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SURVEY

Bottling Up Trust: A Review of Blockchain Adoption in Wine Supply Chain Traceability

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ABSTRACT Though viticulture, wine production and distribution, involves processes mainly revolving around a single component/ingredient — grapes, it still faces the challenges of supply chain management. Supply chains require significant trust among stakeholders, and whilst for the most parts modern day supply chains 'work', it is when failures/mistakes occur that risks are high. Blockchain technology has emerged as a potential solution to confront supply chain-related traceability, transparency, and trust issues — of which extensive work has been done in applying it to wine sector. In this paper, we provide an overview of the technology and its capacity to bring about transformative changes to the viticulture supply chain. The current state of blockchain assimilation in the wine supply chain is presented, whilst highlighting the benefits and challenges associated with utilising blockchain within the wine industry-related supply chains. We pinpoint technological, legal, and adoption obstacles that must be overcome to ensure the successful integration of blockchain within the viticulture supply chain. Drawing on the state-of-the-art and industry practices, we propose directions to overcome hurdles — which may better support enhanced supply chain traceability, amplified transparency, and consumer trust, improved quality assurance and safeguarding against counterfeiting and fraud within the viticulture industry.

INDEX TERMS Blockchain, counterfeiting, sustainability, traceability, transparency, trust, wine supply chain.

I. INTRODUCTION

With the expansion of the global viticulture sector, new challenges and opportunities are emerging, impelled by factors such as globalization, fluctuating consumer demands, and advancements in viticulture and enological technologies [1], [2]. Recent years have seen the industry placing heightened emphasis on traceability, sustainability, and the authenticity of vinous products in reaction to these concerns [3]. Europe, with its expansive history, distinguished reputation, and dominant role in the global viticulture market, is leading the charge in these efforts to enhance supply chain traceability and preserve consumer trust [3], [4]. The European Union has been active in regulating areas relating to wine traceability. First and foremost, the fundamental Regulation (EU) No 1308/2013 establishes the general legal framework for wine products with a strong emphasis on oenological practices, geographical indications, and wine certification. In addition, the recent Regulation (EU) 2021/2117 has amended Regulation (EU) 1308/2013 by overhauling the wine labeling requirements and procedures. These changes will take effect from 8 December 2023 onwards. Finally, next to the aforementioned Regulations, the EU has enacted a number of important delegated acts, such as: i) Commission Delegated Regulation (EU) 2019/934 - as regards wine-growing areas where the alcoholic strength may be increased, authorised oenological practices and restrictions applicable to the production and conservation of grapevine products, the minimum percentage of alcohol for by-products and their disposal, and publication of OIV files, ii) Commission Delegated Regulation (EU) 2019/33 - as regards applications for protection of designations of origin, geographical indications and traditional terms in the wine sector, and iii) Commission Delegated Regulation (EU) 2018/273 - as regards the scheme

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of authorisations for vine plantings, the vineyard register, accompanying documents and certification, the inward and outward register, compulsory declarations, notifications and publication of notified information, relevant checks and penalties, as well as implementing Regulations such as: i) Commission Implementing Regulation (EU) 2019/935 - as regards analysis methods for determining the physical, chemical and organoleptic characteristics of grapevine products and notifications of EU countries decisions concerning increases in natural alcoholic strength, ii) Commission Implementing Regulation (EU) 2019/34 - laying down rules for the application of Regulation (EU) No 1308/2013 as regards applications for protection of designations of origin, geographical indications and traditional terms in the wine sector, and iii) Commission Implementing Regulation (EU) 2018/274 - as regards the scheme of authorisations for vine plantings, certification, the inward and outward register, compulsory declarations and notifications, and relevant checks.

The viticulture sector is contending with an array of challenges that imperil its growth and overall sustainability [5]. These challenges encompass the requirement for enhanced traceability, transparency, and assurance of authenticity in the supply chain [6], [7], largely attributable to the growing incidence of fraudulent wines and consequent detrimental impacts on consumer trust, brand reputation, and the industry's economic stability [8], [9].

The proliferation of counterfeit wines is a critical concern, as it could not only erode consumer trust but also imperil the livelihood of legitimate wine producers [10]. Fraudulent wines are often produced utilising inferior quality grapes, resulting in a substandard product that is then misrepresented as a high-quality wine [11]. Such deceptive practices can undermine the credibility of the entire industry, as consumers are rendered unable to trust the quality of their wine purchases [10]. Estimations suggest that up to 20% of all globally sold wine may be fraudulent [12]. This poses a threat to the economic stability of the viticulture sector, leading to substantial annual revenue losses for genuine producers [10].

The absence of transparency in the wine supply chain constitutes another major obstacle.[1] Contemporary consumers frequently demand intricate knowledge about their consumed products, inclusive of product origin, production process, and the sustainability practices of the manufacturers [13]. Considering that the wine supply chain can involve multiple intermediaries [14], consumers' access to accurate information about their purchased wine [12] may be opaque — which can induce consumer distrust and diminished brand loyalty [9].

Furthermore, the viticulture industry is faced with transport/shipping logistics traceability.[2] With wines being transported across national and international boundaries, it is imperative to trace each wine bottle's journey from the vineyard to the consumer's table [6] to provide assurances with respect to external environmental factors wine bottles were subject to. This not only ensures the wine's authenticity but is also crucial for compliance with various legal regulations related to wine import and export [15]. Insufficient traceability mechanisms may lead not only to harming consumer confidence and trust to both specific products and the market, but may also lead to regulatory violations, penalties, and reputation damage for wine producers [15].

Addressing such challenges is not a trivial task and necessitates the collaboration of all stakeholders in the viticulture industry, from vine growers and wine producers to retailers and regulatory authorities. Innovative solutions such as blockchain technology have been proposed as a means of supporting in building trust between the various stakeholders. Blockchain technology, fundamentally, serves as a distributed ledger designed to store and share data among network participants. Operating within a decentralised framework, it organises data into units called "blocks". Each block undergoes a rigorous verification process, where consensus is reached amongst the various network participants to validate and authenticate the data. This process ensures the integrity and transparency of the system, offering a secure and unalterable record that can be trusted by all stakeholders involved [16]. Blockchain possesses the potential to offer a secure, transparent, and unalterable record of processes within the wine supply chain, thereby providing an avenue to address counterfeiting, transparency, and traceability issues [17], [18], [19].

A. OBJECTIVE OF THE STUDY

This study aims to provide an overview of the prospective benefits, practical applications, and challenges inherent in the deployment of blockchain technology within the wine supply chain, particularly with respect to traceability. The study strives to address the following research questions:

1) `RQ1`: What is the current state of blockchain incorporation within the wine supply chain traceability?
2) `RQ2`: How is blockchain technology currently being used to enhance traceability within the wine supply chain?
3) `RQ3`: What are other potential benefits and challenges of further employing blockchain for wine supply chain traceability?

By scrutinizing the nexus between blockchain technology and wine supply chain traceability, this study aspires to offer insights for industry stakeholders, researchers, and policymakers keen on harnessing the potential of blockchain to augment trust, transparency, and security within the wine sector.

B. LAYOUT OF THE PAPER

The structure of this paper is organised as follows: Section II provides a comprehensive overview of wine supply chain

[1] https://www.thewinegroup.com/supply-chain-transparency/
[2] https://analytics.wine/traceability-in-wine-industry-a-long-term-challenge/

traceability and blockchain technology. In Section III, we explore both contemporary and traditional approaches to traceability in the wine supply chain. Section IV reviews significant research conducted in the field. In Section V, we provide an overview of related work and then in Section VI, we analyse various blockchain-based solutions that have been proposed. Section VII presents a series of case studies focused on traceability, demonstrating the successful integration of blockchain technology across different segments of the wine supply chain and highlights the benefits and insights gained. Section VIII discusses the technical, legal, and adoption challenges associated with implementing blockchain technology within the wine supply chain. Section IX delves into the future directions of blockchain adoption in the wine industry, with a focus on traceability, addressing technological, legal, regulatory, and adoption issues, and exploring potential applications beyond traceability. Finally, Section X concludes the paper by summarising the findings, outlining the implications for the wine industry, and offering recommendations for stakeholders.

II. BACKGROUND

Traceability refers to the capability to trace and track a product or component through its various stages of production and distribution, from its origin to its end use [20]. In the context of supply chains, traceability is of paramount importance as it ensures the transparency and authenticity of products, verifying their origins and ensuring their quality and safety throughout the entire supply chain. Furthermore, traceability systems can provide accurate and timely information for managing risks, recalls, and ensuring regulatory compliance, thereby fostering trust amongst stakeholders and consumers [21]. Implementing traceability in supply chains can be a complex task due to the involvement of multiple stakeholders, data interchange requirements, and technological challenges. Yet, advancements in technologies such as blockchain and the Internet of Things (IoT) have recently shown promise in facilitating more robust and transparent traceability solutions [22].

Indeed, blockchain-based solutions have significant potential across other areas of the agricultural ecosystem including but not limited to: (i) supply chain and market transparency; (ii) traceability, quality, and food safety; (iii) finance, payments, insurance, and e-commerce; and (iv) smart farming and IoT Integration [23] — yet in this paper we focus on aspects specifically related to the wine-related supply chain to provide a more focused perspective of the specific sector.

A. TRACEABILITY IN THE WINE SUPPLY CHAIN

Traceability within the wine supply chain pertains to the systematic process of tracking a viticultural product from its inception in the vineyard through to its ultimate consumption [8], [9], [24], [25], [26], [27]. This procedure necessitates the observation and documentation of every stage of the wine's trajectory, encapsulating grape cultivation, harvesting, vinification, bottling, distribution, and retail sales [9]. The fundamental aim of traceability within the wine supply chain is to ensure the authenticity, quality, and safety of the wine products, whilst concurrently affording consumers an elevated degree of transparency and confidence in their procurement choices [8].

A wine supply chain can be disaggregated into several pivotal stages [28], each harbouring its distinct set of traceability-related challenges and opportunities. Fig. 1[3] depicts a diagram representing a generic wine supply chain process, displaying the diverse stages and the associated traceability components inherent in each stage. This diagram delineates the progression from vineyard cultivation through to retail and consumption, underscoring the significance of collaboration among stakeholders in maintaining efficacious traceability. A short discussion about each of these stages follows in the subsequent sections.

1) VINEYARD AND GRAPE CULTIVATION

This phase incorporates the cultivation and management of grapevines, in tandem with the harvesting of grapes. Traceability within this phase might encompass the documentation of vineyard geolocation, grape varietals, cultivation techniques, and harvest dates [29]. Moreover, traceability may involve the utilization of geolocated pins, mapping tools, and yield estimations to surveil vineyard conditions and performance. Additionally, traceability may extend to the registration of pesticide treatments, adhering to specific regulatory requirements [29].

2) VINIFICATION AND PRODUCTION

Post-harvest, grapes undergo various processes such as crushing, fermentation, maturation, and blending to produce the final wine that is bottled. Traceability could involve the monitoring of the vinification processes employed, the nature and origins of equipment utilized, and the quality control measures enacted.

3) BOTTLING AND PACKAGING

After production, the wine is then bottled and packaged for distribution. Traceability at this phase could incorporate data on bottling dates, batch identifiers, and packaging materials, along with any quality assurance tests conducted.

4) DISTRIBUTION AND LOGISTICS

Viticultural products are transported from the winery to various distribution points, including wholesalers, retailers, or direct-to-consumer channels. Traceability during this distribution phase could necessitate the tracking of wine products throughout the supply chain, ensuring appropriate storage conditions, and maintaining accurate shipment records.

[3]The icons used for representing different stages in the Fig. 1 have been taken from https://www.flaticon.com/ website.

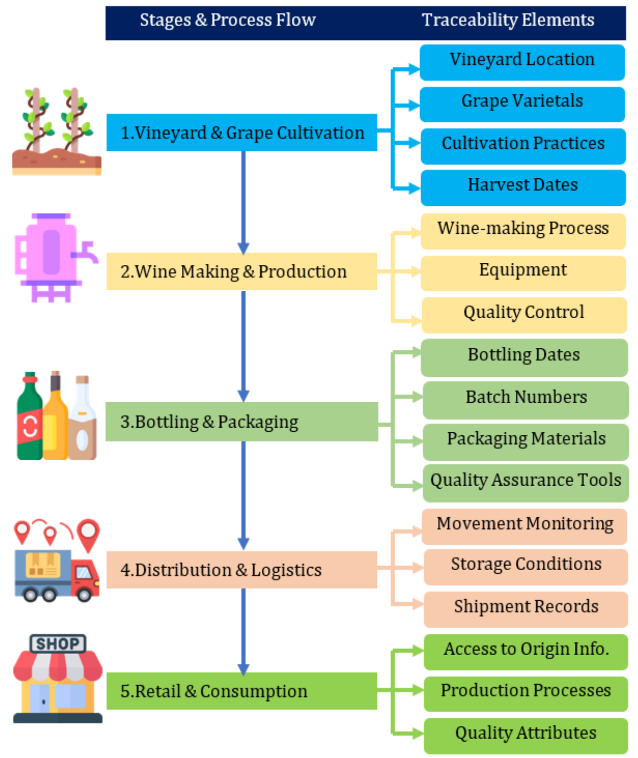

FIGURE 1. **Visual representation of the wine supply chain process, illustrating the five key stages and their associated traceability elements.**

5) RETAIL AND CONSUMPTION

The terminal stage of the wine supply chain entails the sale of viticultural products to consumers, either via physical retail outlets or online platforms. At this stage, traceability can empower consumers to access information regarding the wine's provenance, production procedures, and quality characteristics, thereby assisting them in making informed purchasing decisions.

B. SIGNIFICANCE OF TRACEABILITY IN THE WINE SUPPLY CHAIN

Traceability in the wine supply chain is invaluable [4], playing a decisive role in addressing a multitude of challenges encountered by the wine industry [2], [30]. The implementation of efficient traceability measures can confer a myriad of advantages to all stakeholders involved, encompassing consumers, producers, distributors, and retailers [2], [30]. Fig. 2 delineates the importance of traceability in the wine supply chain, accentuating six primary factors: guaranteeing authenticity and quality [2], augmenting consumer trust and confidence [30], safeguarding brand reputation [2], enabling regulatory compliance [30], enhancing supply chain efficiency [31], and bolstering sustainability initiatives [32]. The aforementioned factors signify a variety of considerations, inclusive of the prevention of fraudulent activities, fostering trust between consumers and manufacturers, adherence to regulatory guidelines, optimization of processes, and the attraction of an ecologically conscious consumer base [2], [30], [31], [32]. An incisive analysis of the aforementioned six cardinal reasons will be presented in the subsequent sections.

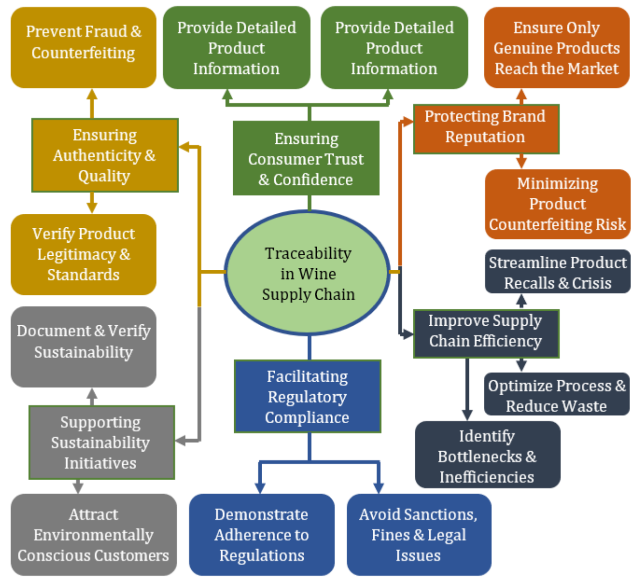

FIGURE 2. **Key Benefits of Traceability in the Wine Supply Chain: Enhancing Quality, Trust, Reputation, Compliance, Efficiency, and Sustainability.**

1) ASSURING AUTHENTICITY AND QUALITY

Given the escalating issue of spurious wines and adulterated products prevalent in the market, as highlighted in Section I, the need to establish a dependable system for verifying the authenticity and quality of wine products is imperative [33]. Traceability can serve as a deterrent to fraud and counterfeiting by proffering a transparent and verifiable record of a wine's provenance, production processes, and distribution history [33], [34]. This information can empower consumers and industry stakeholders to confirm the legitimacy of a product and its adherence to prescribed quality standards [33].

2) AUGMENTING CONSUMER TRUST AND CONFIDENCE

As consumers become increasingly discerning and informed about the wines they consume, there is an amplified demand for heightened transparency and comprehensive product information [35], [36]. Traceability within the wine supply chain can facilitate consumers' access to in-depth information about a wine's provenance, varietal composition, production methods, and quality attributes [37]. This level of transparency can contribute to building trust between consumers and producers, fostering brand loyalty and promoting repeat purchases [35], [36], [37].

3) SAFEGUARDING BRAND REPUTATION

A robust and reliable brand is a pivotal asset within the competitive wine industry [38], [39]. Traceability can aid in protecting brand reputation by ensuring only genuine, superior-quality products are marketed under a specific brand name [39], [40]. By implementing traceability measures, producers can mitigate the risk of their brand being associated with counterfeit or inferior products, which could have severe financial and reputational ramifications [38], [39], [41].

4) FACILITATING REGULATORY COMPLIANCE

With increasing governmental and regulatory scrutiny of the wine industry, traceability assumes a vital role in assuring compliance with these regulations [39], [42]. A well-documented traceability system can assist wineries and other stakeholders in demonstrating adherence to regulations concerning product origin, labeling, and quality standards [43]. This compliance can help wineries evade penalties, sanctions, and potential legal complications [44].

5) ENHANCING SUPPLY CHAIN EFFICIENCY

Traceability systems can potentially identify bottlenecks, inefficiencies, and areas for improvement in the wine supply chain [30]. By tracking and analyzing data at each stage of the supply chain, stakeholders can optimize processes, reduce waste, and augment overall operational efficiency [2]. Additionally, traceability systems may facilitate streamlining product recalls and crisis management initiatives in case of a quality or safety concern [33], [45].

6) SUPPORTING SUSTAINABILITY INITIATIVES

As the wine industry progressively focuses on sustainable and environmentally friendly practices, traceability assumes a key role in tracking and authenticating these efforts [30]. By documenting and verifying sustainable practices at each stage of the supply chain, wineries can manifest their commitment to environmental stewardship and attract environmentally conscious consumers [46].

The preceding discussion underscores the importance of traceability in the wine supply chain due to its crucial role in ensuring authenticity, enhancing consumer trust, protecting brand reputation, facilitating regulatory compliance, improving supply chain efficiency, and supporting sustainability initiatives. Effective traceability systems can benefit all stakeholders in the wine industry and may contribute significantly to its overall success and expansion.

C. OVERVIEW OF BLOCKCHAIN TECHNOLOGY

A blockchain signifies a decentralized, distributed digital ledger system, facilitating multiple participants to securely document and store transactions or data in a manner that is resistant to tampering, transparent, and verifiable [47], [48], [49], [50], [51]. A blockchain comprises a chain of interconnected blocks, each housing a collection of transactions or data records [52]. These blocks are cryptographically interconnected, thereby ensuring the data within each block remains immutable without affecting all subsequent blocks, offering a heightened level of security and data integrity [53], [54]. The key attributes of blockchain technology are elucidated further in the ensuing discourse:

1) DECENTRALIZATION

Deviating from conventional centralized systems, where a singular entity or authority maintains and controls the data, blockchain leverages a distributed network of computers (nodes) for data validation and storage [47]. This decentralization mitigates the risk of a singular point of failure and precludes any singular entity from wielding control over the entire system [55], [56].

2) CONSENSUS MECHANISM

For the integration of a new block into the blockchain, network nodes must attain a consensus regarding the validity of the transactions or data within the block [57]. Various blockchain networks implement different consensus mechanisms, such as Proof of Work (PoW) or Proof of Stake (PoS), to facilitate agreement amongst participating nodes [58], [59].

3) IMMUTABILITY

Once a block is integrated into the blockchain, the data therein becomes practically unalterable, since modifying the information necessitates modification of all subsequent blocks and gaining control over the majority of the network's computational power [57], [60]. This characteristic safeguards the integrity and authenticity of the data stored within the blockchain [55], [61].

4) TRANSPARENCY AND PSEUDONYMITY

Blockchain networks typically offer a transparent view of all transactions or data records, permitting anyone to audit and verify the information [57]. While the identities of transaction participants are safeguarded through pseudonyms (e.g., cryptographic addresses), the transactional details remain visible to all network participants [62].

5) SMART CONTRACTS

Certain blockchain platforms, such as Ethereum, support the utilization of smart contracts, which are self-executing agreements with contractual terms directly inscribed into the code [63], [64]. Smart contracts can automatically execute and enforce contractual stipulations when predefined conditions are satisfied, thereby streamlining processes and minimizing the need for intermediaries [65].

Blockchain technology harbors the potential to revolutionize various sectors by enabling secure, transparent, and efficient data management and transactions, diminishing the need for intermediaries, and fostering trust among participants in a decentralized network [66], [67]. In recent years, blockchain technology has been heralded as a promising solution for enhancing traceability, transparency, and security within supply chains [68], including the wine supply chain.

III. CONTEMPORARY APPROACHES TO WINE SUPPLY CHAIN TRACEABILITY

Historically, various traditional methods and models have been deployed in the traceability of the wine supply chain, facilitating the tracking and authentication of wine products from their origination in vineyards to their ultimate consumers. Notably, in 2003, the Wine Traceability Working Group was co-founded by GS1[4] and international wine traders from nations including France, Germany, South Africa, the United Kingdom, and the United States.[5] This collaborative initiative also partnered with industry counterparts from Argentina, Australia, Chile, New Zealand, Spain, and other prominent wine regions, culminating in the creation of a universally applicable traceability model. The reference wine supply chain developed by this Working Group has been widely adopted in evaluating the critical facets of wine traceability. Despite their merits, conventional methodologies are found wanting with respect to efficiency, security, and transparency [69]. The subsequent discourse will delve into a selection of these prevalent traditional viticultural supply chain traceability techniques.

1) PAPER-BASED DOCUMENTATION

The use of paper-based documentation is an entrenched practice in the traceability of the wine supply chain, with physical records tracking stages from vineyard management, grape cultivation, and harvesting to vinification processes, bottling, distribution, and point of sale [2]. Each stakeholder maintains an independent set of records, thus offering several advantages such as low cost, simplicity, ease of use, technological independence, flexibility, adaptability, and tangible proof. Given its low costs and ease of implementation, it is accessible to small and medium-sized wineries since it does not necessitate specialized technology or equipment [70]. Additionally, the flexibility and adaptability of paper records allow for customization, while physical documentation serves as tangible proof for legal, regulatory, or marketing purposes and can be preserved as a historical artifact [71].

2) BARCODES

Barcodes are a series of parallel lines or patterns that store information that can be scanned and decoded using barcode readers [72]. These codes enhance wine supply chain traceability by enabling the tracking and identification of wine products throughout their journey. The simplicity, automation, and compatibility offered by barcodes are advantageous for traceability. They are cost-effective, easy to create, print, and apply to wine bottles, packaging materials, or pallets [30], [33]. Barcodes are compatible with a wide range of barcode readers and data management systems, which enables easy integration into the existing supply chain infrastructure [2].

3) QR CODES

These two-dimensional barcodes can store more information than traditional barcodes and can be scanned using smartphones or dedicated QR code readers [73]. As these codes can offer increased information storage, thereby being beneficial for improving consumer engagement [74], traceability, transparency, and data management [2]. These codes can also be integrated with digital databases and inventory management systems for efficient and automated data collection, analysis, and reporting [73].QR codes have gained prominence as an advanced solution for bolstering wine supply chain traceability.

4) RFID TAGS

RFID tags, small electronic devices storing information, can be affixed to wine bottles, packaging materials, or pallets, and scanned by dedicated RFID readers to provide real-time information on the location and status of wine products [45]. These tags can store more information than traditional barcodes or QR codes providing a comprehensive view of a wine product's history, origin, and attributes [2]. As these tags are more difficult to duplicate or tamper with compared to barcodes or QR codes, therefore offering a higher level of security and authenticity [75]. This technology offers several advantages for wine supply chain traceability, including real-time tracking, enhanced data storage, increased efficiency, and improved security and authenticity [76]. Because of the advantages offered by this technology, it is increasingly being adopted in different supply chains including wine supply chains to improve traceability.

As the wine industry continues to evolve, ensuring optimal traceability to guarantee authenticity and quality may necessitate the combination of these traditional methods with emerging technologies, catering to the interests of both stakeholders and consumers [2].

A. LIMITATIONS INHERENT TO TRADITIONAL WINE SUPPLY CHAIN TRACEABILITY METHODS

While traditional methodologies deployed in wine supply chain traceability contribute to a certain degree of transparency and authentication, inherent drawbacks challenge their effectiveness. These techniques primarily contend with issues relating to efficiency, security, and data veracity [77]. For instance, while they afford some level of traceability, they are incapable of delivering real-time tracking or exhaustive data storage capacities. Further, conventional methods often lack the robust security measures and manipulation resistance characteristic of more sophisticated technologies such as blockchain [2]. The integrity of data collected and archived through these traditional methods can be compromised, engendering inaccuracies and inconsistencies within the traceability data [78], [79]. The following sections provide a more nuanced understanding of the limitations associated with these methodologies:

1) PAPER-BASED DOCUMENTATION

Despite providing a fundamental level of traceability, paper-based documentation is subject to several restrictions

[4]https://www.gs1.org/home
[5]https://www.gs1.org/sites/gs1/files/2020-11/annual_report_2003_2004.pdf

including inefficiency, restricted accessibility, risk of loss or damage, and vulnerability to fraudulent manipulation [77]. Moreover, paper-based documentation is prone to human error, leading to inconsistencies or inaccuracies in the recorded information [37]. For instance, a wine producer may maintain meticulous records of grape cultivation, harvest, and vinification processes, but these paper records can be easily misplaced or damaged due to accidents, spills, or natural disasters [2]. Furthermore, these physical records can be easily manipulated or falsified, enabling counterfeit or adulterated wines to enter the market, thereby tarnishing the reputation of legitimate brands and posing potential risks to consumer health [80].

2) BARCODES

Despite their simplicity and cost-effectiveness, barcodes possess inherent limitations in terms of information storage, susceptibility to damage, vulnerability to duplication and tampering, and lack of real-time data [77]. For instance, barcodes may not store sufficient information to verify the complete history and origin of a wine product, which is crucial for high-value or rare wines [2]. Counterfeiters can easily duplicate or manipulate barcodes, allowing fraudulent products to infiltrate the market. This vulnerability was starkly illustrated in the infamous "Rudy Kurniawa"[6] case, where counterfeit wine bottles bearing falsified barcodes were sold at auctions, leading to significant losses for collectors and investors [79].

3) QR CODES

Despite offering improved information storage and accessibility over barcodes, QR codes confront challenges pertaining to security [73], [81]. Even with their advanced capabilities, QR codes can be susceptible to duplication, tampering, or manipulation, thereby threatening the authenticity and integrity of wine products [73]. Moreover, the use of QR codes for traceability depends on the availability of smartphones or QR code readers and internet access, which may not be universally accessible, particularly in remote or underdeveloped regions [74].

4) RFID TAGS

While RFID technology presents significant advantages in terms of real-time tracking, enhanced data storage, and increased efficiency, it is not without its challenges. High implementation costs [76], compatibility issues [45], and privacy concerns [77] pose formidable obstacles. For small and medium-sized wineries, the costs associated with implementing and maintaining RFID technology may be prohibitive, hindering widespread adoption. Furthermore, integrating RFID technology into existing supply chain systems may require significant modifications or upgrades, leading to added costs and time investments [45].

[6]https://www.theguardian.com/global/2016/sep/11/the-great-wine-fraud-a-vintage-swindle

As the wine industry grapples with challenges related to counterfeit products, consumer trust, and regulatory compliance, there is a growing demand for more advanced and secure traceability solutions. This has sparked exploration into innovative technologies such as blockchain, which hold the potential to address the limitations of traditional traceability methods and revolutionize the wine supply chain [2], [46], [77], [82].

IV. LEVERAGING BLOCKCHAIN TECHNOLOGY IN THE WINE SUPPLY CHAIN

Contemporary challenges afflicting the global wine industry encompass a broad array of issues, extending from counterfeiting threats to quality control complexities. Emergent within this context is blockchain technology, positioning itself as a potential panacea that can transform traditional operations and deliver a high degree of transparency, traceability, and security in the wine supply chain [82], [83], [84], [85].

Blockchain, as a type of distributed ledger technology, preserves transaction data in a secure, immutable, and decentralized manner [26], [86]. Its implementation in the wine supply chain allows industry stakeholders to verify the origin, authenticity, and quality of a wine product with an unrivaled level of precision [46]. This technology enables each phase of the wine production process - from viticulture and vinification to bottling and labeling - to be cataloged on the blockchain. This creates an indelible digital record, which substantiates consumer confidence and fortifies the reputations of wine producers [46], [82].

A. ADVANTAGES OF INCORPORATING BLOCKCHAIN INTO THE WINE SUPPLY CHAIN

The integration of blockchain technology in the wine supply chain can yield substantial benefits, which might encompass improved provenance, enhanced authenticity, process automation, increased traceability, transparency, superior supply chain management, and enriched consumer engagement [2], [87], [88], [89]. Other notable advantages include the mitigation of fraudulent activity and counterfeiting, as well as potential cost and time savings. Several wine-related enterprises worldwide have begun harnessing blockchain-based solutions for their supply chains. A salient example is the partnership between Tencent, a prominent Chinese tech company, and Changyu Pioneer Wine,[7] a local wine producer. Together, they utilized blockchain technology to monitor and authenticate the entire wine production process, tracing each step from the vineyard to the bottle[8,9] [90]. The succeeding discourse offers a comprehensive analysis of these potential benefits.

[7]http://www.changyu.com.cn
[8]https://analytics.wine/transparency-blockchain-in-wine-spirits-industry/
[9]https://decrypt.co/37464/tencent-blockchain-fake-wine-china

1) PROVENANCE AND AUTHENTICITY

Blockchain systems can establish a comprehensive and immutable record of a wine's origin, detailing critical aspects such as the grape variety, vineyard location, and production methodology [91], [92]. Accessible and verifiable by all stakeholders, this information assures the authenticity and intrinsic value of the wine [82], thus shielding it from fraudulent exploitation. For instance, a prestigious winery could use blockchain to certify the origin of its limited-edition bottles, assuring collectors of their worth [93].

2) AUTOMATION

Smart contracts, a quintessential facet of blockchain technology, can automate various stages of the wine supply chain [94], [95]. These programmable agreements can expedite transactions, such as remittances between producers and distributors, minimizing the reliance on intermediaries, and thus reducing overhead costs [96]. For example, a smart contract could automatically release payment to a grape supplier once the shipment has been received and verified by the buyer [97].

3) TRACEABILITY AND TRANSPARENCY

The adoption of blockchain can engender a transparent, end-to-end perspective of the wine supply chain, permitting stakeholders to track a wine product's journey from vine to glass [82], [98]. This intricate tracking system can enhance quality control measures and foster accountability among all participants in the supply chain [86]. A restaurant, for instance, could use blockchain to ensure its wine offerings have been ethically sourced and properly stored throughout their journey [46].

4) SUPPLY CHAIN MANAGEMENT

Blockchain's ability to provide a real-time overview of the entire wine supply chain can aid in augmenting management and decision-making processes [99], [100]. This heightened visibility can assist businesses in pinpointing potential bottlenecks, optimizing logistics, and minimizing waste within the wine supply chain [101].

5) CONSUMER ENGAGEMENT

Granting consumers access to blockchain-based information can cultivate trust and loyalty [102]. A winery could create a QR code on its bottle labels, linking to a blockchain-powered platform with in-depth information about the wine [31], [103]. By understanding more about their favorite wines using a reliable source, such as production techniques, tasting notes, and aging potential, consumers can enrich their overall wine experience [98].

6) COUNTERFEIT DETERRENCE

The immutable characteristics of blockchain make it particularly resilient to data tampering, thus serving as a potent deterrent to fraudulent activities and counterfeiting within the wine supply chain [104], [105]. High-value wines can be safeguarded through blockchain-based certification, thereby ensuring their authenticity [103]. Luxury wine retailers could employ blockchain to verify the provenance of its exclusive offerings to avoid counterfeit wines, protecting its brand reputation and customer trust [2].

7) COST AND TIME EFFICIENCY

The integration of blockchain in the wine supply chain can not only augment transparency and traceability but may also lead to significant cost and time savings [106], [107]. By streamlining various processes and automating manual tasks, blockchain technology can diminish human error and facilitate efficient communication among parties involved in the wine production and distribution process.

8) INSURANCE

Insurance is critical within wine logistics due to the susceptibility of wine products and various risks involved. Traditional insurance claim processes can be time-consuming, opaque, and prone to disputes due to the lack of reliable, verifiable data. By leveraging blockchain technology, all relevant data—from vineyard conditions to transportation temperatures—can be recorded in real-time on an immutable ledger (a blockchain) — providing a tamperproof means of recording associated data. The immutable nature of the data on the blockchain reduces the chances of fraud. In the event of a dispute, insurers can access a transparent, single source of truth, which expedites the investigation process and helps make informed decisions.

The potential benefits discussed above highlight the transformative potential of blockchain technology in the wine industry. By harnessing this technology, stakeholders can enhance their brand reputation, improve the overall wine experience, and ensure a more sustainable future for the industry.

B. HARNESSING BLOCKCHAIN TECHNOLOGY FOR AUGMENTING TRACEABILITY IN THE WINE SUPPLY CHAIN

The integration or adoption of blockchain technology stands to significantly amplify the degree of traceability within wine supply chains. This is achieved by offering a decentralized, transparent, and secure framework for documenting and monitoring each phase of a wine's lifecycle [84]. The forthcoming discourse endeavors to dissect the complex dimensions of blockchain technology and elucidate the manner in which these attributes can intensify the traceability within wine supply chains.

1) DECENTRALIZATION

Within the scope of the wine supply chain, decentralization facilitates each stakeholder to chronicle their actions autonomously on a shared platform, thereby bolstering traceability [108]. Dispensing with the need for a centralized authority, data is dispersed across an array of nodes, ensuring an exhaustive and equitable log of information throughout all stages of the supply chain, ranging from grape cultivation to wine distribution.

2) TRANSPARENCY

Transparency constitutes another essential characteristic of blockchain technology. By its design, every transaction documented on a blockchain network is accessible to all participants, thereby establishing a transparent and auditable information trail [109]. This characteristic empowers all stakeholders within the wine supply chain, spanning from winemakers to consumers, to track and corroborate the wine's origin, fostering trust and accountability in the process.

3) IMMUTABILITY

The unalterable nature of blockchain ensures that once information is recorded and verified, it is immune to modification or deletion. This protective mechanism enhances traceability by certifying the veracity of the data, a crucial aspect in the wine supply chain where any attempt to distort a wine's origin, production details, or introduce counterfeit products would be effectively deterred [82].

4) SMART CONTRACTS

Smart contracts, often described as automated digital agreements that initiate execution upon the fulfillment of certain pre-set conditions, offer another dimension of traceability enhancement. For example, these contracts can automate processes like quality control, regulatory compliance, and financial transactions in the wine supply chain, thereby diminishing the risk of human error and escalating efficiency [109].

Consider the case of a hypothetical wine producer, ''Block-Wines'', which has successfully incorporated blockchain technology into its supply chain. Every bottle from Block-Wines is assigned a unique QR code, tethered to a blockchain entry. Detailed information about each phase of the wine's lifecycle, including vineyard location, grape variety, harvest timing, and particulars about the fermentation process and bottling, are recorded on the blockchain. As the product navigates through the supply chain, supplemental data such as transportation conditions and storage locations are appended. The consumer, by scanning the QR code, can access this comprehensive history, thereby ensuring the authenticity and quality of the wine, whilst considerably amplifying traceability.

C. BLOCKCHAIN IMPLEMENTATION IN WINE SUPPLY CHAIN

One of the primary blockchain architectures used in wine traceability systems is the permissioned blockchain. Unlike public blockchains like Bitcoin or Ethereum, permissioned blockchains restrict access to authorized participants, making them more suitable for supply chain management [110]. In the context of wine supply chains, this architecture allows for better control over data sharing and privacy while still maintaining transparency among approved stakeholders.

A notable example of a permissioned blockchain implementation in the wine industry is the WineChain project, which utilizes the Hyperledger Fabric framework [8]. Hyperledger Fabric employs a unique consensus mechanism called ''pluggable consensus,'' allowing for the integration of various consensus algorithms based on specific use case requirements [111]. In the case of wine traceability, the Practical Byzantine Fault Tolerance (PBFT), Raft, and Proof-of-Authority consensus algorithms are often preferred due to their ability to provide high throughput and low latency, which are crucial for real-time supply chain operations [112].

Another significant blockchain architecture used in wine supply chains is the consortium blockchain, which operates as a hybrid between public and private blockchains. This model allows multiple organizations within the wine industry to collaborate while maintaining a level of control over the network [113]. The EY OpsChain platform, for instance, has been utilized by several wine producers to create a consortium blockchain for wine traceability [114].

Regarding consensus mechanisms, Proof of Authority (PoA) and Raft have gained traction in wine traceability systems due to their energy efficiency, security, and scalability compared to Proof of Work (PoW) or Proof of Stake (PoS) mechanisms [115]. In a PoA-based wine traceability system, trusted nodes (e.g., major wine producers, distributors, or regulatory bodies) are designated as validators, ensuring the integrity of transactions without the need for resource-intensive mining processes [116]. In a RAFT-based wine supply chain traceability system, a leader node (e.g., a major vineyard, distributor, or regulatory body) coordinates the logging and replication of data across follower nodes, ensuring consistent and fault-tolerant tracking. If the leader fails, a new leader is elected seamlessly, maintaining reliable traceability from vineyard to retailer [117].

The implementation of blockchain in wine supply chains typically involves the use of smart contracts to automate and enforce agreed-upon rules and processes. For example, smart contracts can be programmed to trigger quality control checks at various stages of the supply chain or to execute payments upon successful delivery and verification of wine shipments [86].

To enhance the accuracy and reliability of data recorded on the blockchain, many wine traceability systems incorporate Internet of Things (IoT) devices. These devices, such as temperature and humidity sensors, can automatically record and transmit critical data about storage and transportation conditions directly to the blockchain, minimizing the risk of human error or manipulation [118].

D. DATA INTEGRATION ACROSS THE WINE SUPPLY CHAIN

Integrating data from different stages of the wine supply chain into blockchain systems is fundamental for ensuring transparency, traceability, and quality assurance from vineyard to consumer. At each stage, across grape cultivation, production, bottling, distribution, and retail, a combination of IoT devices, smart contracts, and oracles are employed to securely record and transmit critical data to the blockchain.

For example, in the vineyard, IoT devices such as soil sensors and drones collect data on grape varietals, soil conditions, and weather patterns, which is automatically uploaded to the blockchain. During wine production, key processes such as fermentation, aging, and blending are monitored, with data integrated via smart contracts to ensure immutability and compliance with quality standards. Bottling and packaging data, including batch identifiers and bottling dates, are similarly captured and linked to the blockchain, creating a complete and transparent record of each bottle's journey.

Throughout distribution and logistics, IoT devices track environmental conditions such as temperature and humidity, while GPS systems provide real-time location data, all of which are appended to the blockchain to maintain the integrity of the wine's traceability. Finally, at the retail stage, consumers can use QR codes or RFID tags to access provenance details, offering them full transparency into the wine's history and ensuring the authenticity of the product.

This integration creates a comprehensive, transparent, and immutable record of a wine's journey from vineyard to consumer, enhancing traceability, authenticity, and quality assurance. It involves multiple stakeholders, technologies, and data types. This integration is crucial for ensuring the traceability, authenticity, and quality of wine products from vineyard to consumer [119].

The wine supply chain typically consists of several key stages as depicted in Fig. 1: viticulture, wine production, bottling, distribution, and retail. Each of these stages generates valuable data that can be integrated into a blockchain system to create a comprehensive and immutable record of the wine's journey [120].

1) VINEYARD & GRAPE CULTIVATION

At the vineyard level, data integration begins with the recording of crucial viticultural information. This includes details about grape varieties, planting dates, soil conditions, weather patterns, and vineyard management practices. Internet of Things (IoT) devices, such as soil sensors, weather stations, and drones, play a significant role in collecting this data automatically [121]. For example, soil sensors can record moisture levels, pH, and nutrient content, while drones equipped with multispectral cameras can capture data on vine health and grape ripeness. This data is then uploaded to the blockchain through secure APIs or edge computing devices, ensuring its immutability and traceability [114].

2) WINE MAKING & PRODUCTION

During the wine making process, data related to fermentation, aging, and blending is collected and integrated into the blockchain. This includes information on yeast strains, fermentation temperatures, aging duration, and barrel types. Many wineries are adopting smart tanks and barrels equipped with sensors that automatically record and transmit data on temperature, humidity, and chemical composition to the blockchain [122]. Additionally, data on additives, fining agents, and filtration processes are manually entered by winemakers through secure interfaces, ensuring a complete record of the production process [8].

3) BOTTLING & PACKAGING

At the bottling stage, each bottle is typically assigned a unique identifier, often in the form of a QR code or RFID tag. This identifier is linked to all previous blockchain entries related to that specific batch of wine. Data integrated at this stage includes bottling date, bottle size, closure type, and any specific handling or storage instructions. The integration of this data often involves the use of smart contracts, which automatically verify and record the bottling process, ensuring compliance with regulatory standards and internal quality controls [86].

4) DISTRIBUTION & LOGISTICS

During distribution, blockchain integration focuses on logistics and transportation data. This includes information on shipping routes, storage conditions, and handling procedures. IoT devices, such as temperature and humidity sensors in shipping containers, continuously monitor and record environmental conditions. This data is transmitted to the blockchain in real-time, often utilizing edge computing to process and upload data even in areas with limited connectivity [123]. GPS tracking data is also integrated, allowing for real-time monitoring of wine shipments and providing an additional layer of security against theft or counterfeiting [49].

5) RETAIL & CONSUMPTION

At the retail level, point-of-sale systems are integrated with the blockchain to record final transactions and verify the authenticity of products. When a consumer purchases a bottle of wine, the transaction is recorded on the blockchain, completing the chain of custody. Some advanced systems also integrate consumer feedback and ratings, adding a final layer of data to the wine's blockchain record [124]. Throughout all stages, data integration often involves the use of oracles - trusted third-party services that verify and transmit real-world data to the blockchain. These oracles play a crucial role in ensuring the accuracy and reliability of off-chain data as it is integrated into the blockchain system [125].

To facilitate seamless data integration across these diverse stages, many blockchain implementations in the wine industry utilize interoperability protocols. These protocols allow different blockchain networks (e.g., those used by various stakeholders in the supply chain) to communicate and share data effectively [126].

While blockchain offers a secure and transparent approach to data integration, challenges remain. These include issues of data standardization across different stakeholders, the need for robust data validation mechanisms, and concerns about data privacy, especially when dealing with proprietary information [127].

As the wine industry progressively evolves, the integration of blockchain technology may prove to be instrumental in cultivating a sustainable and reliable supply chain that offers benefits to all stakeholders, from producers to consumers, ensuring the authenticity and quality of wine products for future generations [84]. The adoption of blockchain technology poses immense potential for amplifying traceability in wine supply chains. It offers a solution to the prevalent challenges in traditional systems, including data integrity concerns, inefficiency, absence of real-time data, vulnerability to fraud, inefficient communication, sub-optimal decision making, and diminished consumer trust. While the implementation may necessitate significant modifications and adaptations, the long-term benefits, particularly with respect to enhanced traceability and improved consumer trust, render blockchain an appealing prospect for the wine industry [82]. This augmented traceability not only assures product authenticity, but also fosters trust and accountability among all stakeholders, thereby paving the way for a more resilient and sustainable wine industry.

V. RELATED WORK

The wine industry has faced increasing challenges in recent years due to counterfeiting, adulteration, and the use of hazardous chemicals. Researchers have turned their focus to blockchain technology to address these issues by enhancing traceability, transparency, and trust throughout the wine supply chain. A number of academic and non-academic research articles [2], [8], [13], [17], [37], [42], [50], [87], [104], [128], [129], [130], [131], [132], [133], [134], [135], [136], [137], [138], [139], [140], [141] have been published on the use of blockchain in the wine supply chain. In this section, we review some important studies that investigate the potential benefits and limitations of implementing blockchain-based solutions for achieving traceability in the wine supply chains.

Among the earliest published articles, Biswas et al. [8] and Robertson [134] both proposed blockchain-based traceability systems for the wine supply chain, focusing on creating unique digital identities for wine bottles and recording transactions in a secure and transparent manner. Adamashvili et.al. in [2] used an Agent-Based Model (ABM) approach to compare traditional and blockchain-based wine supply chains, finding that blockchain offers improved traceability, fraud protection, and contamination prevention. The works of Brookbanks and Parry [37], Danese et al. [104], Popovic et al. [17], Cakic et al. [13], and Gayialis et al. [30] further emphasized the benefits of using blockchain for improving data transparency, integrity, and traceability in the wine industry.

While these studies show the potential of blockchain in addressing the aforementioned issues, some of them still need further development, validation, and experimentation. For instance, the methodologies proposed by Popovic et al. [17] and Cakic et al. [13] are conceptual, and the results of Gayialis et al. [139] are limited in their evaluation.

Tokkozhina et al. [50] and Agnusdei et al. [142] focused on the development of IoT-based traceability frameworks, combining blockchain with other technologies such as RFID, NFC tags, and QR codes. These studies contribute to the understanding of how integrated approaches can enhance transparency, efficiency, and security in the wine supply chain. Galati et al. [137] studies how three Italian wineries implement blockchain technology. It uses a case study approach and a conceptual framework based on dynamic capabilities, absorptive capacity, and dominant logic theories. It shows that wineries need knowledge management systems and managerial skills to innovate with blockchain. The paper offers insights into blockchain's value for the wine industry. Cordeiro and Olsen [138] explored the barriers and challenges of implementing blockchain-based traceability systems in the wine global value chain (GVC), specifically focusing on China for Bordeaux wine. Using a qualitative approach and the UTAUT framework [143], their findings highlight the need for coordinated efforts and socially tactile strategies to adopt blockchain-based traceability systems in the wine industry. Cuel and Cangelosi [133] conducted a qualitative study examining the motivations, advantages, and drawbacks of blockchain technology adoption by small Italian wineries. Their findings stress the importance of training and awareness of blockchain implementation and its impact on supply chain management, although the paper's weaknesses include a small sample size and limited perspectives from technology providers and certification bodies. Gayialis et al. [30] developed a business process reference model for wine traceability systems to address traceability challenges in the supply chain. Their work contributes to traceability research by developing a reference model for understanding traceability system functionality and interactions. Tokkozhina et al. [50] explores the use of blockchain technology to enhance traceability and reduce counterfeiting in the wine SC. The authors propose a smart contract architecture using DAML and discuss its benefits and drawbacks. The paper argues that their solution can increase consumer trust by ensuring the authenticity and origin of the wine. The paper also identifies areas for future research on BCT applications in SC.

The literature on blockchain applications in the wine supply chain highlights both the benefits and challenges of implementing traceability and transparency solutions. The existing literature highlights the potential of blockchain for addressing challenges such as counterfeiting, adulteration, and hazardous chemicals. Although many studies are conceptual and lack immediate applicability, they offer valuable insights into the potential of blockchain-based systems to improve the wine supply chain. Future research should focus on testing and validating these proposed solutions in real-world settings and incorporating diverse perspectives to better understand the long-term implications of blockchain adoption in the wine sector.

VI. CONTEMPORARY BLOCKCHAIN-ENABLED SOLUTIONS FOR AUGMENTING TRACEABILITY IN WINE SUPPLY CHAIN

The ongoing embrace of blockchain technology within the viticulture sector has yielded a spate of inventive solutions, specifically crafted to surmount the distinct hurdles encountered in the industry. Table 1 provides a high-level comparison of blockchain-enabled solutions proposed specifically for the wine traceability sector including technical details such as their consensus mechanism and architecture type. Each solution has its unique strengths and focus areas within the wine supply chain. Platforms such as Winechain,[10] VinAssure[11],[12] ChaiVault,[13] and VeChain[14] have effectively harnessed the secure and transparent properties of blockchain, ensuring not only traceability and quality management, but also fostering a profound trust and efficacy within the wine supply chain. These platforms have revolutionized the connections between consumers and wine brands. The ensuing subsections will elaborate on these platforms based on information gathered from their parent organization's website as primary data source and other secondary sources available:

1) WINECHAIN

Developed by Zenithwings,[15] a Portuguese entity renowned for precision farming and Industrial 4.0 solutions, Winechain is a decentralized, blockchain-anchored platform that certifies sustainable wines. Catering to the unique challenges of the wine supply chain, Winechain offers a comprehensive toolkit to bolster traceability, efficiency, and sustainability, spanning the entire process from viticulture to consumer. The platform facilitates wine producers' registration of their products, offering a digital certificate affirming their adherence to sustainability standards. Furthermore, Winechain ensures traceability, authenticity, and quality assurance via smart contracts and distributed ledger technology. For consumers, detailed insights into a wine's origin, composition, processing, and distribution can be gleaned via scanning a QR code or NFC tag. The platform also offers wiNeFTs,[16] Non-Fungible Tokens (NFTs)[17] tied to physical bottles that ensure quality. These can be purchased, sold, securely stored in Winechain's warehouse, or shipped to consumers as per their readiness to consume the wine.

2) VinASSURE

Conceived by eProvenance,[18] VinAssure is a groundbreaking, IBM blockchain-powered[19] platform facilitating a secure and intelligent wine tracking methodology from vineyard to consumer. The platform takes advantage of IBM Blockchain Transparent Supply,[20] an innovative system that expedites the creation of a sustainable, blockchain-anchored ecosystem for enhanced supply chain processes. In addition to blockchain, VinAssure integrates cutting-edge technologies such as artificial intelligence and cloud computing to augment the experiences of all participants. The platform bolsters traceability, efficiency, and profitability within the wine supply chain by constructing a shared, permanent data record. De Maison Selections,[21] a U.S. importer of responsibly sourced wines, cider, and spirits from independent producers in Spain and France, is the inaugural member of VinAssure. Supply chain members and consumers can retrieve information spanning from vineyard to transportation and delivery, verified and stored on the blockchain.

3) CHAI VAULT

The Chai Vault is a blockchain-anchored digital platform, seeking to disrupt the wine supply chain by offering a secure, transparent, and efficient strategy to manage fine wines. It is powered by Everledger blockchain.[22] Wine authenticated through *The Chai Method*® is certified on the blockchain, creating a permanent, digital record of provenance that can be accessed throughout a bottle's lifetime journey. It incorporates both hardware and software in its implementation of *The Chai Method*®, a secure and trustworthy wine authentication and provenance process. Chai Vault's system uses a unique combination of physical and digital security measures, including tamper-evident capsules, proprietary bottle tags, and a secure digital registry.

4) VECHAIN

VeChain, an Ethereum-based[23] blockchain platform, seeks to streamline supply chain management and enhance transparency. The platform has been instrumental in tracking and authenticating wine products, utilizing smart NFC chips embedded in the wine bottles. VeChain has collaborated with D.I.G.,[24] a significant wine importer in China, to inaugurate the Wine Traceability Platform (WTP).[25] This platform uses

[10] https://winechain.pt/
[11] https://newsroom.ibm.com/2020-12-10-eProvenance-Uncorks-VinAssure-TM-an-IBM-Blockchain-Powered-Platform-to-Strengthen-Collaboration-and-Optimize-the-Wine-Supply-Chain
[12] https://www.eprovenance.com/home/services/wine/
[13] https://www.chaivault.com/
[14] https://www.vechain.org/
[15] https://www.zenithwings.com/
[16] https://winechain.co/how-it-works
[17] For a primer on NFTs that spans across technical and legal issues see [144].
[18] https://www.eprovenance.com/home/
[19] https://cloud.ibm.com/catalog/services/blockchain-platform#about
[20] https://www.ibm.com/docs/en/transparent-supply?topic=overview
[21] https://demaisonselections.com/
[22] https://everledger.io/
[23] https://ethereum.org/en/
[24] https://www.prnewswire.com/news-releases/the-wine-traceability-platform-co-developed-by-vechain-and-dig-kickstarted-its-second-phase-with-the-introduction-of-penfolds-bin-407-300896782.html
[25] https://www.nfcw.com/technology/wine-traceability-platform-wtp/

TABLE 1. Comparision of Blockchain-enabled Wine Supply Chain Platforms.

Feature	WineChain [145]	VinAssure [146], [147]	Chai Vault [148]	VeChain [149], [150]
Blockchain Platform	Bitcoin and Ethereum (Quantum Chain Platform QTUM [151])	Hyperledger Fabric (IBM Blockchain Transparent Supply)	Hyperledger Fabric (Everledger [152])	VeChainThor
Blockchain Type	Private/ Permissioned	Private/ Permissioned	Private/ Permissioned	Private/ Permissioned
Consensus Mechanism	PoS	Raft	Raft	PoA
Stakeholder Involvement	Producers, distributors, consumers	Producers, distributors, retailers, consumers	Producers, authenticators, consumers	Producers, logistics providers, retailers, consumers
Geographic Focus	Global, with emphasis on French wines	Global	Global, with emphasis on fine and rare wines	Global, with strong presence in Asia
Consumer Interaction	Mobile app for bottle verification and purchase	Web interface for product information	Mobile app for authentication and information	Mobile app for product verification
Data Integration	Manual input and IoT devices	IoT sensors and supply chain systems	NFC tags and expert verification	IoT sensors and supply chain systems
Additional Services	Wine investment and trading platform	Analytics and insights for supply chain optimization	Wine collection management	Multi-industry traceability solutions

VeChain's one-stop BaaS platform VeChain ToolChain.[26] WTP permits consumers to scan NFC tags on wine bottles, offering access to data such as origin, vintage, grape variety, winery, and quality assurance.

WineChain emphasizes direct producer-to-consumer connections, VinAssure leverages IBM's robust blockchain infrastructure for comprehensive supply chain tracking, Chai Vault focuses on authentication of fine and rare wines, and VeChain offers a broader supply chain solution that includes, but is not limited to, the wine industry.

These emergent blockchain-anchored solutions hold offer significant potential to improve wine supply chain traceability. The aforementioned platforms, namely Winechain, VinAssure, Chai Vault, and VeChain, leverage the secure and transparent nature of blockchain to address the unique challenges encountered by the wine industry. Through the effective utilization of blockchain technology, these platforms ensure accurate documentation of provenance, enhance authenticity, thwart fraudulent activities, streamline communication, and foster trust within the wine supply chain. As the viticulture sector continues to adopt blockchain technology, these inventive solutions hold significant potential to revolutionize the ways wines are traced, verified, and enjoyed by consumers, thus fostering a deeper rapport between consumers and wine brands [2], [13].

VII. CASE STUDIES OF BLOCKCHAIN ADOPTION FOR ENHANCED WINE SUPPLY CHAIN TRACEABILITY

The incorporation of blockchain technology in the viticulture sector has witnessed a gradual yet significant ascendancy as an array of stakeholders discern the potential merits in bolstering traceability and transparency throughout the supply chain [46] [71]. This trend is in line with the broader adoption of blockchain for supply chain traceability across various sectors, including food and pharmaceuticals [46]. The case studies delineated below furnish concrete examples of the avant-garde methodologies employed by wineries and producers in integrating blockchain technology to tackle specific quandaries, cultivate consumer trust, and safeguard their brand equity. These case studies unveil the multifaceted applications of blockchain in the wine supply chain and proffer invaluable insights into the triumphs and impediments encountered during the deployment.

1) CASE STUDY: CANTINA PLACIDO VOLPONE

Cantina Placido Volpone,[27] a quintessential Italian winery ensconced in Puglia, was established in 1976 by a consortium of families who shared an ardor for the region's opulent natural heritage. In the year 2017, the winery undertook a trailblazing blockchain-based initiative in concert with Ernst & Young[28] and the start-up EZ LAB.[29] The objective was to augment transparency and fortify the sanctity of the "Made in Italy" agricultural products. This blockchain framework mandates each constituent in the supply chain to contribute and record data through cryptographically secure digital signatures. The production phase is pivotal as it encompasses critical data germane to the final product's quality. Agronomists document specifics such as geolocation, fertilizers, and agrochemicals, while transporters log particulars pertaining to the quality and quantity of the grapes. Subsequent to vinification, relevant data is chronicled, and the wine is bottled, labeled, and dispatched to wholesalers with pertinent timestamps. Each bottle is affixed with a QR code, granting consumers access to comprehensive information. This implementation has yielded salubrious results in terms of traceability, consumer trust, and environmental consciousness, notwithstanding a negligible

[26] https://www.vechain.com/product/toolchain

[27] https://placidovolpone.it/
[28] https://www.ey.com/it_it?
[29] https://www.ezlab.it/

impact on sales [42], which the winery ascribes to market heterogeneity and an extensive export share. The blockchain label has garnered interest among consumers, and the number of QR code scans has increased, demonstrating growing interest in the technology and the product's history.[30]

2) CASE STUDY: CHATEAU STE. MICHELLE

Chateau Ste. Michelle,[31] a prominent American viticultural company, adopted VinAssure, a blockchain-anchored technology, with the intent of ascertaining that its wines are delivered to consumers in pristine condition. Peter Click, the Vice President of International Sales at the winery, underscored the indispensability of this technology in preserving the wine's caliber throughout the distribution continuum. VinAssure accumulates temperature data in the blockchain and assigns an eProvenance Score, indicative of the preservation or degradation of the wine's quality. Through judicious utilization of this tracking data, Chateau Ste. Michelle ensures optimal temperature conditions throughout the transit, thereby engendering transparency and cultivating trust between the producer and the consumers.

3) CASE STUDY RICCI CURBASTRO, RUFFINO, AND TORREVENTO

Ricci Curbastro,[32] Ruffino[33] and Torrevento,[34] esteemed Italian wineries, have espoused the blockchain-infused My Story[35] platform to fortify transparency and traceability within their supply chains.[36] The platform aggregates data throughout the transformational trajectory from grape to bottle, encompassing soil and meteorological measurements, grape provenance, additive utilization, tank operations, bottling procedures, and transportation surveillance. Upon scanning the QR code affixed to the wine bottle, consumers are furnished with a cornucopia of information encompassing the wine's timeline, locales, and consumption recommendations. The information is meticulously verified by DNV experts in collaboration with the wine producers to ensure authenticity. The data repository is maintained within a blockchain-empowered ecosystem, courtesy of VeChain, which functions as a catalyst for trust. The platform is scalable and offers features such as user management and IoT device integration. Through the allocation of unique identifiers to each product, My Story enables consumers to access verifiable information regarding the wine's journey from grape to bottle, thereby empowering them to make sagacious purchasing decisions.

[30]https://placidovolpone.it/produzione/vini-bianchi/altomare/altomare-blockchain-2017/
[31]https://www.ste-michelle.com/
[32]https://www.riccicurbastro.it/en/home-2/
[33]https://ruffino.com/
[34]https://www.torrevento.it/en/
[35]https://www.dnv.com/mystory/MyStory-blockchain-powered-Digital-Assurance-solution.html
[36]https://www.dnv.com/mystory/mystory-winemakers.html

These case studies highlight the effective use of blockchain technology within the wine supply chain, showcasing its potential to improve traceability, transparency, and consumer trust. Winiries such as Cantina Placido Volpone, Chateau Ste. Michelle, Ricci Curbastro, Ruffino, and Torrevento have harnessed blockchain to address distinctive challenges, safeguard their brands, and engender customer loyalty. Employing strategies like QR codes, temperature monitoring, and verified data acquisition, these wineries have experienced improvements on traceability, brand visibility, and operational efficiency. These case studies highlight the growing adoption of blockchain in the wine industry, providing invaluable insights into the potential benefits and pitfalls of integrating blockchain into supply chain traceability, thus charting the course for a more transparent and trustworthy wine market.

VIII. CHALLENGES TO BLOCKCHAIN IMPLEMENTATION & ADOPTION IN WINE SUPPLY CHAIN TRACEABILITY

Embracing blockchain technology to augment traceability within the wine supply chain entails grappling with an exclusive gamut of challenges [36], [153], [154], [155]. To fully harness the latent potential of this groundbreaking technology, it is vital to comprehensively address these challenges. These challenges can be primarily partitioned into three salient categories: technological intricacies, legislative and regulatory complications, and the hurdles inherent in driving adoption [36], [153], [154], [155].

The technological intricacies encompass considerations such as accurate data input, interoperability between systems, scalability to accommodate expanding operations, standardization to streamline integration, and ensuring security and privacy to safeguard sensitive information [153], [155].

Legislative and regulatory complications are attributable to the necessity of complying with existing laws and industry requirements. These challenges are further compounded by the constantly evolving legislative environment that governs blockchain technology [153], [155].

Adoption-related hurdles primarily revolve around catalyzing collaboration among the plethora of stakeholders within the wine supply chain. These include producers, distributors, retailers, and regulators, among others, and promoting widespread acceptance and integration of this cutting-edge technology remains a critical issue [153], [155].

A. TECHNOLOGICAL INTRICACIES

While the advent of blockchain technology heralds a significant opportunity to augment traceability in the wine supply chain, it is incumbent upon us to acknowledge and scrutinize the intricate technical hurdles that might surface during the phases of implementation and functioning [153], [155]. These hurdles span a multitude of dimensions, encompassing:

1) DATA INPUT ACCURACY

Blockchain's immutability, a cornerstone feature, is predicated upon the accuracy of the data fed into the system [107].

Erroneous or manipulated data, once recorded, can tarnish the integrity and reliability of the entire blockchain [156]. In the context of wine supply chain traceability, this can manifest in the dissemination of misleading information about the provenance, handling, and quality of wine, ultimately eroding consumer trust [157]. The challenge lies in devising stringent data validation mechanisms that are not prohibitively costly or operationally cumbersome.

2) INTEROPERABILITY AND INTEGRATION

The implementation of blockchain necessitates seamless communication with existing systems in the supply chain [94], [107], such as ERP (Enterprise Resource Planning) and SCM (Supply Chain Management) systems. If the blockchain system fails to integrate effectively with these systems, there could be data silos and incoherent records. For wine traceability, this means that critical information might not be accurately or promptly reflected across the supply chain, hindering effective decision-making and transparency.

3) SCALABILITY

As the volume of transactions and data within the wine supply chain burgeons, the blockchain must sustain performance without prohibitive costs or delays [61], [68], [107]. Conventional blockchain systems, especially public ones, have been criticized for their limited scalability. If scalability is not addressed, this could impact real-time traceability and result in a sluggish system incapable of supporting a dynamic and global wine supply chain [68].

4) STANDARDIZATION

A lack of industry-wide standards for blockchain implementation can engender a fragmented ecosystem, wherein different stakeholders employ disparate blockchain platforms with incompatible protocols [46], [107]. In the wine industry, this could impede the free flow of data across the supply chain, thereby undermining the very traceability and transparency that blockchain endeavors to enhance [68]. The development of universal standards necessitates a concerted effort among technologists, industry stakeholders, and regulators.

5) SECURITY AND PRIVACY

While blockchain is lauded for its security, it is not impervious to breaches or exploits [158], [159]. The wine industry deals with sensitive data including proprietary production techniques, contractual agreements, and financial transactions. Furthermore, consumer privacy, particularly in regions with stringent data protection laws, must be safeguarded [36], [158], [159], [160]. The failure to adequately secure this data not only risks financial and reputational damage but also non-compliance with legal obligations.

6) ENERGY CONSUMPTION

The traditional Proof-of-Work (PoW) consensus mechanism in blockchain is notoriously energy-intensive [2], [31], [33]. In an age where sustainability and environmental stewardship are increasingly pertinent, especially in an industry as closely tied to the land as viticulture, the adoption of an energy-intensive technology may be viewed as incongruous with these values [2], [31], [33]. This may impede adoption among environmentally-conscious stakeholders.

While the blockchain industry has made significant strides in addressing energy concerns with the development of Proof-of-Stake (PoS) and other low-energy-consuming consensus algorithms [161], several challenges persist. The transition from established Proof-of-Work (PoW) systems to more energy-efficient models often faces technical and community-related hurdles, proving to be complex, time-consuming, and potentially disruptive [162]. However, recent advances in Layer 2 solutions, such as rollups and sharding, have shown promise in enhancing PoS scalability while minimizing energy use. These techniques allow blockchain networks to process more transactions off-chain or in parallel, reducing the load on the main chain and optimizing resource usage. Additionally, innovations like liquid staking protocols and decentralised validator networks are emerging to enhance security and performance, making PoS ecosystems more resilient and efficient. It has been highlighted that as blockchain networks grow, maintaining energy efficiency while ensuring high performance and security is a delicate balancing act [163], with even PoS systems potentially facing increased energy demands as they scale [164] — and therefore integrating such advanced mechanisms will be crucial in maintaining the balance between energy efficiency, performance, and security.

These technological intricacies require careful attention through innovative solutions, regulatory collaboration, and industry-wide cooperation. Only through such a comprehensive approach can blockchain technology realize its full potential in enhancing wine supply chain traceability, ensuring authenticity, and fostering consumer confidence.

B. LEGISLATIVE AND REGULATORY COMPLICATIONS

As an incipient technology still striving for comprehensive mainstream acceptance, blockchain faces a labyrinth of legislative and regulatory intricacies [160], especially in its application to the wine supply chain [153], [155]. The understanding of these complications and their subsequent navigation are pivotal in the effective implementation and adoption of blockchain technology in the wine supply chain. These complications encompass:

1) CROSS-BORDER REGULATORY DIFFERENCES

Wine supply chains often transcend national borders, engendering a plethora of regulatory disparities. Differing attitudes and regulations toward blockchain technology across jurisdictions can create challenges in global traceability efforts [160], [165], [166], mandating an intricate understanding of varied regulations and a methodical strategy to ensure compliance across all operational domains.

2) COMPLIANCE WITH DATA PROTECTION AND PRIVACY REGULATIONS

Adherence to data protection and privacy laws, especially the GDPR[37] might appear less straightforward by comparison to more traditional supply chain digital solutions by virtue of the decentralized, immutable nature of blockchains [167].

Traditional data protection mechanisms such as the assignment of data protection roles, the fulfillment of the conditions for lawful processing of personal data, the exercise of the data subject rights are taking a new shape within blockchain ecosystems. Nonetheless, there is a growing body of GDPR related literature that aims to bridge the gap in the relationship between the GDPR and blockchain based environments. While it is clear that some adaptations are necessary, aligning blockchains and the GDPR might not be as incompatible as originally thought [168].

3) DEVELOPING ADEQUATE DATA GOVERNANCE FRAMEWORKS

As blockchain technology evolves, questions about intellectual property rights and ownership become increasingly pertinent in its application [169] including in the wine supply chain. Unclear ownership of data can result in legal disputes that might impede the progress of blockchain implementation in supply chains [170]. Data governance frameworks must be evolved to establish clear guidelines regarding ownership in the context of blockchain-based systems.

4) SMART CONTRACTS AND LEGAL ENFORCEABILITY

The utilization of smart contracts within the blockchain presents a novel paradigm for legal enforceability [171]. As automated, self-executing contracts, they could potentially revolutionize transactions within the wine supply chain. Traditional contract law rules are generally able to observe and support the development of smart contract arrangements [172]. Nonetheless, as smart contracts evolve and aim to automate more complex transactions (including different stages of the wine supply chain), traditional contract law schemes might need interpretative and, if necessary, regulatory adaptations in order to remain up-to-date and flexible enough, so as not to impede the further deployment of smart contracts in supply chain relationships.

5) REGULATORY OVERSIGHT AND LICENSING

Given the relatively new emergence of blockchain, the regulatory landscape is continually evolving, leading to uncertainties [173], [174], [175], [176]. Existing regulations might not account for the unique attributes of blockchain, hence creating an ambiguity that may deter potential adopters within the wine supply chain. Regulatory authorities need to provide clear guidance and oversight, ensuring that blockchain technology adheres to ethical, legal, and quality standards.

[37] https://www.consilium.europa.eu/en/policies/data-protection/data-protection-regulation/

6) LIABILITY AND DISPUTE RESOLUTION

In case of a dispute or error in the blockchain, determining liability can be a complex issue given the decentralized nature of the technology [177], [178]. This could hinder adoption of the blockchain technology in the wine supply chain. While traditional dispute resolution mechanisms are not completely inadequate in accommodating blockchain-related disputes [179], the development of novel, blockchain-based dispute resolution mechanisms might add an extra layer of dispute resolution flexibility and trust [180].

Addressing these legislative and regulatory complications is essential for creating an environment conducive to the adoption of blockchain technology in wine supply chain traceability. Proactive engagement with regulators, thorough legal counsel, and continual adaptation to the evolving landscape are essential for successfully leveraging the potential of blockchain technology.

C. ADOPTION-RELATED HURDLES

Adoption-related hurdles can profoundly impact the successful implementation of blockchain technology [36] in the wine supply chain traceability [153], [155]. These hurdles originate from a variety of factors, including technological literacy, organizational inertia, resource constraints, and systemic requirements for collective action. Delving into these hurdles offers a nuanced understanding of the complexities involved:

1) LACK OF UNDERSTANDING AND AWARENESS

The nascent and technical nature of blockchain technology can contribute to a lack of understanding and awareness among key stakeholders, hindering adoption [160], [181]. Many actors within the wine supply chain may not fully comprehend the intricacies, benefits, and potential risks of blockchain, leading to hesitance in adoption. To address this hurdle, comprehensive educational initiatives, tailored training programs, and dissemination of information through case studies and success stories are paramount.

2) RESISTANCE TO CHANGE

Inherent resistance to change within established organizations, or even within industry-wide norms, can present a formidable barrier to the implementation of innovative technology such as blockchain [160], [182], [183] in the wine supply chains. Overcoming this resistance necessitates a strategic change management approach, involving clear communication about the benefits of blockchain, demonstration of successful use cases, and fostering a culture of innovation and adaptability within the industry.

3) COSTS AND RESOURCE ALLOCATION

The financial and human resources required for blockchain implementation can pose significant challenges [160], [183], [184], especially for smaller entities in the wine supply chain. The costs involved in system development, integration, data migration, training, and ongoing maintenance can be substantial [160]. To alleviate this concern, shared blockchain initiatives or adoption of blockchain-as-a-service models can offer cost-effective solutions.

4) COLLABORATION AND STANDARDIZATION

Blockchain's effectiveness in supply chain traceability is inherently contingent upon collaboration among various actors and the standardization of processes and protocols [160], [183]. This can be difficult to achieve due to highly competitive dynamics, disparate systems, and the need for consensus on shared standards within the wine industry. Industry associations and regulatory bodies could play a pivotal role in fostering collaboration and facilitating the development of shared standards.

Overcoming adoption-related hurdles is critical to unlock the potential of blockchain technology in wine supply chain traceability. It requires concerted efforts towards education, change management, innovative resource allocation strategies, industry-wide collaboration, and strategies to leverage network effects. Despite the challenges, with the right approaches, blockchain could significantly transform the traceability and transparency of the wine supply chain.

To visually encapsulate these challenges along with their related aspects, they are summarized in Fig. 3.

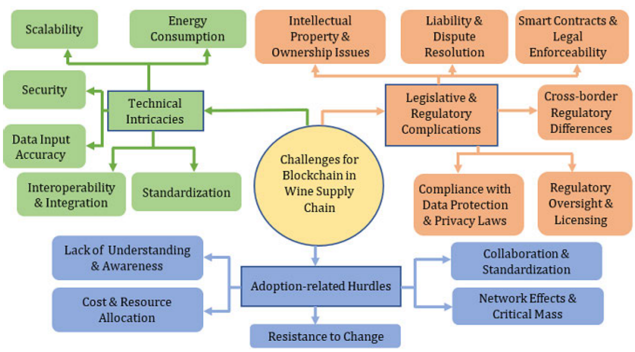

FIGURE 3. Challenges with blockchain adoption in wine supply chain.

IX. STRATEGIC RECOMMENDATIONS AND FUTURE DIRECTIONS FOR BLOCKCHAIN INTEGRATION IN WINE SUPPLY CHAIN TRACEABILITY

As the exploration of blockchain technology and its potential applications in the wine supply chain traceability continues to evolve, it becomes crucial to prognosticate the future trajectory of this emerging field and outline strategic recommendations to overcome the identified intricacies, complications, and hurdles discussed in the section VIII. This section delineates a series of prospective directions and strategic suggestions rooted in our analysis of the technical, legislative, regulatory, and adoption-related challenges encountered in harnessing blockchain technology within the viticulture industry. It aims to provide actionable insights for stakeholders, including wineries, supply chain actors, technology providers, policymakers, and academic researchers, to navigate the complexities of this transformative technology and capitalize on its potential to foster enhanced transparency, accountability, and trust within the wine supply chain.

A. TECHNOLOGICAL RESEARCH AVENUES

The integration of blockchain technology into wine supply chain traceability presents several unique technological challenges, as previously discussed in sub-section VIII-A. However, these challenges also point towards a plethora of research opportunities to refine and adapt blockchain solutions for this industry. The key technological challenges are elucidated further in the ensuing discourse:

1) DATA VALIDATION MECHANISMS

To address issues of data input accuracy, a critical field of exploration is the development and application of rigorous data validation mechanisms. This might involve leveraging advanced machine learning and artificial intelligence techniques to automatically detect and flag suspicious or inconsistent data entries [185], [186], [187], thereby enhancing the accuracy and reliability of data captured on the blockchain [188], [189], [190]. Ensuring data integrity is paramount to maintaining the trustworthiness of the blockchain system.

2) INTEROPERABILITY AND STANDARDIZATION

As the wine industry consists of a multitude of disparate systems, the question of interoperability is of paramount importance. Future research should focus on developing universal standards and protocols that facilitate seamless data exchange among various systems [122], [191]. In tandem, strategies to effectively integrate blockchain technology with existing platforms warrant considerable attention, including the creation of adaptable APIs and custom connectors [188], [189], [190]. This will ensure that different stakeholders can communicate and share data efficiently.

3) SCALABILITY SOLUTIONS

The scalability of blockchain solutions is another critical research avenue. As the size of the wine industry's supply chain and transaction volume expands, blockchain networks must be equipped to efficiently handle this growth. Therefore, the development of advanced consensus mechanisms, off-chain solutions, and innovative data storage optimizations are pressing research priorities [188], [189], [190]. Scalability solutions will enable the system to manage large volumes of transactions without compromising performance.

4) SECURITY AND PRIVACY MEASURES

The robust protection of sensitive data is a non-negotiable requirement for blockchain adoption in any industry. Future research needs to explore state-of-the-art encryption methods, access control measures, and secure data storage solutions, potentially drawing on advances in fields such as quantum cryptography and secure multi-party computation [188],

[189], [190]. Ensuring data security and privacy will help in gaining the trust of all stakeholders involved.

5) SUSTAINABLE TECHNOLOGY PRACTICES

With environmental consciousness increasingly becoming a societal priority, the high energy consumption of certain blockchain networks, particularly those relying on proof-of-work consensus mechanisms, is a significant deterrent to adoption. Exploring environmentally friendly alternatives, such as proof-of-stake or proof-of-authority, is crucial [161]. Moreover, the intersection of blockchain technology with green energy sources and practices presents a fascinating research direction [188], [189], [190]. Sustainable practices will make blockchain technology more acceptable and feasible in the long run.

By exploring these research avenues, technological barriers currently hampering blockchain adoption in wine supply chain traceability can potentially be overcome, to foster an environment where the full potential of this technology can be realized [188].

B. LEGAL AND REGULATORY RESEARCH AVENUES

The integration of blockchain technology into wine supply chain traceability presents numerous legal and regulatory hurdles VIII-B. However, the existence of these hurdles concurrently signals the necessity for targeted research to shape the legislative and regulatory environment for successful blockchain adoption. The key hurdles in the area are elucidated further in the ensuing discourse:

1) COLLABORATION WITH REGULATORS AND POLICYMAKERS

The dynamic nature of blockchain technology necessitates ongoing dialogue and collaboration with regulators and policymakers to ensure that legislation keeps pace with technological advancements [192]. Research must emphasize creating open lines of communication, fostering a shared understanding, and promoting knowledge exchange between technologists and legislative bodies [193].

2) CROSS-BORDER REGULATORY FRAMEWORK

Given the international nature of the wine supply chain, the development of harmonized cross-border regulatory frameworks is paramount [194]. Future studies should identify best practices in different jurisdictions and aim to create consensus on common standards [2]. This would facilitate blockchain adoption on a global scale by providing clarity and reducing compliance burdens for all actors in the supply chain.

3) INTELLECTUAL PROPERTY AND DATA OWNERSHIP

A complex issue in the blockchain space is intellectual property and data ownership [195]. Rigorous academic investigation is needed to define data ownership in the context of a distributed ledger and to identify how traditional intellectual property rights can be effectively protected in this new domain.[38]

4) RECOGNITION AND ENFORCEABILITY OF SMART CONTRACTS

Blockchain technology enables the use of smart contracts, self-executing contracts with the terms of the agreement directly written into code. Smart contracts pose a new type of code that guarantees the execution of the written code as is without the possibility of that code to be altered. This new paradigm has raised many legal questions and research efforts should focus on providing legal clarity with respect to their use [196] (especially when considering when things go wrong), as well as exploring the challenges and solutions related to their enforceability [197].

5) LIABILITY AND DISPUTE RESOLUTION MECHANISMS

When conflicts arise in the blockchain ecosystem, identifying the liable parties and resolving disputes can be complex due to the distributed nature of the system [196]. As such, a pertinent area for research lies in developing clear liability frameworks and efficient dispute resolution mechanisms specifically designed for blockchain-based systems [198].

C. ADOPTION RESEARCH AVENUES

The successful adoption of blockchain in enhancing wine supply chain traceability necessitates concerted efforts to overcome various adoption-related hurdles VIII-C. Accordingly, several research avenues are recommended to address these challenges:

1) RAISE AWARENESS AND EDUCATE STAKEHOLDERS

One of the primary obstacles to blockchain adoption is the lack of understanding of the technology among stakeholders. A directed research approach can facilitate the creation of educational programs and resources tailored to various stakeholders, including winemakers, distributors, retailers, and consumers [199]. Empirical studies can aid in identifying effective methods for communicating complex technical concepts in accessible terms to diverse audiences.

2) DEMONSTRATE USE CASES AND SUCCESS STORIES

Building a robust body of case studies demonstrating the benefits and practical applications of blockchain in the wine supply chain can stimulate interest and acceptance among stakeholders [200]. These use cases would serve as practical templates for stakeholders to grasp the transformative potential of blockchain and its tangible impact on traceability, transparency, and consumer trust.

3) PROVIDE FINANCIAL SUPPORT AND RESOURCES

The financial implications of blockchain adoption can deter many potential adopters. Research can inform policymakers

[38] See https://www.wipo.int/export/sites/www/cws/en/pdf/blockchain-for-ip-ecosystem-whitepaper.pdf

and industry leaders about the need for financial support mechanisms, such as grants, incentives, or subsidies, for entities keen to experiment with blockchain technology [201]. Analytical studies may be required to outline the cost-benefit scenarios associated with such adoption.

4) FOSTER COLLABORATION AND INDUSTRY CONSORTIA

To ensure broad adoption and interoperability, the establishment of industry consortia is essential [202]. Such bodies could enable cross-industry collaboration, standardization, and shared learning. Research should focus on the structures, governance models, and best practices for such consortia to be effective.

5) ENCOURAGE EARLY ADOPTERS AND NETWORK GROWTH

As with any network-dependent technology, blockchain systems benefit from a 'network effect', whereby the value of the system increases with the number of participants [203]. Research should explore strategies for incentivising early adopters and promoting network growth, thereby enhancing the system's overall value and appeal.

Addressing these adoption research avenues can drive the development of strategies and initiatives that promote a favorable environment for the widespread adoption of blockchain technology in the wine supply chain traceability. It can play a pivotal role in enabling a more transparent, secure, and reliable wine industry.

As discussed in section VIII, the journey towards full-fledged adoption of blockchain in wine supply chains is fraught with numerous technological, legal, regulatory, and adoption-related challenges. It is through rigorous, interdisciplinary, and collaborative research, as outlined in the subsections IX-A, IX-B, and IX-C, that these challenges can be systematically addressed. This research will facilitate the development of robust, scalable, and legally compliant blockchain solutions, foster a more informed and receptive environment among stakeholders, and ultimately, enable the wine industry to reap the full benefits of blockchain technology. The academic community, in concert with industry practitioners, technologists, and policymakers, plays a pivotal role in guiding this transformative journey and ensuring that the promise of blockchain in wine supply chain traceability transitions from mere potential to tangible reality.

X. CONCLUSION

This paper sheds light on and underscores the significance of harnessing blockchain technology to revolutionize the wine supply chain. Through an analysis of literature and industry practices, the paper has identified key technological, legal and regulatory, and adoption challenges and proposed future directions and recommendations to overcome them. By addressing these challenges and implementing the proposed recommendations, stakeholders in the wine industry can pave the way for widespread adoption of blockchain technology, leading to improved supply chain management practices and enhanced consumer confidence and satisfaction. The implementation of these recommendations will also lead to progressing the state-of-knowledge and drive positive change in the wine industry. This paper provides insights into blockchain adoption in the wine industry and offering practical recommendations for future research and implementation. The findings of this research have significant implications for practitioners, policymakers, and researchers, and can help progress the state-of-knowledge in the field of supply chain management, blockchain technology, and the wine industry. Embracing blockchain in the wine industry has the potential to uncork a new era of transparency, traceability, and trust, leading to improved quality assurance, increased consumer confidence, and a more resilient and efficient wine supply chain.

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