
Blockchain and Artificial Intelligence for Wine Industry Traceability and Recommendation: Current Trends and Research Gaps

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Abstract

The wine industry faces growing demands for supply chain transparency, product authenticity verification, and consumer-oriented digital services. This paper presents a literature review of blockchain and artificial intelligence (AI) technologies and their applications in the wine industry. Drawing on existing research, the study examines the foundational principles of blockchain technology and its deployment in supply chain management, AI-based recommendation systems and their adaptation to wine-food pairing tasks, the digital transformation of the wine industry within Industry 4.0 and 5.0 frameworks, and fuzzy logic-based multi-criteria decision-making (MCDM) models for technology evaluation. The review identifies key research gaps, including the limited development of hybrid systems that integrate supply chain traceability with AI-driven recommendations in a unified ecosystem, insufficient application of fuzzy MCDM methods in blockchain platform selection for domain-specific contexts, and the underdevelopment of cross-cultural wine-food pairing models. The analysis demonstrates that the convergence of blockchain and AI technologies offers a promising foundation for the digital transformation of the wine industry, combining supply chain transparency with intelligent, personalized consumer services. Future research directions are discussed, emphasizing the need for integrated hybrid approaches that address the identified gaps.

Keywords: blockchain, artificial intelligence, wine industry, supply chain, recommendation systems, fuzzy MCDM, digital transformation, traceability

1. Introduction

The global wine industry is undergoing a significant shift driven by increasing consumer expectations regarding product transparency, authenticity, and personalized experience. In contemporary markets, consumers demand not only high - quality products, but also reliable information about product origin, production processes, and compatibility with food pairings

(Chiaraluce, Bentivoglio, Finco, Fiore, & Galati, 2024). Simultaneously, producers face persistent challenges related to counterfeit products, fragmented supply chain data, and the need for more effective digital communication with end consumers.

The emergence of blockchain technology and artificial intelligence (AI) offers new possibilities for addressing these challenges. Blockchain provides a decentralized, immutable infrastructure for supply chain data management, while AI enables the development of intelligent, personalized recommendation services (Zheng, et al. 2017, Russell 2010). When integrated into a unified digital ecosystem, these technologies can support both the operational transparency of wine producers and the experiential needs of consumers.

Georgia, recognized as the birthplace of wine with over 8,000 years of uninterrupted winemaking tradition and more than 500 native grape varieties, represents a particularly relevant context for such developments (Adamashvili, Zhizhilashvili, & Tricase, 2024). The qvevri winemaking method, a UNESCO-recognized intangible cultural heritage, further underlines the importance of authenticating and tracing Georgian wine in global markets.

Despite growing interest in blockchain and AI applications across various industries, their integrated use in the wine sector remains underexplored. Most existing studies address either supply chain traceability or recommendation systems in isolation, without combining these dimensions into a coherent hybrid architecture. Furthermore, the application of fuzzy logic-based MCDM methods to blockchain platform selection in domain-specific contexts such as the wine industry has received limited scholarly attention.

This paper presents a structured literature review covering: the foundations and supply chain applications of blockchain technology; AI-based recommendation systems, with a focus on wine-food pairing; the digital transformation of the wine industry in the context of Industry 4.0 and 5.0; fuzzy logic and MCDM approaches relevant to technology evaluation; and an analysis of existing research gaps and future directions.

2. Blockchain Technology: Foundations and Applications

2.1 Foundational Principles

Blockchain is a distributed ledger technology that enables secure, transparent, and immutable recording of transactions through a decentralized architecture (Antonopoulos A. M., 2014). The technology is built on a chain of blocks structure, where each block contains a set of transactions cryptographically linked to the preceding block, ensuring data integrity and preventing unauthorized modifications (Nakamoto, 2008; Copigneaux, 2020).

A key characteristic of blockchain is its decentralization, which distributes data storage across multiple network nodes. Unlike traditional centralized systems, blockchain eliminates the single point of failure (SPOF) and ensures continuous synchronization of the ledger among participants (Zheng, Xie, Dai, Chen, & Wang, 2017). Consensus mechanisms - most notably Proof of Work (PoW) and Proof of Stake (PoS) - govern agreement among network participants on transaction validity. PoW relies on computational resources to solve cryptographic puzzles, while PoS uses participants' stake in the network as the basis for validation (Buterin, 2013).

A critical component of blockchain ecosystems is the smart contract: self-executing code that automatically enforces predefined conditions (Wohrer, 2018; Taherdoost, 2023). Smart contracts reduce the need for intermediaries, automate processes, and increase operational efficiency (Antonopoulos A. M., 2018). Blockchain platforms are broadly classified into public, private, and consortium types. Public blockchains such as Ethereum provide open access and strong decentralization, while private and consortium blockchains offer controlled access and higher throughput for organizational applications (Kechagias, 2023; Zheng, Xie, Dai, Chen, & Wang, 2017).

2.2 Blockchain in Supply Chain Management

Supply chain management encompasses the complex, multi-stage process of production, processing, storage, transportation, and distribution of goods (Kshetri, 2018). Traditional supply chain systems relying on centralized databases are prone to information fragmentation and reduced data reliability (Sabeti, 2019; Parry, 2024). Blockchain addresses these limitations by providing a unified, transparent, and tamper-resistant data infrastructure accessible to all authorized participants (Danese, 2021).

One of the most significant applications of blockchain in supply chain management is product traceability - maintaining a complete, verifiable record of a product's movement from raw material origin through production to final delivery (Wang, 2021; Abeyratne & Monfared, 2016). Traceability is particularly valuable in contexts where quality control and authenticity verification are critical, such as high - value food and beverage products (Cimino, 2012).

Contemporary research confirms that blockchain technology is especially effective for managing supply chains of high-value food products, reducing informational asymmetry and enabling reliable communication of provenance to consumers (Chiaraluce, Bentivoglio, Finco, Fiore, & Galati, 2024). Smart contracts further extend these capabilities by automating processes such as payment authorization and quality verification, reducing manual intervention and operational costs (Christidis, 2016; Buterin, 2013).

In the wine industry, the "Farm to Table" concept - tracking a product from vineyard to consumer - is particularly well-suited to blockchain implementation (Galvez, 2018; Casino, 2019).

Blockchain enables the registration of wine batches and bottles, documentation of production processes, and recording of laboratory analysis results. QR code integration further enables consumers to access the full provenance history of a product through a simple scan (Kamilaris et al., 2019; Biswas, 2017). Studies confirm that this approach increases consumer trust and reduces the risk of counterfeit products (Kechagias, 2023; Pesme, 2023).

3. Artificial Intelligence and Recommendation Systems

3.1 AI-Based Recommendation Systems

Artificial intelligence encompasses computational methods capable of performing tasks characteristic of human intelligence, including learning, analysis, decision-making, and adaptation (Russell 2010). Among the most practically significant AI applications are recommendation systems - data-driven tools that analyze user behavior, preferences, and contextual factors to generate personalized suggestions (Aggarwal, 2016; Ricci, Rokach, & Shapira, 2021).

Recommendation systems are broadly classified into three categories. Content-based systems analyze item characteristics and past user behavior to identify similar objects. Collaborative filtering leverages collective behavioral data to identify similarities among users and generate recommendations accordingly. Hybrid systems combine multiple approaches to mitigate the limitations of individual methods and improve accuracy (Adomavicius, 2005).

Knowledge-based recommendation systems are particularly relevant in domains where user interaction data is limited but structured expert knowledge exists. These systems encode domain rules and expert logic to guide recommendations (Burke, 2000; Ricci et al., 2021). Natural language processing (NLP) further extends the capabilities of modern recommendation systems by enabling the analysis of textual user feedback and facilitating conversational interfaces (Jurafsky, 2000; Cambria & White, 2014).

3.2 AI Approaches for Wine-Food Pairing

Wine-food pairing is a complex task that combines sensory characteristics, chemical composition, and cultural traditions to identify harmonious combinations (Harrington, 2007; Spence, 2020). Traditional pairing guidance relies on principles established in sommelier practice, encompassing acidity, tannins, sweetness, alcohol content, body, and textural characteristics. For example, high-tannin wines pair well with fatty dishes, while high-acidity wines complement sour or citrus-forward foods (King & Cliff, 2005). From an informatics perspective, these sensory and physicochemical attributes can be modeled as input features for AI-based recommendation systems, where acidity, sweetness, tannins, body, fat content, spiciness, texture, and flavor

intensity are translated into decision criteria for content-based and knowledge-based recommendation models (Patsatsia, 2026).

AI-based approaches to wine-food pairing primarily draw on knowledge-based models that encode expert rules and domain knowledge. This approach is particularly effective when large-scale user behavioral data is unavailable, but well-defined logical rules govern the task (Burke, 2000). Score-based models assign compatibility ratings to wine-food pairs, enabling ranked recommendations and comparison of alternatives (Aggarwal, 2016).

A notable emerging direction is cross-cultural recommendation modeling, which accounts for diverse culinary traditions. In a globalized context, consumers frequently seek combinations that cross cultural boundaries, such as Georgian wine with Italian cuisine or vice versa (Prescott, 2013). Bidirectional recommendation systems-providing wine suggestions for a given dish and dish suggestions for a given wine-represent a further development that enhances flexibility and user experience (Gupta & Katarya, 2024).

Context-aware recommendation systems, which factor in occasion, mood, and social setting, are also gaining attention in the wine domain, where selection is influenced not only by product characteristics but also by consumption context (Adomavicius, 2005). The integration of AI in wine-food pairing thus creates opportunities for intelligent, personalized services grounded in sensory science and cultural knowledge (Jannach, Zanker, Felfernig, & Friedric, 2010).

4. Wine Industry Digital Transformation: Industry 4.0 and 5.0

Contemporary industrial development is shaped by successive technological paradigms that progressively transform production, management, and consumer relations. Industry 4.0 - the fourth industrial revolution is characterized by the integration of cyber-physical systems, the Internet of Things (IoT), big data analytics, and AI into unified smart ecosystems (Xiang, et al., 2023). Smart Factories within this paradigm operate as interconnected environments where devices and systems function as a cohesive whole (Kaur, Potdar, & Agrawal, 2023).

In viticulture and wine production, Industry 4.0 enables smart viticulture systems that use sensors, IoT devices, and data analytics to monitor soil moisture, climatic conditions, and grape quality in real time, improving yields and reducing resource consumption (Matese & Di Gennaro, 2015). Blockchain technology is a key component of Industry 4.0 supply chain management, providing data reliability, transparency, and traceability while AI enables data analysis, forecasting, and personalized services (Javaid, Haleem, Singh, & Suman, 2022).

The combined use of IoT, AI, and blockchain in the wine industry represents a promising integrated approach for real-time supply chain monitoring, quality traceability, and intelligent

consumer interaction-a direction increasingly recognized in recent literature as central to the sector's digital transformation (Adamashvili, Zhizhilashvili, & Tricase, 2024).

Industry 5.0 advances beyond the efficiency-driven focus of its predecessor to emphasize human-centered, sustainable, and socially responsible technology deployment (Nahavandi, 2019). This paradigm recognizes that technology should augment human capabilities rather than merely automate processes, and that systems should be tailored to individual needs (Xu, X, Lu, Y, Vogel-Heuser, B, & Wang, L, 2021). In the wine industry, Industry 5.0 principles are particularly meaningful: wine is not only a product but a cultural and experiential object, and consumers value not just quality but narrative, origin, and personalized engagement (Spence, 2020). The integration of blockchain and AI technologies thus supports both the operational goals of Industry 4.0 and the human-centered orientation of Industry 5.0, creating a foundation for holistic digital transformation (Leng, Ruan, Jiang, Xu, & Liu, 2020; Carayannis & Morawska-Jancelewicz, 2022).

5. Fuzzy Logic and Multi-Criteria Decision Making

Fuzzy logic, introduced by Lotfi A. Zadeh, provides a mathematical framework for modeling uncertainty, imprecision, and subjective evaluation (Zadeh, 1965). Unlike classical Boolean logic, which assigns binary truth values, fuzzy logic operates with membership degrees in the continuous interval $[0, 1]$, enabling the representation of linguistic categories such as "high security" or "low cost" in quantitative form. Membership functions define the degree to which a given value belongs to a particular fuzzy set (Zimmermann, 2011).

Triangular Fuzzy Numbers (TFNs), defined by three parameters (l, m, u) representing the lower bound, most probable value, and upper bound respectively, are among the most widely used constructs in practical fuzzy modeling. TFNs provide a compact and intuitive method for encoding expert judgment under uncertainty (Zimmermann, 2011). Related work in the Georgian scientific context has also explored advanced fuzzy-based approaches to decision analysis (Sirbiladze, Khutsishvili, & Ghvaberidze, 2014).

Multi-Criteria Decision Making (MCDM) provides a methodological framework for evaluating alternatives across multiple, often conflicting criteria. Fuzzy MCDM integrates fuzzy logic into this framework, enabling the formalization of qualitative, subjective, and uncertain assessments in a structured quantitative model (Kahraman, 2008). The key advantages of fuzzy MCDM include: the accommodation of uncertainty and subjectivity; formalization of expert knowledge; integrated evaluation across heterogeneous criteria; and flexibility in weighting criteria according to context.

In the context of blockchain platform selection, decision-making requires the simultaneous analysis of parameters including scalability, security, decentralization, interoperability, cost, ecosystem maturity, and smart contract support-many of which resist precise numerical specification (Belotti, Božić, Pujolle., & Secci, 2019). Scenario-based fuzzy MCDM analysis, in which different criteria receive different weights depending on the application context (e.g., security-oriented vs. performance-oriented scenarios), allows decisions to be adapted to real requirements. While some recent studies have applied fuzzy MCDM to blockchain platform evaluation in general enterprise contexts (Muradi, 2022), their application to domain-specific hybrid platforms-particularly in the wine industry-remains limited (Belotti, Božić, Pujolle., & Secci, 2019).

6. Research Gaps and Future Directions

Analysis of the existing literature reveals that while significant progress has been made in blockchain supply chain applications and AI-based recommendation systems individually, their integration into unified digital ecosystems remains limited and fragmented (Saber, 2019). The main research gaps identified from the reviewed literature are summarized in

Table 2.

Table 2. Research Gaps in Blockchain-AI Integration for the Wine Industry

Research area	Current focus	Limitation	Identified gap
Blockchain in wine supply chain	Traceability and authenticity	Limited consumer-facing intelligence	Need for blockchain-AI integration
Wine-food recommendation	Sensory and preference-based pairing	Weak link with provenance data	Need for traceability-enriched recommendations
Blockchain platform selection	General technical evaluation	Limited domain-specific fuzzy MCDM	Need for wine-industry-oriented platform selection
Cross-cultural pairing	Local or general pairing principles	Limited intercultural pairing models	Need for intercultural sensory models

Blockchain-based supply chain systems are primarily oriented toward data storage and verification, with limited incorporation of intelligent, consumer-facing functionality (Tian, 2017). Conversely, recommendation systems for wine and food pairing largely operate independently of supply chain data. Although wine-food pairing can be modeled through sensory and physicochemical attributes and translated into feature-based or rule-based recommendation logic (Patsatsia, 2026), conventional recommendation approaches generally rely on item features, user preferences, or interaction data rather than verified product provenance information (Ricci, Rokach, & Shapira, 2021). The integration of traceability with intelligent recommendation in a single ecosystem thus remains a significant research gap.

Cross-cultural wine-food pairing models are insufficiently developed: most existing approaches are bounded by single cultural or geographic contexts, limiting their applicability in multicultural settings (Harrington, 2007; Spence, 2020). The development of models capable of integrating diverse culinary traditions-such as Georgian and Italian wine and cuisine-represents an underexplored direction.

Fuzzy MCDM methods are rarely applied to blockchain platform selection in domain-specific applications. Existing evaluations typically rely on fixed metrics that do not adequately capture uncertainty or contextual dependency (Belotti, Božić, Pujolle., & Secci, 2019). Methodological frameworks that combine fuzzy logic, MCDM, and domain requirements for sector-specific blockchain adoption remain scarce.

Future research should address these gaps through the development of integrated hybrid architectures that combine blockchain-based traceability, AI-driven recommendations, and structured decision-making models. Particular attention should be given to: the enrichment of recommendation systems with verified supply chain data; the development of cross-cultural sensory pairing models grounded in Georgian and Mediterranean wine traditions; the application of scenario-based fuzzy MCDM to blockchain platform selection in the wine industry context; and the validation of proposed systems with real-world user feedback and industry data.

7. Conclusion

This paper has reviewed the current state of research at the intersection of blockchain technology, artificial intelligence, and the wine industry. The analysis demonstrates that blockchain offers robust capabilities for supply chain transparency and product traceability, while AI-based recommendation systems provide a foundation for personalized, knowledge-driven consumer services. The Industry 4.0 and 5.0 frameworks underscore the importance of integrating these technologies within human-centered, sustainable digital ecosystems.

Fuzzy logic and MCDM methods provide valuable tools for navigating the complexity of technology selection under uncertainty—a challenge particularly relevant when evaluating blockchain platforms for domain-specific applications. The review identifies key research gaps that limit the practical realization of integrated blockchain-AI systems in the wine industry, including the absence of unified hybrid architectures, underdeveloped cross-cultural pairing models, and insufficient application of fuzzy MCDM to blockchain platform selection in domain-specific contexts.

Addressing these gaps represents a meaningful direction for future research, with practical implications for wine producers, technology developers, and consumers. The convergence of blockchain and AI technologies, grounded in the rich cultural heritage of wine-producing regions such as Georgia and Italy, offers a promising pathway toward more transparent, intelligent, and personalized digital services in the wine industry.

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