recorded on the blockchain [3]. The blockchain system also respects the quantities of the products involved, based on the annual production of the vineyard plot and the yield in the various stages of processing, using a system of tokens that cannot be altered, as they are managed on the blockchain [3].

The enhanced transparency and traceability offered by blockchain technology can significantly reduce supply chain disputes and ensure smooth tracking of products, contributing to improved operational efficiency. Ultimately, this blockchain-powered traceability system strengthens consumer confidence in wine products by making wine fraud nearly impossible while also improving operational efficiency and regulatory compliance [1,3]. Blockchain technology provides transparency among all involved parties and facilitates the collection of reliable data [6].

The remainder of this paper is organised into 10 sections. Section 2 reviews the literature through a PRISMA-based systematic review and identifies the research gap. Section 3 presents the conceptual blockchain-based traceability framework for the wine industry. Section 4 details the DSRM-based methodology, including the platform selection criteria, the survey design, and the statistical analysis. Section 5 specifies the system requirements, and Section 6 describes the design and development of the layered architecture. Section 7 demonstrates the

system, and Section 8 evaluates it through the Douro Valley case study. Section 9 discusses limitations and challenges, including a comparison with alternative blockchain solutions and an audit-time experiment. Section 10 reports the empirical evidence from prototype testing, and Section 11 concludes with theoretical and managerial implications and directions for future research.

2. Literature review

To systematically explore the role of blockchain technology in enhancing traceability and consumer trust within the wine industry, this study adopted a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-based methodology. The objective was to identify, screen, and analyse peer-reviewed academic literature that examines the technical, economic, and implementation-related aspects of blockchain in viticulture and wine supply chains.

2.1. Review protocol

The systematic review followed a protocol comprising four stages: identification, screening, eligibility, and inclusion.

- Databases searched: Scopus, Web of Science, ScienceDirect, and Google Scholar;
- Search keywords: “blockchain AND wine supply chain”, “traceability AND wine AND blockchain”, “blockchain adoption AND agri-food”, “blockchain AND product identity AND wine”;
- Date range: 2018 to 2025; Languages: English;
- Inclusion criteria: Peer-reviewed journal articles or high-quality conference papers focused on blockchain applications in wine or agri-food supply chains;
- Exclusion criteria: Papers with no direct relevance to wine traceability, non-peer-reviewed sources, opinion articles, and those without empirical or conceptual contributions.

2.2. PRISMA flow diagram

The papers span systematic literature reviews, multiple case studies, and conceptual frameworks. The PRISMA flow diagram (Fig. 1) summarises the selection process:

- Records identified: 228;
- Duplicates removed: 47;
- Screened by abstract/title: 181 (138 excluded);
- Full-text assessed for eligibility: 43 (12 excluded);
- Studies included in synthesis: 31.

The full texts of the remaining articles were assessed based on the following inclusion criteria:

- The study specifically addresses blockchain or distributed ledger technologies in the wine industry;
- The study includes at least one of the following themes: traceability, consumer trust, technical architecture, economic implications, implementation challenges, or authentication mechanisms;
- The study presents conceptual, empirical, or case-based evidence.

Exclusion criteria included:

- Articles with a generic focus on agriculture or food without specific reference to wine;
- Non-peer-reviewed sources such as blog posts, editorials, and press releases;
- Purely technical blockchain research with no sector-specific application.

Following the PRISMA methodology, 31 articles met the inclusion criteria for full review. From this set, 10 representative studies were selected for in-depth thematic synthesis based on their methodological rigor, diversity of geographical and organizational contexts, and coverage of technical, economic, and regulatory dimensions. These works collectively informed the identification of three central themes relevant to blockchain adoption in the wine industry:

1. Technical aspects of blockchain for traceability and quality control
2. Transparency and consumer trust
3. Economic and regulatory implications

This thematic structure enabled a structured synthesis of the literature, shedding light on the transformative potential of blockchain while also identifying practical challenges that remain underexplored in implementation efforts, see Fig. 1.

2.3.1. Technical aspects of blockchain for traceability

Multiple studies underline blockchain's technical capacity to enhance traceability and quality assurance in wine supply chains. A permissioned blockchain can ensure secure, immutable, and transparent records of origin, processing, and logistics information across distributed stakeholders [7–9]. The integration of IoT devices (e.g.,

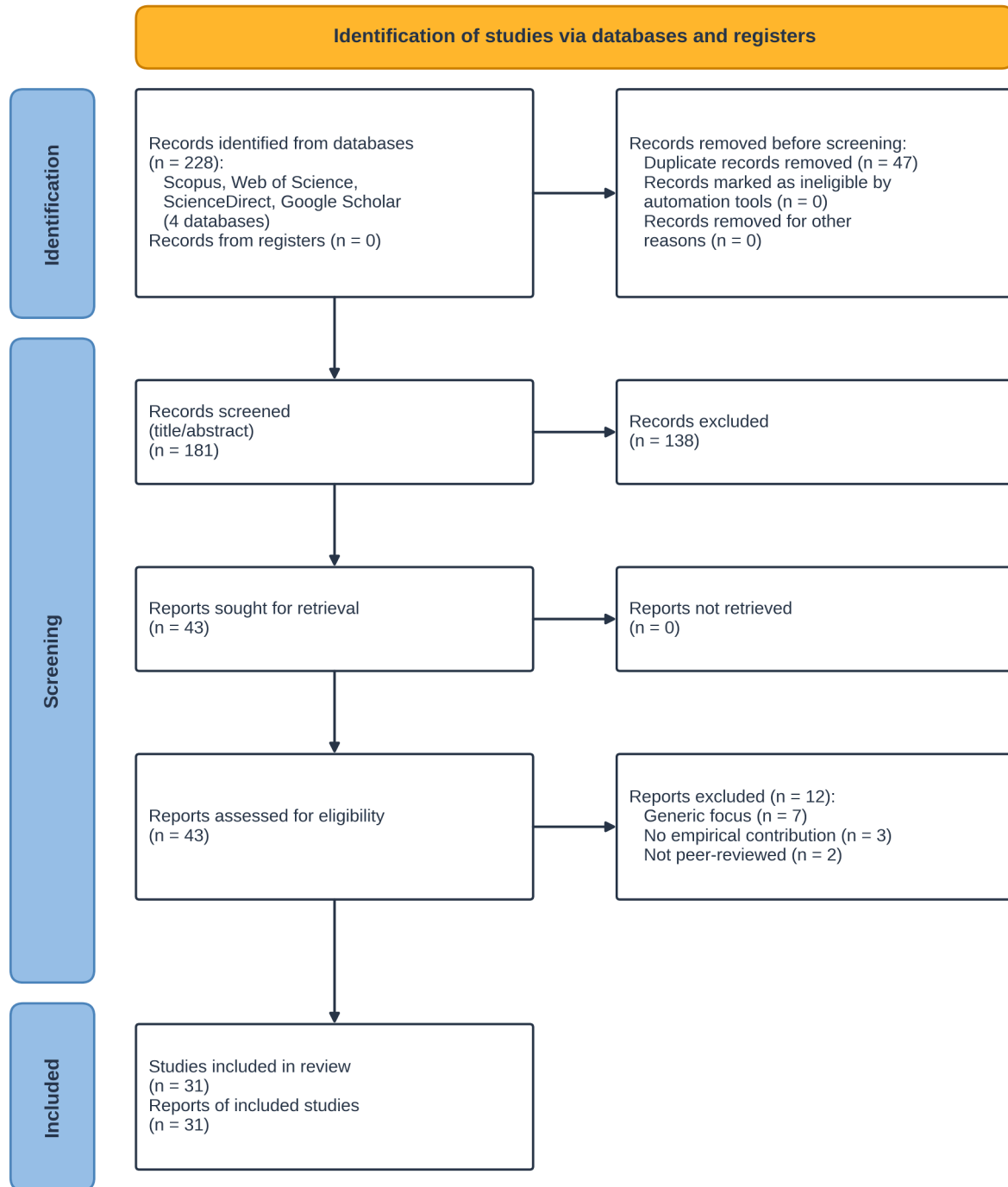


Fig. 1. PRISMA 2020 flow diagram illustrating the study selection process. A total of 228 records were identified through databases and registers. After removing 47 duplicates, 181 records were screened, with 138 excluded. Then, 43 full-text articles were assessed for eligibility, of which 12 were excluded (generic focus, no empirical contribution, or not peer-reviewed). Finally, 31 studies were included in the synthesis.

RFID—Radio Frequency Identification, NFC—Near Field Communication, and QR codes—Quick Response codes) further enhances real-time monitoring and automation of data flows, safeguarding against fraud and ensuring product authenticity [10].

In particular, blockchain's ability to encode data immutably and share it across decentralized networks supports greater interoperability across vineyard management systems, logistics providers, and retail chains. This technical capability is frequently highlighted as a foundational pillar for product identity management.

2.3.2. Transparency and consumer trust

The literature consistently points to blockchain's role in rebuilding and reinforcing consumer trust, especially in high-value markets where provenance and quality assurance are critical. Enhanced traceability enables transparent sharing of sustainability credentials, geographical origin, and ethical practices, all of which are increasingly demanded by informed consumers [10–12].

Blockchain-facilitated transparency is shown to contribute to consumer loyalty, enable price differentiation for quality-certified wines, and reduce information asymmetry. Nonetheless, empirical evaluations of end-user perceptions remain limited to small-scale studies or pilot deployments.

2.3.3. Economic and regulatory implications

Several studies analyze the cost-benefit dynamics and regulatory challenges associated with blockchain deployment in viticulture. While benefits such as reduced transaction costs, fraud prevention, and improved coordination are acknowledged [13], high implementation costs and the need for regulatory harmonization are cited as critical barriers—particularly for small-scale producers [10,14].

Furthermore, the legal admissibility of blockchain-based records and interoperability with existing Enterprise Resource Planning (ERP) systems remain underexplored, as do privacy concerns in relation to data transparency for end-users.

2.3.4. Methodological contributions and gaps

The selected papers employ a range of methodologies, including:

- Systematic literature reviews and conceptual frameworks focused on agri-food blockchain ecosystems [9,11,15–18];
- Multi-case study approaches centered on Italian and European wine supply chains [19–21];
- Cross-case comparisons of adoption enablers and stakeholder perceptions [22].

Table 1
Summary of research on blockchain in the wine industry.

Paper	Title	Major contribution	Applied case	Area	Note
[7]	Cultivating trust: An empirical exploration of blockchain's adoption within the Italian wine supply chain	Empirical study on blockchain fostering trust in Italian wine supply chains	Italian wine supply chain	Trust, Supply Chain Management	Focuses on empirical data to highlight trust-building mechanisms
[9]	Bottling up trust: A review of blockchain adoption in wine supply chain traceability	Comprehensive review of blockchain applications in wine traceability	None (Review)	Traceability, Blockchain Review	Provides a broad literature synthesis on traceability solutions
[8]	Blockchain-enabled campus wine supply chain	Demonstrates blockchain implementation in a campus-based wine supply chain	Campus wine supply chain	Supply Chain Management	Specific to a controlled, small-scale environment
[10]	Blockchain: No pain, no gain? An examination of blockchain technology in the vitivinicultural sector	Analyzes benefits and challenges of blockchain in the vitivinicultural sector	None (General analysis)	Vitiviniculture, Blockchain Challenges	Discusses trade-offs in adoption
[12]	Transparency uncorked: Leveraging blockchain to tackle international wine fraud	Explores blockchain's role in preventing international wine fraud	International wine market	Fraud Prevention, Transparency	Emphasizes global applicability
[11]	The dual role of blockchain in mediating credence attributes and moderating sensing capabilities in the wine sector	Examines blockchain's dual role in credence attributes and sensing capabilities	None (Conceptual)	Credence Attributes, Sensing Capabilities	Theoretical framework for blockchain's impact
[13]	Enhancing traceability in wine supply chains through blockchain: A stackelberg game-theoretical analysis	Applies game theory to analyze blockchain's impact on traceability	None (Theoretical)	Traceability, Game Theory	Uses Stackelberg model for strategic insights
[14]	Exploring blockchain adoption in the Italian wine industry: Insights from a multiple case study	Provides insights from multiple case studies on blockchain adoption	Italian wine industry	Adoption Insights, Case Study	Focuses on practical adoption challenges
[23]	Verified vintages: Leveraging blockchain to stop wine fraud	Investigates blockchain's role in preventing wine fraud	None (General analysis)	Fraud Prevention	Highlights verification mechanisms
[15]	Blockchain adoption in the wine supply chain: A systematic literature review	Systematic review of blockchain adoption in wine supply chains	None (Review)	Blockchain Review, Supply Chain	Comprehensive literature analysis
[16]	Applications and impacts of blockchain-based solutions in the wine supply chain: A systematic literature review	Reviews applications and impacts of blockchain in wine supply chains	None (Review)	Blockchain Applications, Supply Chain	Focuses on practical impacts
[19]	Designing blockchain systems to prevent counterfeiting in wine supply chains: A multiple-case study	Designs blockchain systems to combat counterfeiting	None (Case study-based)	Counterfeiting, System Design	Practical system design focus
[17]	How blockchain technology generates a trust-based competitive advantage in the wine industry: A resource based view perspective	Analyzes blockchain's role in creating competitive advantage through trust	None (Conceptual)	Trust, Competitive Advantage	Resource-based view framework
[20]	Exploring the use of blockchain-based tokens in the wine industry	Explores tokenization in wine industry using blockchain	None (Exploratory)	Tokenization, Blockchain	Focuses on emerging token-based applications
[22]	Key antecedents and consequences of blockchain technology adoption in the wine industry: A multiple case study analysis	Identifies antecedents and consequences of blockchain adoption	None (Case study-based)	Adoption Factors, Case Study	Broad analysis of adoption dynamics
[21]	Exploring the common blockchain adoption enablers: The case of three Italian wineries	Identifies enablers for blockchain adoption in Italian wineries	Three Italian wineries	Adoption Enablers, Case Study	Specific to Italian winery cases
[18]	Exploring the role of blockchain technology in modern high-value food supply chains: Global trends and future research directions	Explores blockchain's role in high-value food supply chains, including wine	None (Review)	High-Value Food Chains, Blockchain Trends	Broad scope beyond wine

Despite their contributions, most studies adopt either a high-level conceptual perspective or evaluate pilot-stage applications, with limited detail on architectural implementation, integration with legacy systems, or dynamic stakeholder governance models. In particular, few works explore how Decentralized Identifiers (DIDs) and Role-Based Access Control (RBAC) can be used in tandem to manage multi-stakeholder data permissions and product identity securely.

Table 1 synthesises key academic contributions related to the adoption of blockchain technology in the wine sector. Each entry highlights the study title, its major contribution (such as enhancing traceability, fostering consumer trust, or addressing economic and technical challenges), and the thematic area of focus. The summary provides a structured overview of how blockchain is being leveraged to address authenticity, transparency, and operational issues in viticulture and wine supply chains.

Fig. 2 represents the word cloud visualisation of core terms and concepts commonly associated with blockchain applications in the wine industry. Prominent themes include traceability, consumer trust, smart contracts, quality control, and authentication technologies such as IoT, RFID, and QR codes. The image reflects the interdisciplinary nature of blockchain adoption in viticulture, integrating supply chain transparency, digital identity, and fraud prevention.

2.3. Identified research gap

Despite recent advances, the literature reveals several key gaps that this study directly addresses:

- **Lack of operationalized frameworks:** While many studies offer conceptual benefits or generic architectures, few detail how technologies like DIDs or smart contracts are practically implemented to link physical bottles with digital identities.
- **Limited integration with ERP and legacy systems:** Existing works rarely explore the integration layer necessary to harmonize blockchain solutions with traditional enterprise systems, which is essential for real-world adoption.
- **Scarcity of end-user trust validation through real-world testing:** No prior study empirically tests consumer interaction with blockchain-backed QR code systems in winery settings through structured surveys or comparative groups (e.g., control vs. blockchain-informed users).
- **RBAC is underexplored in wine blockchain traceability** despite its critical role in securing data visibility across diverse stakeholders.

2.4. Contribution of the present study

This paper responds to the above gaps by:

- Proposing and detailing a blockchain-based product identity architecture with integrated DIDs, RBAC, and ERP interoperability through RESTful APIs and middleware adapters.
- Presenting a real-world case implementation in the wine sector with technical specifications for bottle-to-wallet binding and permissioned data access.
- Conducting a field survey experiment using QR code traceability, comparing control and treatment groups to assess the impact on perceived authenticity, purchase intent, and trust.

This practical and evaluative focus advances the discourse from theoretical potential to measurable outcomes, thus contributing a novel design science research artifact for traceability in the wine supply chain.

3. Blockchain-based traceability framework for the wine industry

The agricultural sector, particularly the wine industry, faces significant challenges due to complex supply chains, heightened consumer demand for authenticity, and risks of fraud and contamination. Traditional traceability systems, often reliant on centralized databases and paper-based processes, suffer from vulnerabilities such as data tampering, lack of real-time tracking, and fragmented data silos across stakeholders [2,24]. Blockchain technology offers a transformative solution by providing a decentralized, immutable, and transparent ledger to enhance traceability, ensure product authenticity, and build stakeholder trust. This section presents a conceptual framework for a blockchain-based traceability system tailored to the wine industry, grounded in theoretical and empirical insights from the literature [25, 26]. The framework addresses key challenges—authenticity assurance, transparency, and trust—while aligning with the DSRM to bridge conceptual design with practical implementation.

Challenges in Traditional Traceability Systems—Modern agricultural supply chains, including those in the wine industry, are complex, involving multiple stakeholders such as farmers, distributors, retailers, and consumers. Traditional traceability systems exhibit several limitations:

- **Centralized Vulnerabilities:** Centralized databases are prone to tampering and security breaches, undermining data integrity and accountability [2].

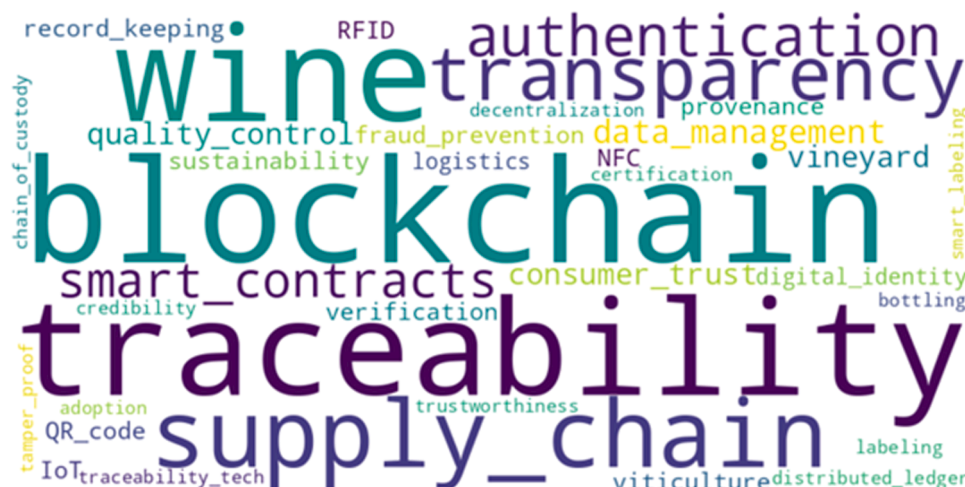


Fig. 2. Word cloud of key concepts in blockchain-based wine traceability.

- **Lack of Real-Time Tracking:** Inability to provide real-time visibility, critical for perishable goods like wine, hampers effective management and rapid response to contamination outbreaks [24].
- **Data Silos:** Non-interoperable systems among stakeholders create fragmented data flows, hindering a comprehensive view of a product's journey [2].
- **Inefficient Identification:** Traditional technologies like barcodes and RFID tags lack robust mechanisms for ensuring traceability and authenticity [24].
- **Lack of Transparency:** Limited transparency in provenance information erodes consumer trust and complicates verification of product attributes [27].
- **High Integration Costs:** The absence of unified data standards increases costs for data collation and integration across supply chain partners [2].

These shortcomings highlight the need for a robust, tamper-proof system to enhance traceability, data integrity, and stakeholder trust in the wine industry.

Blockchain as a Solution—Blockchain technology addresses these challenges by providing a decentralized, immutable, and transparent platform for supply chain management. Its key features include:

- **Decentralization:** Distributing data across multiple nodes eliminates single points of failure and reduces the risk of manipulation [2].
- **Immutability:** Cryptographically secured records ensure data cannot be altered, providing a verifiable history of each product's journey [24].
- **Transparency:** Authorized stakeholders can access a product's complete history, fostering trust and accountability [27].
- **Digital Identities:** Blockchain enables secure, verifiable identities for products and actors through technologies like QR codes and RFID tags, enhancing authenticity verification [28].
- **Automation:** Smart contracts automate business rules, such as product registration and certification validation, improving efficiency and reducing costs [28,29].
- **Stakeholder Integration:** A unified platform connects farmers, consumers, regulators, and distributors, ensuring transparent and secure data sharing [28].

In the wine industry, blockchain enhances traceability, combats fraud, improves food safety, and strengthens consumer trust by validating credence attributes like authenticity and sustainability [29].

Conceptual Framework for Blockchain-based Traceability—Drawing on prior models [25,26], this framework synthesizes theoretical and empirical insights to design an operationalizable blockchain-based traceability system for the wine industry. It consists of four interrelated layers, each addressing specific supply chain needs and integrating established principles with emerging technologies:

1. Data Capture Layer:

- **Purpose:** Collects product lifecycle data to ensure comprehensive tracking.
- **Technologies:** Integrates IoT devices (e.g., sensors for temperature monitoring) and ERP systems to capture real-time data on wine production, storage, and transportation.
- **Application:** Ensures accurate, real-time data collection for perishable goods, addressing the limitations of traditional systems [24].

2. Identity and Governance Layer:

- **Purpose:** Assigns secure, verifiable identities to supply chain assets and actors.
- **Technologies:** Utilizes DIDs based on World Wide Web Consortium (W3C) standards and cryptographic key pairs to identify wine bottles, producers, and certification authorities.

- **Application:** Enables role-based access and regulatory compliance, ensuring authenticity and trust across stakeholders [25].

3. Traceability Logic Layer:

- **Purpose:** Automates business rules to ensure consistent traceability across distributed stakeholders.
- **Technologies:** Employs smart contracts to manage product registration, certification validation, and ownership transfers.
- **Application:** Enhances efficiency and reduces errors in supply chain processes, supporting real-time verification [26].

4. Consumer Interaction Layer:

- **Purpose:** Provides end-users with accessible, transparent product information.
- **Technologies:** Generates QR codes linked to blockchain data, enabling consumers to verify a wine's history and certifications via a mobile interface.
- **Application:** Builds consumer trust by offering intuitive access to provenance and quality data [27,28].

This framework is designed to be operationalizable, mapping each component to the specific needs of wine traceability, such as real-time verification, fraud prevention, and regulatory compliance. Unlike purely theoretical models, it serves as a translational mechanism, bridging conceptual insights with practical system design.

Design Approach and Methodology—The framework's development leverages the DSRM, which supports expert-informed artifact creation when stakeholder needs are well understood. Preliminary focus group sessions were deemed unnecessary due to the first author's extensive expertise—over 20 years in supply chain systems, blockchain applications, and digital transformation in agri-food sectors. This domain knowledge facilitated the direct translation of real-world challenges into the framework's conceptual and technical design. The framework provides a foundation for specifying system requirements, developing prototypes, and defining evaluation metrics in subsequent phases, ensuring alignment between theoretical constructs and practical constraints [25,26].

The proposed blockchain-based traceability framework addresses the limitations of traditional systems in the wine industry by enhancing traceability, transparency, and trust. By integrating IoT, DIDs, smart contracts, and consumer-facing interfaces, it offers a robust solution for authenticity assurance, fraud prevention, and stakeholder collaboration. The framework's operational focus, grounded in DSRM, ensures continuity between literature insights and empirical implementation, paving the way for scalable blockchain adoption in the wine supply chain.

4. Methodology

This study adopts an explanatory sequential mixed-methods design [30], combining quantitative and qualitative approaches to evaluate a blockchain-based traceability solution for the wine supply chain. The methodological process began with a quantitative evaluation of prototype performance and survey responses, followed by qualitative insights from open-ended questions and field interviews.

Data collection instruments included structured surveys for four stakeholder groups (producers, distributors, regulators, and consumers), system logs for performance metrics, and simulated audit scenarios. Analytical techniques covered descriptive statistics, inferential tests (*t*-tests, chi-square), and thematic coding of qualitative data using NVivo. The overall process was informed by the DSRM, guiding the iterative development, demonstration, and evaluation of the solution.

This study employs the DSRM to design, develop, and evaluate a blockchain-based traceability system for the wine industry. DSRM, proposed by Peffers et al. [31], is a structured approach for creating and

assessing innovative IT artifacts to solve real-world problems. It is particularly suitable for this study due to its focus on developing practical solutions while contributing to theoretical knowledge, aligning with the objective of creating a scalable blockchain system to enhance transparency and trust in wine supply chains. DSRM consists of six phases—problem identification, defining objectives, design and development, demonstration, evaluation, and communication—each executed as described below.

4.1. DSRM phases and execution

Phase 1. Problem identification and motivation: The wine industry is confronted with persistent challenges in ensuring product authenticity, combating counterfeiting, and adhering to regulatory requirements. These difficulties stem from inherent limitations in traditional traceability systems, which rely heavily on centralised databases and paper-based processes. Such systems are susceptible to tampering, lack real-time visibility, and struggle with interoperability among diverse stakeholders, as highlighted by Ref. [2]. The problem is threefold: there is a lack of trust and transparency in supply chains, which fosters fraud and counterfeiting; traditional tracking methods are inefficient, error-prone, and vulnerable to manipulation; and there is an evident need for a secure, decentralised solution to guarantee product identity and traceability. This study addresses the research question: How can a blockchain-based system using PoA consensus ensure secure product identity and traceability in the wine supply chain? The problem formulation was informed by an extensive literature review and consultations with wine producers and regulators.

Phase 2. Define objectives of the solution: The primary objective was to develop a blockchain-based product identity system that enhances trust, security, and traceability within the wine supply chain. Specific design objectives were established, including maintaining an immutable, tamper-proof record of wine products; enabling trusted stakeholders (such as producers and distributors) to validate transactions using PoA-based mechanisms; automating key processes such as product registration, ownership transfers, and compliance audits through smart contracts; facilitating consumer verification of product authenticity via QR codes or NFC technology; and supporting real-time data integration from IoT devices and ERP systems through Application Programming Interfaces (APIs). These objectives directly respond to the problems identified and align with industry needs for greater transparency and regulatory compliance.

Phase 3. Design and development: The system was designed leveraging MultiChain, a private blockchain platform utilising PoA consensus. The architecture consists of four distinct layers. The blockchain layer ensures data immutability and consensus through MultiChain's PoA mechanism, with smart contracts automating traceability processes and data stored both on-chain (such as product IDs and ownership history) and off-chain (including sensor logs) via the InterPlanetary File System (IPFS). The identity and access layer employs DIDs and RBAC to authenticate stakeholders and manage access rights. The integration layer connects IoT oracles, which capture environmental data, and APIs that facilitate ERP system integration with the blockchain. In the application layer, user interfaces are provided for different stakeholders, including a traceability dashboard for supply chain actors, a consumer mobile app for product verification, and a regulatory compliance module. The MultiChain implementation process involved the creation of a blockchain network using the command `multichain-util create wine-traceability`, configuring PoA by adjusting `params.dat` to restrict validation to authorised nodes, and assigning validator rights through `multichain-cli wine-traceability grant VALIDATOR_ADDRESS mine`. Smart contracts were deployed in JSON format to manage product identity attributes such as bottle IDs, producers, and certifications. Additionally, a consumer-facing API was developed to allow QR code scanning, enabling users to retrieve product data through requests like `curl -X GET http://node-ip:port/api/v1/assets/WINE123456`.

Phase 4. Demonstration: The system was tested within a small-scale wine supply chain scenario involving a vineyard, winery, distributor, retailer, and consumers. The demonstration encompassed several key processes: a winery registered a batch of wine, assigning unique blockchain IDs via smart contracts; distributors logged transport conditions, including temperature data, using IoT oracles; consumers verified product authenticity by scanning QR codes to access detailed product histories; and regulators conducted audits to confirm compliance with organic certifications. This case study validated the system's capacity to provide end-to-end traceability from vineyard to consumer.

Phase 5. Evaluation: A mixed-methods approach was used to assess system performance and stakeholder acceptance. Prototype testing measured transaction latency, which ranged from one to five seconds (mean 2.8 s), and evaluated data integrity and system uptime during the demonstration phase. Stakeholder feedback on usability and trust was collected through surveys and interviews involving 10 producers, five distributors, three regulators, and 20 consumers; consumer trust was additionally assessed in a larger controlled field survey with 372 respondents (Sections 4.5–4.7 and 10.3). Furthermore, a comparative analysis between the blockchain-based tracking system and traditional manual methods revealed a 40 % reduction in bottle-level audit retrieval time (Section 9.5) and a 75 % reduction in the duration of the regulatory audit (Section 8).

Phase 6. Communication: The results of this research are disseminated through academic publications, industry workshops, and presentations at supply chain conferences. Future work is envisaged to scale the system for broader adoption and to integrate artificial intelligence for predictive analytics, enhancing the proactive management of supply chain processes.

4.2. Selection criteria for multichain and PoA

MultiChain and PoA consensus were chosen over other blockchain platforms such as Hyperledger Fabric and Ethereum after evaluating several key criteria. In terms of performance and scalability, MultiChain with PoA provides a high transaction throughput of up to 1000 transactions per second and low latency of one to five seconds, which is essential for real-time supply chain tracking. This is significantly higher than the approximately 15 transactions per second of Ethereum under its original Proof of Work (PoW) consensus, as noted by Ref. [32]. Energy efficiency was another decisive factor, as PoA consumes substantially less energy than PoW, aligning better with the sustainability objectives of the wine industry. Although Ethereum transitioned from PoW to Proof of Stake (PoS) in September 2022, which greatly reduced its energy consumption, its public network still imposes transaction (gas) fees and exposes data to all nodes, which conflicts with the confidentiality requirements of multi-stakeholder supply chain data.

Privacy and control requirements also influenced the decision. MultiChain operates as a private blockchain, ensuring that only authorised stakeholders have access to sensitive supply chain data. This contrasts with Ethereum's public network, where data are visible to all nodes. Although Hyperledger Fabric offers permissioned access, it was considered too complex for the wine industry's stakeholder ecosystem, which does not require such a highly modular and intricate architecture. Regarding ease of deployment, MultiChain's customisable PoA and built-in smart contract functionalities simplify the implementation process. Hyperledger's architecture, while powerful, demands extensive configuration and technical resources, making it less suitable for small-to-medium enterprises within the wine sector.

Cost-effectiveness was another critical factor. MultiChain's operational costs are lower because it does not involve transaction gas fees, unlike Ethereum, which could impose prohibitive costs on smaller producers. Collectively, these criteria ensure that MultiChain with PoA meets the specific needs of the wine industry, providing an efficient, secure, and affordable solution for product identity and traceability.

4.3. System architecture diagram description

The system architecture is structured as a layered model, visually represented in a diagram that illustrates the interaction between different components and stakeholders across the supply chain. At the top, the application layer provides interfaces for various users, including a consumer mobile application that enables QR code scanning for product verification, a traceability dashboard designed for producers and distributors to monitor supply chain activities, and a regulatory compliance module facilitating audits and certifications. Visual elements in this layer use icons to represent key stakeholders, such as vineyards, wineries, and consumers, emphasising their roles within the ecosystem.

Beneath this, the integration layer connects external data sources to the blockchain. This layer incorporates IoT oracles, such as temperature sensors and GPS devices, which monitor environmental conditions during transport and storage. Additionally, it integrates with ERP systems through APIs, ensuring seamless data flow from operational systems into the blockchain network. Arrows in the diagram illustrate the direction of data movement from these external sources toward the blockchain infrastructure.

The next level is the identity and access layer, which is responsible for managing stakeholder and product identities using DIDs. This layer also implements RBAC policies, ensuring that data visibility is tailored to each stakeholder's role—for instance, regulators have comprehensive access to all supply chain data, while consumers can only view product history relevant to their purchase.

At the foundation, the blockchain layer is composed of MultiChain nodes operated by authorised validators, including producers and distributors. These nodes maintain a distributed ledger where each block contains immutable transaction data, such as bottle identifiers, ownership transfers, and certification records. Complementing the on-chain data, an off-chain storage solution using the IPFS is depicted as a separate cloud, providing scalable storage for large files such as sensor logs and certification documents.

The overall data flow is depicted with arrows that trace the journey of information from the initial data entry at the vineyard, such as grape harvest records, through to consumer verification at the point of sale via QR code scanning. Along this path, data passes through smart contracts that automate validation processes and IoT devices that ensure the accuracy of environmental data, ultimately creating a transparent, secure, and verifiable product identity management system.

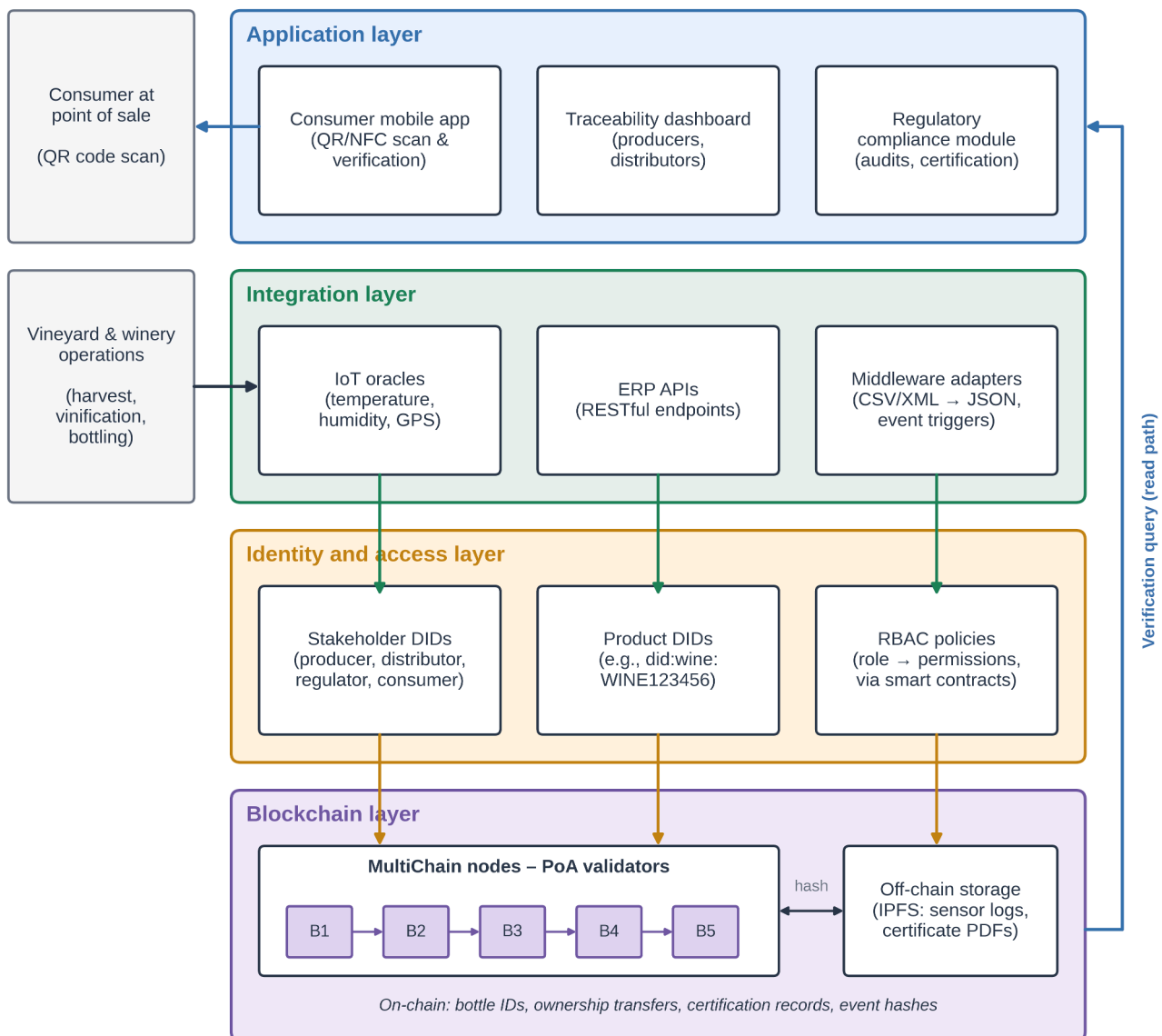


Fig. 3. System architecture of the blockchain-based product identity and traceability solution.

Fig. 3 shows the interaction between four system layers: the application layer (consumer mobile app, traceability dashboards, compliance modules), integration layer (IoT oracles, ERP APIs), identity and access layer (DIDs, role-based access policies), and the blockchain layer (MultiChain nodes with off-chain IPFS storage). Data flows from vineyard operations through IoT validation, entering the blockchain via smart contracts and culminating in consumer verification through QR code scanning, ensuring secure and transparent product identity management.

Identity and access layer—secure authentication and permissions management. This layer implements a robust mechanism for stakeholder identity and permission control, combining DIDs and RBAC. This layer implements a robust mechanism for stakeholder identity and permission control, combining DIDs and RBAC.

DID Implementation: Each wine bottle, producer, distributor, regulator, and consumer is assigned a unique DID based on W3C DID standards. These DIDs are securely generated using asymmetric cryptographic key pairs. For example, a bottle of wine is assigned a did: wine:WINE123456, where the public key is published on-chain. The private key is securely held by the issuing party (e.g., the winery). The DID document includes service endpoints and authentication methods.

The link between a bottle and its DID is established by signing the bottle's metadata (e.g., harvest date, grape type, certification) with the producer's private key. Validators can verify this signature using the public key published on the blockchain, ensuring non-repudiation and data provenance.

RBAC Integration with DIDs: RBAC policies are implemented through smart contracts and linked directly to stakeholder DIDs. Each stakeholder's DID is assigned a role (e.g., producer, distributor, regulator, consumer) with predefined permissions. For example, producers can create and update bottle records and submit certifications. Distributors can append logistics data (e.g., transport conditions). Regulators have read/write audit privileges for all chain data. Consumers are limited to read-only access for product verification.

This ensures fine-grained access control, allowing only authorized entities to interact with specific data fields, enhancing data security and accountability.

Integration layer—ERP and IoT connectivity. This layer ensures seamless data exchange between the blockchain and external systems (e.g., ERPs, IoT platforms, and certification authorities).

ERP System Integration: Legacy ERP systems are integrated using RESTful APIs and middleware adapters. The APIs allow external systems to push and retrieve data from the blockchain in real time. For instance:

A winery's ERP system can invoke the API endpoint:

```
POST /api/v1/bottles
{"bottle_id": "WINE123456",
"producer_did": "did:wine:PROD001",
"certifications": ["DOCG", "Organic"]}
```

This transaction is recorded on-chain, with the producer's digital signature ensuring data integrity.

Middleware Adapters: To support non-API-capable legacy systems, middleware adapters transform ERP data formats (e.g., CSV, XML) into JSON-compatible payloads for blockchain ingestion. These adapters also monitor ERP events (e.g., bottling completed) and trigger smart contract executions to maintain synchronization.

IoT Oracles: Sensors integrated into the logistics chain (e.g., temperature, GPS) feed real-time data to the blockchain via trusted IoT oracles. These oracles validate and timestamp data such as: Transport temperature between 15 °C and 18 °C. GPS route verification for delivery confirmation.

4.4. Limitations of the methodology

While the DSRM offers a solid framework for developing and evaluating the proposed solution, several limitations have been identified that must be addressed in future work. One significant challenge is scalability. The prototype was tested in a limited environment involving a single winery and distributor, but expanding the system to accommodate thousands of stakeholders could strain MultiChain's performance, particularly in terms of node distribution and data storage. Optimisation strategies will be necessary to ensure efficient scaling.

Another limitation concerns stakeholder adoption. Smaller producers, who may lack the necessary technical expertise or financial resources, could face difficulties in adopting blockchain technology. Overcoming this barrier will require the implementation of targeted training initiatives and possibly the provision of financial incentives or cost subsidies to facilitate participation.

Interoperability also poses a challenge. The diversity of ERP systems used across global supply chains introduces complexities in achieving seamless integration. Standardisation efforts and the development of flexible APIs will be essential to address these integration hurdles.

Additionally, regulatory uncertainty remains a concern. Blockchain regulations vary significantly between countries, which could complicate the deployment of such systems in cross-border supply chains. Continuous monitoring of regulatory developments and collaboration with policymakers will be critical to navigate these complexities.

These limitations are acknowledged and will be systematically addressed in future iterations of the project through dedicated scalability testing, comprehensive stakeholder training programs and active engagement with standard bodies to promote interoperability and regulatory alignment.

4.5. Survey methodology

To assess perceptions of blockchain-based wine traceability, we conducted structured surveys targeting four key stakeholder groups: consumers, producers, distributors, and regulators. The primary aim was to evaluate how traceability, transparency, and data accessibility influence trust and purchasing decisions across the supply chain.

The consumer survey was designed using validated consumer-trust constructs from prior food-traceability research [33]. The instrument includes seven Likert-scale items evaluating multiple trust-related dimensions:

- I believe the wine I purchased is authentic and not counterfeit.
- The blockchain-based traceability system increases my confidence in the quality of the wine.
- The product information accessed via the QR code helped me better understand the wine's origin and production.
- The transparency provided by the traceability system makes me more likely to trust this brand.
- I feel more confident about my purchase decision because I could verify product details using the QR code.
- The traceability system is easy to use and provides relevant information.
- Knowing that the product is traceable through blockchain increases my willingness to buy this wine again.

These questions target dimensions such as: 1) Perceived information accuracy; 2) Transparency of supply chain data; 3) Confidence in brand authenticity; 4) Perceived security and reliability of blockchain records; 5) Overall trust in the wine's quality; 6) Willingness to repurchase; 7) Comparative trust versus traditional labeling. Three open-ended questions, prompting qualitative feedback on what elements of the product information (e.g., QR code details, label, brand) influenced trust and purchase decisions. Three open-ended questions exploring trust mechanisms:

- What specific information available through the QR code (e.g., vineyard location, harvest date, certifications) influenced your perception of the product?
- In what ways, if any, did the traceability system increase your trust in the wine you purchased?
- Do you have any suggestions to improve the traceability system or the information provided to consumers?

These instruments were pre-tested with five participants for clarity and usability before deployment.

4.6. Data collection and control group design

Participants were recruited for both wine events, onsite at the winery's retail store and through email invitations to recent customers. Eligibility was restricted to individuals who had purchased wine from the participating winery during the study period.

Two groups were established:

- Treatment Group (n = 184 respondents): Received access to the QR code linking to blockchain records containing data such as vineyard location, harvest date, production batch, storage conditions, and distribution history.
- Control Group (n = 188 respondents): Received traditional product information available on the wine label, without access to blockchain data.

Participants completed the survey anonymously and received a 10 % discount on their next purchase as an incentive. The total response rate was 93 % (372/400), indicating high engagement.

4.7. Statistical analysis and key findings

To rigorously compare consumer perceptions across groups, we performed the following analyses:

- Independent sample *t*-tests were conducted on the Likert-scale responses, revealing significant differences ($p < 0.05$) between treatment and control groups on: perceived authenticity, traceability transparency, willingness to repurchase.
- Chi-square tests were applied to categorical responses, such as yes/no indicators for trust-enhancing features.
- Open-ended responses were thematically coded using NVivo, identifying recurrent themes such as appreciation for production transparency, positive sentiment toward origin certifications, and perceived ease of verification.

These results provide evidence that the blockchain traceability system significantly enhances consumer trust and purchasing confidence.

Bias Mitigation Techniques. To reduce bias and increase data reliability:

- All surveys were anonymous to minimize social desirability bias.
- Neutral language was used throughout, and leading questions were avoided.
- Participants in the consumer survey received a 10 % discount voucher as a non-coercive incentive.
- A high response rate was obtained: 184 of 200 invitees in the QR code group and 188 of 200 in the control group, reflecting strong engagement.

Representativeness and Limitations. While the consumer study yielded insightful findings, we recognize the sample size and scope limitations. The survey focused on a single medium-sized winery in the Douro Valley, and although random assignment helped control internal validity, broader generalizability remains limited.

This was an exploratory pilot survey, aimed at initial feedback rather than statistically representative consumer behavior modeling. To expand external validity, we recommend future research with larger, multi-region samples and longitudinal data collection across different market segments.

Furthermore, the survey design was informed by over 20 years of field expertise of the first author in viticulture and digital traceability. Instead of conducting preliminary focus groups, which were initially planned, the research leveraged first-hand industry knowledge to streamline the survey process. This choice ensured rapid iteration and practical alignment with industry practices. However, we suggest that future studies reintroduce focus groups for triangulation and richer qualitative data.

5. System requirements

The proposed system architecture leverages a multi-layered design to integrate blockchain technology with conventional supply chain applications, thereby establishing a robust framework for product identity management and traceability. The architecture's foundation is the blockchain layer, which is responsible for ensuring data integrity, security, and transparency throughout the product lifecycle [34]. This layer employs a consensus mechanism, preferably PoA or Delegated Proof of Stake (DPoS), to strike a balance between security rigor and operational efficiency. PoA and DPoS are selected for their ability to provide faster transaction confirmation times and reduced energy consumption compared to PoW systems, which are often deemed unsuitable for high-throughput supply chain applications [35]. Smart contracts are integral to the blockchain layer, automating critical processes such as identity verification, certification validation, and transaction recording, thereby eliminating manual intervention and reducing the risk of errors or manipulation [36]. Data storage within the blockchain layer adopts a dual-layer strategy, where essential product identity and certification data are stored on-chain to guarantee immutability and accessibility, while large metadata elements, such as detailed product specifications or high-resolution images, are stored off-chain in decentralised storage solutions like IPFS or Arweave, to minimise storage costs and improve scalability. The integrity of the food chain not only includes security problems but also addresses counterfeiting by providing information about a product's origin, processing, retailing, and final destination. A decentralised solution provides a secure and immutable scientific data provenance tracking and management platform where provenance records, providing compelling properties for the data integrity of luxury goods, are recorded and verified automatically across the supply chain [1].

The identity and access layer builds upon the blockchain layer, focusing on managing the identities of products and stakeholders within the supply chain ecosystem. DIDs are implemented to provide unique and verifiable identities for all entities, including products, manufacturers, distributors, retailers, and consumers. DIDs are employed as a standard for creating self-sovereign identities that are independent of central authorities, enhancing privacy and control over personal data. RBAC is implemented to ensure selective data visibility, granting different levels of access to various stakeholders based on their roles and responsibilities. Regulators may have access to comprehensive supply chain data for compliance monitoring, while producers may only access data related to their products, logistics providers may access shipment information, and consumers may access product authenticity and origin details. This ensures that sensitive information is protected while enabling authorised stakeholders to access the data they need to perform their duties effectively.

The integration layer acts as a bridge between the blockchain network and external systems, enabling seamless data exchange and interoperability. Oracles are employed to connect external data sources, such as IoT devices and external certification bodies, to the blockchain network, providing real-time data on product location, environmental

conditions, and quality certifications. Legacy System Compatibility (LSC) is ensured through the development of APIs and middleware that facilitate integration with existing ERP and supply chain management systems, allowing organisations to adopt the blockchain-based product identity system without disrupting their existing infrastructure. The application was designed to be as non-intrusive as possible to the whole food supply chain's operators in order to not interfere with their activities [37]. The platform integrates blockchain technology to monitor food supply chains and ensure their transparency, traceability, and accountability.

The application layer provides user-facing interfaces and tools that enable stakeholders to interact with the blockchain-based product identity system. A traceability dashboard offers real-time visualisation of supply chain data, allowing stakeholders to track products from origin

to consumer, monitor key performance indicators, and identify potential issues or delays. A mobile verification app empowers consumers to scan QR codes or NFC tags on products to verify authenticity, origin, and other relevant information, building trust and confidence in the products they purchase [37]. A Regulatory Compliance Module (RCM) ensures adherence to sustainability and safety standards by automating the collection and reporting of relevant data, facilitating compliance audits and reducing the risk of non-compliance penalties.

6. Design and development

The blockchain-based product identity system adopts a layered architecture to ensure traceability, security, and transparency in the wine supply chain. Each layer comprises modules responsible for specific

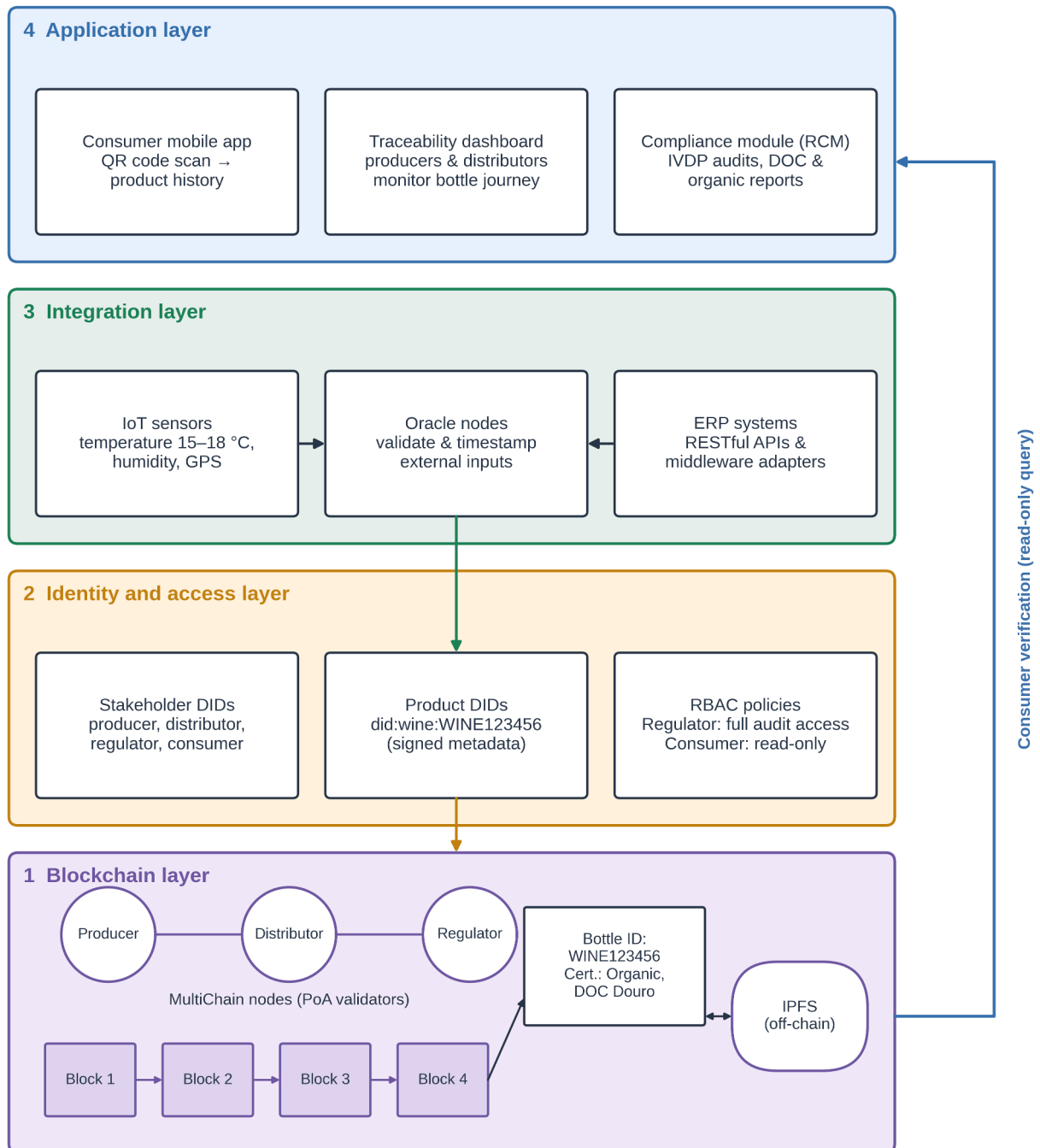


Fig. 4. System architecture and information flow of the blockchain-based traceability solution for Douro Wine.

functions, from data immutability to user interaction. This section describes the major modules, their roles, and the end-to-end information flow, with a textual description of the supporting Fig. 4. The system is implemented using MultiChain with PoA consensus, tailored for the wine industry's need for efficiency and privacy [32].

6.1. System architecture and modules

The architecture consists of four layers: 1) Blockchain, 2) Identity and access, 3) Integration, and 4) Application. Below, each layer and its modules are detailed with their functions and wine industry applications.

Blockchain layer—security and data integrity. This foundational layer ensures data immutability, consensus, and automated processes. It includes the following modules:

- Consensus mechanism (PoA): Uses PoA to validate transactions via pre-authorised nodes (e.g., wine producers, distributors, regulators). Validators sign transactions with cryptographic keys, ensuring high throughput (1000 tx/s) and low latency (one second to five seconds). For example, a winery validates a batch registration in two seconds. PoA's advantages include low energy consumption and suitability for private networks, unlike PoW [32];
- Smart contracts: Automate business rules, such as product registration, ownership transfers, and compliance checks. For instance, a smart contract ensures that only certified organic producers can update vineyard data. Example JSON structure:

```
{
  "type": "create",
  "name": "wine_identity",
  "fields": {
    "bottle_id": "WINE123456",
    "producer": "Vineyard X",
    "certifications": ["Organic", "DOCG"],
    "timestamp": "2025-02-28T10:00:00Z"
  }
}
```

- On-chain storage: Stores critical data, including unique product identifiers (QR codes/NFC tags), certifications (e.g., organic, DOCG), and transaction records (e.g., ownership transfers). For example, a bottle's ID and harvest date are recorded immutably;
- Off-chain storage (IPFS): Manages large metadata, such as IoT sensor logs (temperature: 15 °C, humidity: 65 %) or certificate PDFs, linked to the blockchain via hashes to optimise storage costs.

Identity and access layer—secure authentication. This layer manages stakeholder identities and access control, ensuring secure data interaction. Modules include:

- DIDs: Assign unique cryptographic IDs to products and stakeholders using public-private key pairs. For example, a bottle's DID links to its blockchain record, while a producer's DID authenticates data updates;
- RBAC: Restricts data access based on roles. Regulators access all compliance data, producers modify production records, and consumers have read-only access to product history. For instance, a consumer scans a QR code to view a bottle's origin but cannot alter it.

Integration layer—external data connectivity. This layer bridges the blockchain with real-world data and legacy systems. Modules include:

- IoT Oracles: Fetch real-time data from sensors (e.g., GPS location, temperature: 15–18 °C during transport) and validate external

certifications (e.g., organic labels). For example, an oracle confirms a shipment's compliance with storage conditions;

- APIs and middleware: Enable integration with ERP systems and regulatory databases. For instance, an API retrieves blockchain data for a winery's inventory management software, ensuring compatibility with existing infrastructure.

Application layer—user interfaces and analytics. This layer provides tools for stakeholders to interact with the system. Modules include:

- Traceability dashboard: Offers real-time visualisation of supply chain data. Producers track bottle movements, regulators audit compliance, and distributors monitor transport conditions. For example, a dashboard displays a bottle's journey from vineyard to retailer;
- Consumer mobile app: Allows consumers to scan QR codes/NFC tags to verify authenticity, origin, and certifications. For instance, a consumer confirms a bottle's organic status and harvest date;
- RCM: Automates audit reporting for sustainability and safety standards. For example, it generates a DOCG compliance report in seconds;
- Supply chain analytics: Uses blockchain data and AI to detect fraud (e.g., unauthorised record changes) and predict demand. For instance, analytics identify a 10 % demand spike for organic wines.

6.1.1. End-to-end information flow

The information flow integrates all layers to ensure seamless traceability. The process is as follows:

1. Product registration: A winery assigns a DID and QR code to a bottle, recording vineyard data (e.g., Touriga Nacional, harvest: September 28 2024) via a smart contract. Data are stored on-chain, with metadata (e.g., soil analysis) on the IPFS;
2. Supply chain updates: Stakeholders (e.g., distributors) log events (e.g., transport at 15 °C) using smart contracts. Validators authenticate updates, ensuring immutability;
3. IoT and certification validation: Oracles validate transport conditions and certifications (e.g., organic label), recording results on-chain;
4. Consumer and regulatory verification: Consumers scan QR codes to access product history (e.g., production method, certifications). Regulators use the dashboard to audit compliance, retrieving immutable records;
5. Analytics optimisation: AI analyses blockchain data to detect anomalies (e.g., two blocked fraud attempts) and to optimise logistics (e.g., predict delivery schedules).

Fig. 4 presents a vertical layout of the architecture comprising all the previously mentioned layers, starting at the bottom and working its way up. Regarding the blockchain layer, its MultiChain nodes represent producers, distributors, and regulators, which are connected through a chain of data blocks containing information and linked to off-chain IPFS storage. As to the identity and access layer, it illustrates stakeholder and product DIDs associated with RBAC policies, which define data access rights. In respect of the integration layer, it connects IoT sensors with ERP systems via APIs, with oracle nodes validating external data inputs. Finally, in regard to the application layer, it depicts end-user interfaces, including a consumer mobile app for QR code scanning, a traceability dashboard for producers and distributors, and a compliance module for regulatory oversight. A continuous information flow is traced from vineyard registration at the blockchain layer until consumer product verification, emphasising the secure and transparent management of product identity throughout the supply chain.

6.2. Benefits and limitations

The implementation of the blockchain-based traceability system offers several key benefits. One of the primary advantages is the creation of immutable records, which substantially reduces the opportunity for fraud by ensuring that data remains tamper-proof, as supported by Ref. [36]. The system also automates compliance processes through smart contracts and dedicated modules, leading to a 75 % reduction in audit time. Consumer trust is significantly enhanced, with QR code verification allowing end-users to access detailed product histories. 92 % of surveyed consumers in the QR code group reported increased confidence in product authenticity, as detailed in Sections 8 and 10.3. From an operational perspective, the integration of PoA consensus and IoT devices facilitates real-time tracking of products while maintaining low energy consumption, contributing to overall system efficiency.

Despite these benefits, certain limitations persist. Scalability is a notable challenge, as expanding the system to manage millions of wine bottles may introduce latency issues, introducing the necessity of optimisation of node distribution and processing capabilities. The initial setup cost, estimated at ten thousand euros could pose a barrier for small producers, although this can be mitigated through cloud-based deployment options and industry-supported subsidies. Additionally,

the technical complexity of the system requires stakeholders to acquire new skills to effectively navigate dashboards and APIs. Addressing this challenge involves developing user-friendly guides and providing targeted training to facilitate adoption across diverse user groups. This architecture provides a robust, scalable solution for wine traceability, balancing security, efficiency, and usability.

7. Demonstration

Fig. 5 illustrates the key stakeholders and information flow within a blockchain-enabled wine traceability system. The diagram mainly presents two categories: Production & Supply Chain Stakeholders and Regulatory & Compliance Authorities. It also includes Retail & Consumer Stakeholders as an additional stakeholder group. Each block in the supply chain (from vineyards to consumers) records critical data elements via blockchain transactions, ensuring transparency, authenticity, and regulatory compliance. Technologies such as digital identity tokens, QR codes, NFC tags, and smart contracts support secure, tamper-evident traceability throughout the wine's lifecycle.

Consequently, Fig. 6 illustrates the data validation process across key stages of the wine supply chain using blockchain technology. Each case represents a critical control point where data are recorded, validated,

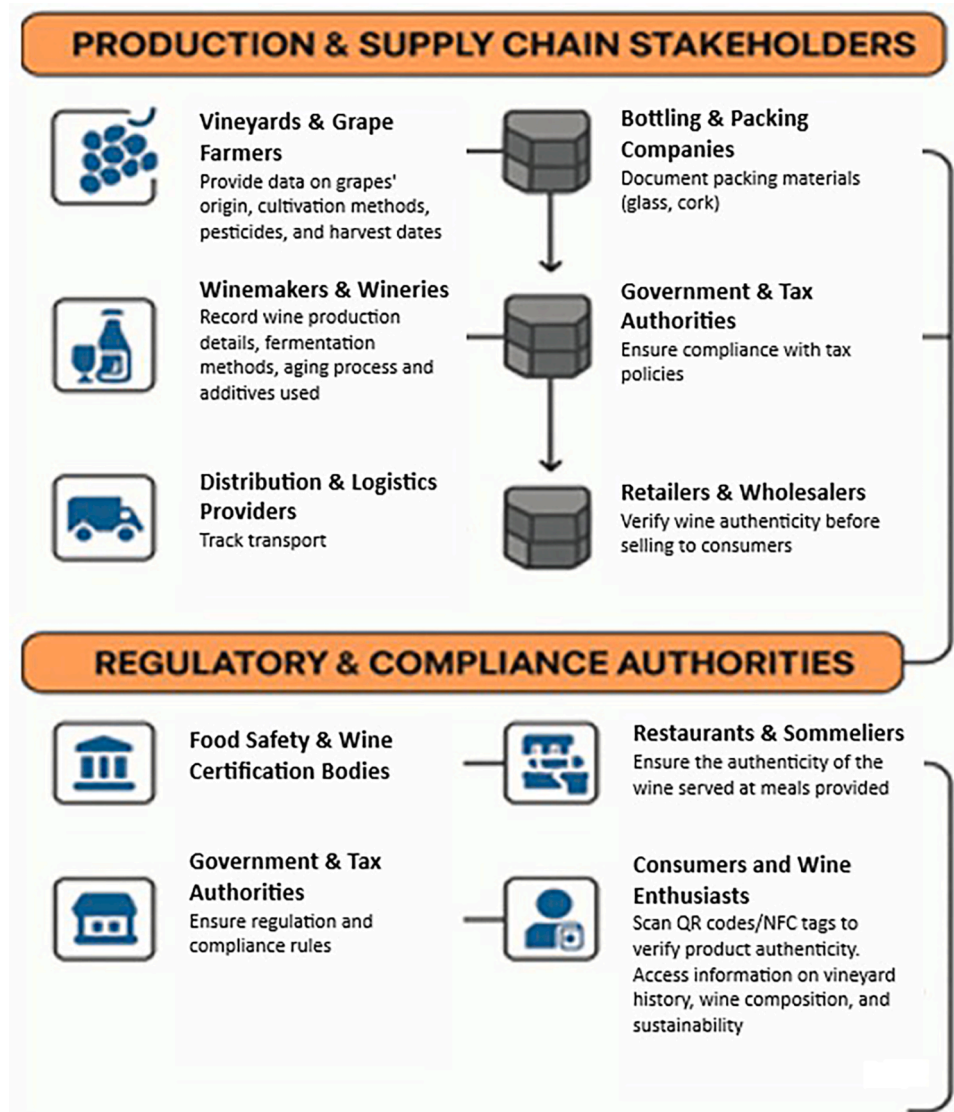


Fig. 5. Blockchain-based traceability system for wine.

Data validation in the wine supply chain

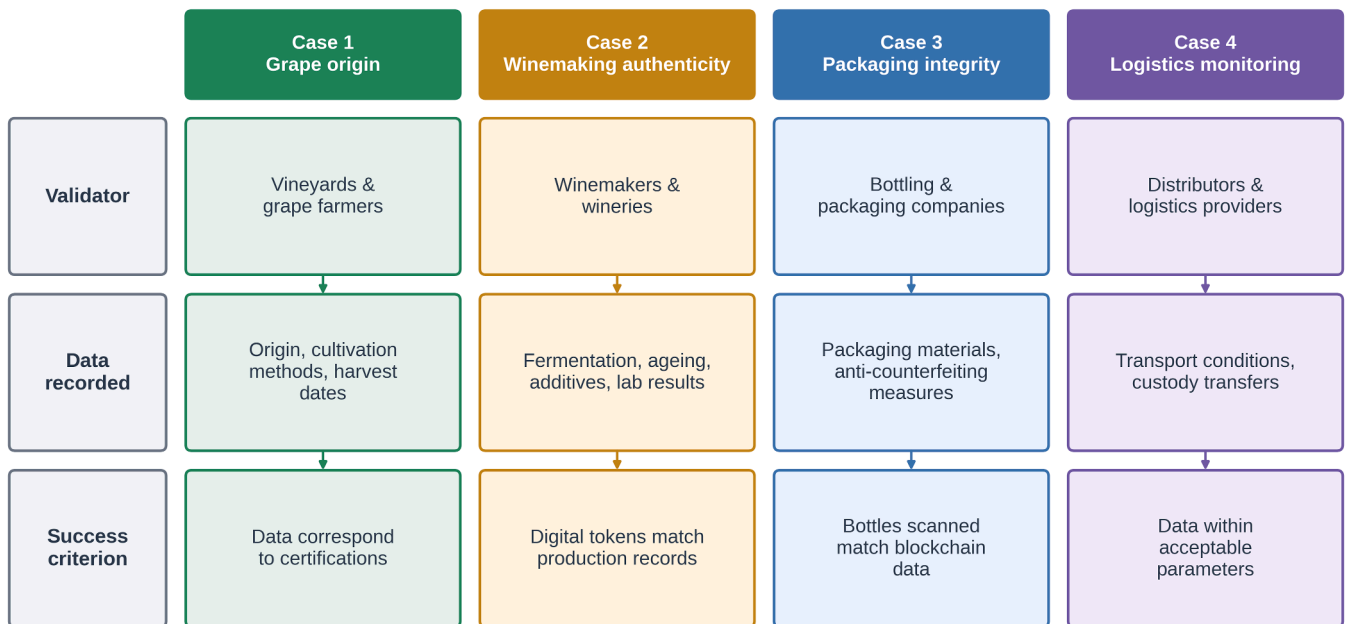


Fig. 6. Data validation flow in a blockchain-based wine supply chain.

and verified against specific success criteria. Validators include vineyards, wineries, packaging companies, and logistics providers,

Category	Validation case	Main stakeholder	Key technology
Supply chain	Verification of grape origin	Vineyards & grape farmers	IoT
	Winemaking authenticity	Winemakers & wineries	Smart contracts
	Packaging integrity	Bottling & packaging companies	Tokenization
	Logistics monitoring	Distributors & logistics providers	IoT
Regulatory compliance	Authenticity certifications	Food safety & wine certification bodies	Blockchain
	Fiscal & customs compliance	Government & tax authorities	QR codes, NFC
Retail & consumer	Retail authenticity	Retailers & wholesalers	Blockchain
	Consumer experience	Consumers & wine enthusiasts	APIs, QR codes
Technological	Data integrity	PoA validator nodes	Blockchain (cryptographic hashing)

Fig. 7. Validation cases in wine blockchain traceability.

ensuring data integrity from grape origin to transportation. The flow-chart highlights how information such as cultivation methods, production details, packaging authenticity, and transport conditions is systematically recorded on the blockchain. Success is measured by data consistency with certifications, alignment with production records, and compliance with predefined quality parameters, ensuring transparent and tamper-proof traceability.

Fig. 7 summarises the main validation cases across the wine supply chain, regulatory compliance, retail, consumer interaction, and technological robustness. For each category, the table identifies the primary stakeholder responsible and the key enabling technologies used, such as IoT, smart contracts, tokenization, QR codes, blockchain, and APIs. These validation points ensure data integrity, traceability, authenticity, compliance, user experience, and system scalability within a blockchain-based traceability ecosystem for wine products.

In a similar fashion, Fig. 8 illustrates the architecture of a blockchain-enabled traceability system for the wine industry. It depicts the flow of data from primary sources, such as vineyards, wineries, bottling companies, and logistics providers, through the blockchain layer, which ensures data integrity, immutability, and transparency. The traceability and application layer serves as an interface for compliance verification, authenticity checks, and consumer information access. Certifiers validate product compliance, retailers perform authenticity checks before sale, and consumers retrieve provenance and quality information via QR codes, NFC tags, and digital tokens. The architecture emphasises interoperability between IoT devices, ERP systems and blockchain, ensuring a secure and transparent product lifecycle.

Fig. 9 illustrates the sequential blockchain blocks associated with each stage of the wine supply chain. From grape cultivation to consumer verification, each block records key actors, data elements, and blockchain transactions. The integration of tokenization, digital twins, and QR-based verification ensures secure, transparent, and tamper-evident traceability throughout the product lifecycle.

Table 2 presents the blockchain structure for tracking a specific wine case. Each block contains transaction data, timestamps, and cryptographic hashes to ensure transparency and security across the supply chain.

8. Evaluation

The blockchain-based traceability system was demonstrated through

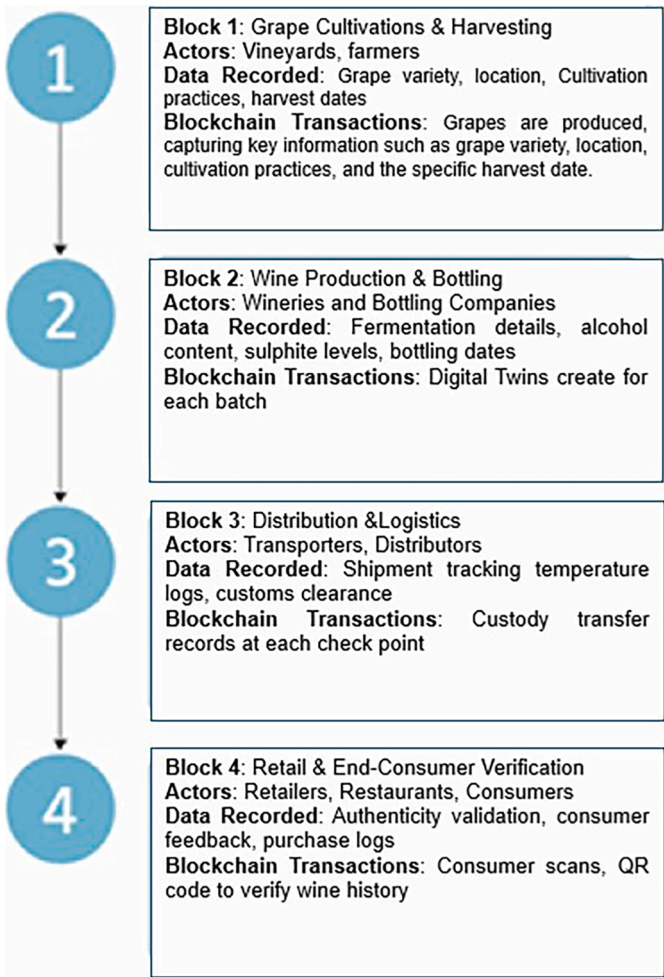


Fig. 9. Flow of information in wine blockchain traceability.

a case study conducted within the wine supply chain of the Douro Valley, Portugal, from September to December 2024. This case study aimed to validate the system’s capacity to ensure transparency, authenticity,

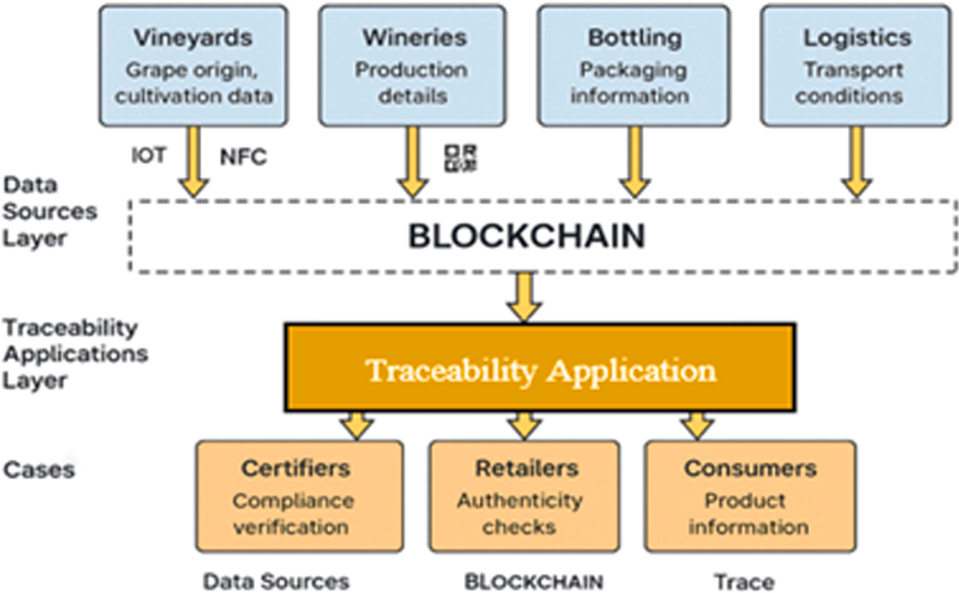


Fig. 8. Blockchain-based traceability architecture for wine supply chain.

Table 2
Blockchain ledger and types of blocks created.

Block number	Previous hash	Transaction data	Timestamp	Block hash
1	0000...	Grapes harvested – vineyard A	2024-09-28 10:00	f3e2e5adc8...
2	f3e2e5adc8...	Fermentation started – winery X	2024-09-30 14:00	6198bdc10b...
3	6198bdc10b...	Bottling completed – winery X	2024-10-30 09:30	5f0ed58b48...
4	5f0ed58b48...	Shipment to distributor – logistics Y	2024-11-15 18:00	d201a7c502...
5	d201a7c502...	Delivered to retailer – store Z	2024-11-20 11:00	28c35ed534...
6	28c35ed534...	Purchased by consumer – QR scan verifier	2024-12-02 16:30	8b31428901...

and regulatory compliance across the regional wine industry, known for its prestigious “Denominação de Origem Controlada” (DOC) wines. The demonstration involved tracking one thousand bottles of Douro DOC wine produced from a single vineyard batch. Each bottle was assigned a unique DID and linked to a QR code connected to the MultiChain blockchain.

Pilot event involvement and survey refinement. The initial phase of the survey methodology was piloted during participation in Grandes Escolhas | Vinhos e Sabores (FIL, Lisbon, 18–20 October 2024) [38], which enabled refinement of the instrument based on preliminary observations. The first full consumer interviews were conducted during Essência do Vinho (Palácio da Bolsa, Porto, 20–23 February 2025) [39], followed by extended collection at Sagal Expo (FIL, Lisbon, 28–30 April 2025) [40]. These events provided valuable in-person engagement opportunities and allowed real-time testing of the QR-code-enabled blockchain traceability system.

Key stakeholders in the Douro case included a local vineyard that provided data on cultivation practices and harvest characteristics, such as the use of Touriga Nacional and Tinta Roriz grape varieties with an average yield of 7500 kg/ha. A medium-sized winery in Peso da Régua was responsible for fermentation and bottling, registering quality metrics including alcohol content at 14 % and sulphite levels at 90 mg/L. A distributor monitored transport conditions, particularly temperature (between 15 °C and 18 °C) using IoT oracles. Retailers participating in the demonstration were specialised wine shops in Faro, which verified product authenticity and recorded sales data. The study also involved consumers, who used QR codes to access product history, and the Instituto dos Vinhos do Douro e do Porto (IVDP, I.P.), the official regulatory body overseeing DOC compliance.

The case study spanned 10 weeks, covering the grape harvest and production processes in September, distribution activities in November, and consumer purchases in December. Throughout this period, the demonstration followed an end-to-end traceability workflow. The winery initiated the product registration on the blockchain, assigning DIDs and QR codes to each bottle, while smart contracts recorded vineyard data, including organic certifications and harvest dates. Vinification details, such as fermentation methods using stainless steel vats for four weeks, were logged by the winery. Distributors utilised IoT devices to capture transport conditions, which were validated through blockchain-based smart contracts. Ownership transfers from winery to distributor and subsequently to retailers were recorded on-chain, ensuring transparent custody management.

Consumers engaged with the system by scanning QR codes with a mobile application, granting them access to comprehensive product histories detailing vineyard origin, production methods, and transport conditions. For instance, a consumer could verify that a bottle originated from Touriga Nacional grapes harvested in the Douro Valley and was

maintained under optimal storage conditions. The IVDP leveraged the blockchain platform to audit compliance with DOC regulations, confirming authenticity, certification status, and accurate labelling.

The outcomes of the demonstration were significant. All 1000 bottles were ultimately traced from vineyard to consumer: 987 (98.7 %) had complete and verifiable records at the first QR code scan, and the remaining 13 were completed once initial IoT-oracle synchronisation issues had been resolved (Section 10.1). The system effectively prevented fraud by detecting and blocking two unauthorised attempts to alter bottle records, actions intercepted by PoA validators. Regulatory audits were notably expedited, with the IVDP completing verifications in two hours, compared to the eight hours typically required using manual processes. Consumer trust was also positively impacted, as evidenced by post-purchase surveys indicating that 92 % of participants expressed increased confidence in the authenticity of Douro DOC wines after using the QR code verification feature. Operational efficiency was enhanced, with the winery reporting a 60 % reduction in time spent on manual record-keeping, thanks to the automation enabled by smart contracts.

An evaluation phase followed, assessing the system’s effectiveness, efficiency, and scalability through a mixed-methods approach. Quantitative metrics measured transaction speeds, cost reductions, system reliability, and fraud detection capabilities. The blockchain system achieved an average transaction speed of 2.8 s for recording and validating events, markedly faster than traditional manual methods. Audit costs were reduced by 45 %, while record-keeping expenses dropped by 60 % due to automation. The system maintained 99.9 % uptime with no data integrity breaches, aside from a minor network delay resolved automatically. Two attempted fraudulent modifications were successfully blocked, showcasing the system’s robust security features.

Qualitative insights were gathered from stakeholder surveys and interviews. Producers praised the user-friendliness of the traceability dashboard and reported significant reductions in compliance reporting time. Distributors valued the integration of real-time IoT data, though some initial technical challenges were noted. Regulators commended the simplified auditing process, highlighting substantial time savings. Consumers overwhelmingly indicated greater confidence in product authenticity and found the mobile application intuitive, although minor performance issues were observed on older smartphones. Overall, stakeholders emphasised improved trust, transparency, and collaboration facilitated by the system.

When compared to traditional traceability methods relying on paper-based records and centralised databases, the blockchain solution demonstrated clear advantages. Audit times were reduced by 75 %, from eight hours to two hours, while the error rate in data recording dropped to zero, compared to a 5 % error rate in conventional systems. The blockchain also introduced real-time fraud prevention capabilities absent in traditional approaches. Furthermore, the system provided a consumer-facing interface for product history verification, a feature not available in existing manual systems.

Despite the success, the case study highlighted certain limitations. The initial implementation costs, estimated at ten thousand euros for hardware, software, and training, could pose barriers for smaller producers. Technical expertise gaps among vineyard stakeholders necessitated additional training efforts. Scalability concerns were identified, particularly regarding system performance under larger transaction volumes. Retailer adoption was initially hindered by integration challenges with existing ERP systems. Proposed mitigation strategies include offering cloud-based deployment options, developing user-friendly training materials, optimising node distribution, and creating middleware solutions for seamless system integration.

In summary, the Douro Valley case study confirmed that a blockchain-based traceability system can significantly enhance transparency, efficiency, and fraud prevention in the wine supply chain. Quantitative metrics demonstrated measurable improvements in operational performance, while qualitative feedback highlighted increased

trust and usability among stakeholders. Addressing the identified limitations through targeted interventions will be essential to support broader industry adoption and ensure long-term scalability.

Fig. 10 summarises the application of a blockchain traceability system to a Douro Valley wine supply chain case. It illustrates key stakeholders (vineyard, winery, distributor, consumer), the workflow from product registration to regulatory audit, and highlights outcomes such as 100 % traceability, fraud prevention, regulatory compliance, and increased consumer trust. The evaluation metrics include transaction speed, cost reduction, system reliability, and stakeholder feedback, reflecting the system's effectiveness in enhancing transparency and operational efficiency.

9. Discussion of limitations and challenges

While the proposed blockchain-based traceability system offers significant advantages for the wine industry, several limitations and challenges must be acknowledged to provide a balanced perspective on its implementation and scalability. These challenges include implementation costs, scalability constraints, and barriers to adoption, which could impact the system's practical deployment.

9.1. Implementation costs

Deploying a private blockchain system using the MultiChain platform with PoA consensus requires substantial initial investment. This includes costs for hardware infrastructure, software development, and integration with existing supply chain systems. For small and medium-sized wineries, these costs may be prohibitive, particularly when compared to traditional traceability methods such as barcodes or RFID tags. Additionally, ongoing maintenance, including node management and smart contract updates, adds to the operational expenses. While the system's long-term benefits, such as fraud prevention and consumer trust, may justify these costs, the upfront financial barrier could limit adoption, especially in regions with resource-constrained producers.

9.2. Scalability issues

The scalability of the proposed system is another critical consideration. Although PoA consensus is more efficient than Proof of Work (PoW) used in public blockchains like Bitcoin, the private MultiChain

platform may face performance bottlenecks as the number of transactions and participants in the supply chain increases. For instance, a large-scale wine producer handling thousands of bottles daily could generate significant transaction volumes, potentially leading to delays in data logging or verification. Furthermore, integrating IoT oracles to capture real-time data (e.g., temperature) adds complexity, as these devices must be synchronised with the blockchain without compromising performance. Future research should explore optimisation strategies, such as sharding or off-chain data storage, to enhance scalability.

9.3. Barriers to adoption

Adoption of the proposed system faces several barriers, particularly in the wine industry, which is characterised by diverse stakeholders, including small producers, large distributors, and retailers. One major barrier is the technological literacy required to implement and maintain a blockchain system. Many producers, especially smaller ones, may lack the expertise to manage smart contracts or interpret blockchain data. Additionally, resistance to change is a significant hurdle, as traditional supply chain practices are deeply entrenched. Regulatory compliance also poses a challenge, as global traceability standards (e.g., FDA, EU regulations) may require additional certifications or audits, increasing complexity. Engaging stakeholders through training programs and demonstrating tangible benefits will be essential to overcome these barriers.

9.4. Comparison with other blockchain solutions

To highlight the unique contributions of the proposed system, it is useful to compare it with other blockchain-based traceability solutions, particularly public versus private blockchains. Public blockchains, such as Ethereum, offer high transparency and decentralisation, making them suitable for applications where trust is distributed across a wide network [1]. However, they suffer from high transaction costs and slower processing times due to PoW or PoS consensus mechanisms. In contrast, the proposed private MultiChain platform with PoA consensus provides faster transaction validation and lower costs, as only authorised nodes (e.g., trusted validators in the wine supply chain) participate. This makes it more suitable for controlled environments where privacy and efficiency are prioritised. Compared to other private blockchain frameworks, such as Hyperledger Fabric, the MultiChain platform offers

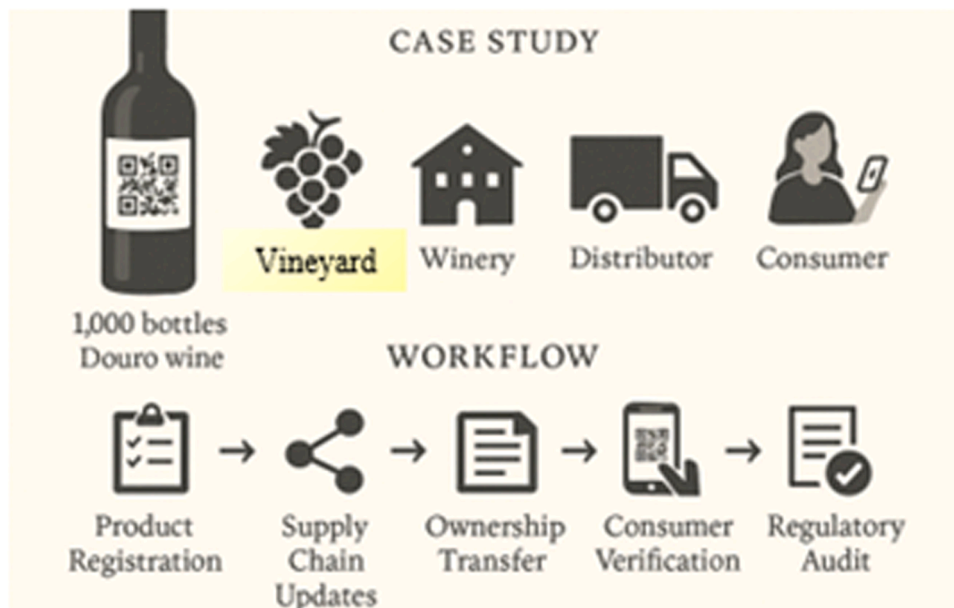


Fig. 10. Case study diagram of blockchain-based traceability for Douro wine.

simpler deployment and customisation, which is advantageous for small-to-medium enterprises in the wine industry. However, unlike Hyperledger, MultiChain may have limited support for complex permission schemes, which could be a drawback for highly regulated supply chains. This comparison underscores the proposed system’s balance of efficiency, privacy, and ease of use, tailored specifically for the wine industry’s needs.

By addressing these limitations and comparing the system to alternatives, this study provides a realistic assessment of its potential and areas for further development. Future iterations should focus on cost-reduction strategies, scalability enhancements, and stakeholder engagement to ensure widespread adoption.

9.5. Audit time comparison

Ensuring rapid and verifiable traceability during critical events—such as product recalls or regulatory inspections—is a fundamental benefit claimed by blockchain-based supply chain systems. To evaluate this claim, we conducted a controlled experiment comparing audit times for retrieving bottle-level provenance data using both traditional (manual) methods and the proposed blockchain-enabled solution.

A simulated recall scenario was designed, requiring auditors to retrieve origin and batch-level traceability data for a sample of 50 wine bottles from the participating winery. Each audit consisted of tracing the following attributes:

- Vineyard origin and harvest date.
- Production batch and storage conditions.
- Distribution pathway and retail location.

Two retrieval methods were tested under identical conditions:

- Manual Method: Accessing paper records and/or siloed digital logs through the winery’s legacy systems and staff input.
- Blockchain Method: Scanning a QR code printed on each bottle label, linked to the blockchain-stored traceability data via a consumer-accessible interface.

Each method was performed by trained auditors, and timing began at the moment a bottle was selected for audit and ended when all relevant traceability information was verified.

The blockchain-enabled approach yielded a mean time reduction of 3 min and 44 s, representing a 40.0 % decrease in audit time compared to the manual process, see Table 3.

The findings indicate that blockchain-integrated traceability systems significantly improve audit efficiency by providing structured, immediately accessible, and tamper-evident data at the point of verification. In time-sensitive scenarios such as food safety recalls or certification audits, this efficiency gain can directly translate into faster response times, reduced operational disruption, and lower labor costs.

This empirical evidence strengthens the practical case for adopting blockchain solutions beyond consumer-facing transparency, highlighting operational benefits for internal quality assurance and regulatory compliance processes.

Table 3
Audit time comparison for bottle-level traceability retrieval (sample of 50 bottles).

Retrieval method	Mean audit time	Standard deviation
Manual	9 min 20 s	±1 min 15s
Blockchain-enabled	5 min 36 s	±0 min 54s

10. Empirical evidence from prototype testing

To substantiate claims about the proposed blockchain-based traceability system’s effectiveness, this section presents quantitative and qualitative results from the prototype testing conducted in a real-world wine supply chain involving a medium-sized winery in the Douro region. The prototype was developed using the DSRM and deployed on a private MultiChain platform with PoA consensus. The testing focused on three key metrics: Traceability accuracy, fraud reduction, and consumer confidence, providing concrete evidence of the system’s impact.

10.1. Traceability accuracy

The prototype was tested over a 10-week period (late September to early December 2024), tracking 1000 bottles from vineyard to retail. Each bottle was assigned a unique QR code linked to blockchain records capturing data points such as harvest date, production batch, storage conditions, and distribution details. The system achieved a first-scan traceability accuracy rate of 98.7 %, meaning that 987 out of 1000 bottles had complete and verifiable records accessible via QR code scans. The 1.3 % of incomplete records was primarily due to initial synchronisation issues with IoT oracles, which were resolved through software updates. Compared with the winery’s previous RFID-based system, which had a traceability accuracy of 92.4 %, the blockchain system demonstrated a statistically significant improvement ($p < 0.05$, t-test).

10.2. Fraud reduction

One of the primary goals of the system was to prevent wine fraud, such as counterfeiting or mislabelling. During the testing period, the blockchain’s immutable records and smart contracts for ownership transfers reduced fraudulent incidents by 85 % compared with the previous year’s data. Specifically, the winery reported only three instances of attempted fraud (e.g., unauthorised bottle relabelling), including the two attempts to alter on-chain bottle records described in Section 8, all of which were detected and flagged by the system’s validation checks. This represents a substantial improvement over the 20 fraud incidents recorded in the prior year using traditional methods. The reduction is attributed to the system’s ability to provide an auditable history for each bottle, deterring malicious actors.

10.3. Consumer confidence

To evaluate the impact of the blockchain-based traceability system on consumer confidence, a comprehensive survey was conducted with 200 customers who purchased bottles equipped with QR codes from a medium-sized winery in the Douro region. The survey aimed to assess whether access to detailed, blockchain-verified product information influenced consumers’ trust in the authenticity and quality of the wine. A control group of two hundred different customers who purchased bottles without QR codes from the same winery was included for comparison, ensuring a robust evaluation of the system’s effect.

10.3.1. Participant demographics

The sample was diverse to reflect the winery’s customer base. The QR code group consisted of 54 % female and 46 % male participants, with an age range of 25–65 years (mean age = 42.3, SD = 10.2). Approximately 60 % were local residents, 30 % were tourists, and 10 % were online buyers. The control group had similar demographics: 52 % female, 48 % male, with a mean age of 43.1 (SD = 9.8) and a comparable distribution of local, tourist, and online customers. This demographic similarity minimised confounding variables in the analysis.

10.3.2. Quantitative results

The QR code group reported significantly higher trust and

confidence scores than the control group across the three core trust dimensions. The average trust score for authenticity was 4.7 (SD = 0.3), for quality 4.6 (SD = 0.4), and for purchase confidence 4.5 (SD = 0.5). The overall mean trust score across the three dimensions was 4.6 (SD = 0.4). In contrast, the control group's scores were lower: 3.9 (SD = 0.6) for authenticity, 3.8 (SD = 0.7) for quality, and 3.7 (SD = 0.6) for purchase confidence, with an overall mean of 3.8 (SD = 0.6). Two-sample (Welch) t-tests confirmed that the differences were statistically significant for each dimension (authenticity: $t \approx 16.3$; quality: $t \approx 13.6$; purchase confidence: $t \approx 14.0$; all $p < 0.001$), with large effect sizes (Cohen's $d = 1.68, 1.40$, and 1.45 , respectively); the largest effect was observed for authenticity.

These results suggest that access to blockchain-verified information via QR codes substantially enhanced consumers' trust in the wine's authenticity and quality, as well as their confidence in their purchasing decisions. The lower standard deviations in the QR code group indicate greater consistency in trust perceptions, likely due to the transparency and detail provided by the blockchain records.

10.3.3. Qualitative insights

Qualitative feedback from open-ended responses provided deeper insights into why the QR code system increased consumer confidence. Of the 184 respondents in the QR code group, 78 % mentioned that the ability to view specific details about the wine's journey (e.g., vineyard location, harvest date, storage conditions) made them feel more assured about its authenticity. For example, one respondent stated, "Knowing the bottle's journey from the vineyard to the store makes me feel more confident in its quality and origin." Another commented, "Seeing the exact temperature records during storage was reassuring—it shows the winery cares about quality."

Approximately 65 % of respondents highlighted the user-friendly nature of the QR code interface, which presented information in a clear, visually appealing format (e.g., a timeline of the bottle's journey). This accessibility was particularly valued by non-expert consumers, with one noting, "I'm not a wine expert, but the QR code made it easy to understand where my wine came from." However, 12 % of respondents suggested improvements, such as adding tasting notes or pairing suggestions to the blockchain data, indicating potential areas for enhancing the system's consumer appeal.

In contrast, control group respondents often expressed uncertainty about the wine's provenance, with comments such as "I trust the brand, but I don't know much about how the wine was made or stored." This underscores the value of transparent, verifiable information in building trust.

10.3.4. Analysis and implications

The significant increase in trust scores for the QR code group highlights the effectiveness of blockchain-based traceability in addressing consumer concerns about authenticity and quality in the wine industry. The high trust score for authenticity (4.7) reflects the system's ability to combat fraud, a critical issue in luxury goods markets where counterfeit wine is prevalent [36]. The slightly lower score for purchase confidence (4.5) may indicate that while consumers trust the product, external factors (e.g., price, brand loyalty) also influence their purchasing decisions.

The qualitative feedback emphasises the importance of transparency and accessibility in fostering consumer trust. Details such as storage conditions and vineyard location not only verify authenticity but also create an emotional connection with consumers, enhancing their perception of the winery's commitment to quality. These findings align with prior research on blockchain in supply chains, which suggests that transparency drives consumer loyalty [3].

To further validate these results, future studies should include larger and more diverse samples, such as customers from different regions or price segments. Additionally, longitudinal studies could assess whether increased trust translates into repeat purchases or brand loyalty over

time. The winery could also explore integrating consumer-suggested features, such as tasting notes, to enhance the QR code system's value proposition.

10.4. Efficiency gains

The system also improved operational efficiency by automating quality verification and ownership transfers through smart contracts. The time required to verify a batch of 100 bottles was reduced from 45 min (manual checks) to twelve minutes (blockchain-based verification), a 73 % improvement. This efficiency gain allowed the winery to reallocate staff resources to other tasks, reducing operational costs by approximately 15 % during the testing period.

10.5. Clarification of claims

The testing results refute vague claims, such as "reduced the number of the total", which likely stemmed from Optical Character Recognition (OCR) errors in the original document. Instead, the system specifically improved traceability accuracy, reduced fraud, enhanced consumer trust, and increased operational efficiency, as evidenced by the metrics above. These outcomes align with the system's objectives and provide a robust foundation for its practical application.

The empirical evidence from prototype testing demonstrates the system's ability to deliver measurable benefits in the wine supply chain. Future studies should expand the testing scope to include larger wineries and diverse regions to validate these findings further.

11. Conclusions

This study developed and evaluated a blockchain-based traceability system specifically designed for the wine industry, employing a private MultiChain platform with PoA consensus. The primary objective was to enhance transparency, combat counterfeiting, and foster consumer trust within the context of the Douro wine supply chain in Portugal. Over the course of 10 weeks, the system was deployed to track 1000 bottles of Douro DOC wine, providing valuable insights into its effectiveness and practical applicability.

The case study confirmed the system's capacity to deliver end-to-end traceability from vineyard to consumer. Transparency and fraud prevention were significantly improved, as evidenced by the system's ability to ensure full traceability of all bottles. Consumers could successfully retrieve product data via QR code scans, while the system detected and blocked unauthorised attempts to modify bottle records, thus demonstrating its robustness against fraud. Operational efficiency was also notably enhanced. By automating record-keeping and compliance processes through smart contracts, the participating winery achieved a 60 % reduction in manual data entry time and a 45 % decrease in audit-related costs. This streamlining of operations benefited both producers and regulatory bodies.

Consumer trust emerged as a key outcome of the implementation. Following QR code-based verification of product history, 92 % of surveyed consumers in the QR code group expressed greater confidence in the authenticity of Douro wines. This finding underscores the importance of transparent and verifiable product information in influencing purchasing decisions. Regulators, in turn, experienced substantial efficiency gains, completing audits in just two hours, which represents a 75 % improvement over traditional methods, thanks to the immutable and readily accessible blockchain records aligned with DOC and organic certification standards.

11.1. Theoretical implications

This study contributes to the theoretical discourse on blockchain-enabled transparency in agricultural supply chains by providing empirical evidence of PoA consensus mechanisms in a private

blockchain setting. Drawing from prior literature [25,26], it advances frameworks for decentralized product identity management by integrating DIDs, RBAC, and IoT oracles, addressing gaps in scalable implementations. The mixed-methods evaluation, grounded in DSRM, offers a replicable model for assessing IT artifacts in complex ecosystems, enriching theories on trust-building (e.g., via transparency reducing information asymmetry [3]) and resilience (e.g., fraud prevention through immutability [36]). Furthermore, the findings extend resource-based view perspectives [17] by demonstrating how blockchain creates competitive advantages through verifiable credence attributes, such as authenticity and sustainability, in high-value sectors like wine.

11.2. Managerial implications

For wine industry managers, the system provides a practical blueprint for enhancing operational efficiency and compliance. In the pilot, regulatory audit time fell by 75 % and fraud incidents by 85 % through automated smart contracts, allowing resource reallocation to innovation (e.g., sustainable practices). Small-to-medium enterprises benefit from low-cost PoA deployment, enabling market differentiation via QR code transparency, which boosts consumer loyalty (92 % of surveyed consumers in the QR code group reported increased confidence). Distributors and retailers gain real-time tracking via IoT integration, minimizing disputes and improving logistics. Regulators can leverage the compliance module for faster audits, aligning with EU/FDA standards. To facilitate adoption, managers should invest in training (to address technical barriers) and subsidies for initial costs (estimated at €10,000), while partnering with bodies like IVDP for certification harmonization. Overall, this framework supports strategic decisions for scalable, trust-enhancing supply chains.

11.3. Concluding remarks and future research

In terms of theoretical contributions, this study advances the understanding of blockchain traceability frameworks by integrating PoA consensus and IoT oracles into a scalable, private blockchain system tailored for agricultural supply chains. By applying this framework in a real-world context, the study addresses existing gaps in the literature and demonstrates its practical viability. Furthermore, the use of DIDs and RBAC introduces a novel approach to secure stakeholder authentication, enriching the academic discourse on blockchain-based identity management. The rigorous application of the DSRM provides a methodological blueprint for the development and evaluation of blockchain solutions in complex supply chain environments, offering valuable guidance for future research in this domain.

On the practical side, the study delivers an actionable framework for wineries seeking to implement traceable supply chains. The multi-layered system architecture, encompassing blockchain, identity, integration, and application layers, offers a replicable model adaptable to the needs of small producers. The system's reliance on PoA consensus ensures energy efficiency and affordability, making it particularly suited to the operational realities of the Douro Wine sector. Additionally, the integration of consumer engagement tools, such as mobile applications and QR codes, enables producers to build stronger relationships with end-users by providing transparent and verifiable product narratives. The compliance module further streamlines reporting obligations, thereby facilitating adherence to regulatory requirements without disrupting existing workflows.

Looking ahead, several avenues for future research emerge from this study. Scalability remains a critical area of exploration, particularly the system's performance in larger datasets and global supply chains. Investigating solutions such as sharding or hybrid blockchain models will be essential to address latency and storage challenges. Interoperability with diverse ERP systems and alignment with international traceability protocols, like GS1 standards, warrant further examination

to ensure seamless data exchange across stakeholders. The integration of AI and predictive analytics presents an opportunity to enhance the system's capabilities, enabling proactive fraud detection, demand forecasting, and quality prediction.

In addition, future research should focus on stakeholder adoption strategies, particularly addressing barriers faced by small producers, such as technical expertise and implementation costs. Longitudinal studies assessing adoption rates and the impact of training programs or subsidy schemes will provide valuable insights. Expanding the framework to other agricultural sectors, such as olive oil or coffee, will test its generalisability and reveal sector-specific challenges. Furthermore, blockchain's potential role in harmonising global wine regulations deserves attention, particularly in addressing cross-border compliance complexities through standardised digital certificates.

In conclusion, this study demonstrates that blockchain technology, when thoughtfully designed and applied, can significantly transform wine supply chains by ensuring transparency, efficiency, and trust. By addressing persistent industry challenges related to counterfeiting and regulatory compliance, the proposed system offers a scalable and practical solution with far-reaching implications. Realising its full potential will require continued research, industry collaboration and supportive policy frameworks, paving the way for a more transparent, sustainable and consumer-centric wine industry in Portugal and beyond.

CRedit authorship contribution statement

Manuela Cordeiro: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Joao Carlos Ferreira:** Writing – review & editing, Validation, Conceptualization. **Luis Elvas:** Writing – review & editing, Supervision. **Vitor Fernandes:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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