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Blockchain in Agri-Food:

A First Draft of a European Blueprint for Standards and Interoperability

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Executive Summary

This paper explores the evolving role of blockchain technology in enhancing sustainability, transparency, and efficiency within Europe's agri-food sector. In light of the European Union's Green Deal commitment to achieve climate neutrality by 2050, blockchain is increasingly viewed as a promising tool for meeting ambitious sustainability goals, especially in complex, multi-stakeholder sectors like agri-food, where transparency and trust are essential. With its secure and tamper-proof data management capabilities, blockchain offers solutions for improving traceability, data sharing, and environmental monitoring across food supply chains. Yet, substantial barriers continue to limit its adoption on a broad scale, as well as might prevent the enthusiasm for technology fit exploration in particular use cases.

The paper starts with an overview of blockchain's current standing within agri-food, recognising its benefits but noting that many applications are still confined to pilot and conceptual or theoretical phases. Apart from widely recognized challenges preventing or slowing down further adoption, the absence of unified standards, limited interoperability both between blockchain platforms and with traditional data systems, and the need to address agri-food-specific requirements remain as a level of necessity. These issues create disconnected "blockchain islands" that hinder a more seamless integration across supply chains and other applications.

To address these challenges, the paper guides through the role of standards in supporting agri-food blockchain solutions and contributing to broader EU sustainability objectives. Through a close look at current blockchain standards and protocols, the paper explores three key areas where blockchain, supported by robust standards, could make a meaningful impact, specifically, supply chain management, climate resilience, and smart farming. These examples illustrate how blockchain can be considered in the light of enhancing traceability, reducing environmental impact, and facilitating data integrity when built on consistent, interoperable frameworks.

The paper concludes with targeted recommendations to encourage standards-focused further work and foster interoperability, directed at the European Commission, policymakers, industry players, and standards bodies. These recommendations advocate for building a supportive blockchain ecosystem aligned with EU regulatory frameworks, setting the stage for sustainable and efficient growth in the agri-food sector and aligned with a well-balanced value proposition.

Purpose disclaimer

While this paper highlights blockchain's potential to support traceability, sustainability, and data integrity in the agri-food sector, we recognise that the technology continues to evolve and presents numerous practical, technical, and governance challenges. This work does not position blockchain as a universal solution or panacea but rather positions it as one of several tools that worth exploring. We support a rational, evidence-based approach to evaluating where and how blockchain can add meaningful value, with particular emphasis on interoperability and standards as fundamental enablers of any future adoption.

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Declaration on Generative AI

During the preparation of this work, the authors used generative AI tools, including OpenAI GPT-4 and Claude Sonnet 4, to assist with grammar and spelling checks, as well as for refinement and summarization support. All content was critically reviewed and finalized by the authors to ensure accuracy and originality.

Rationale & Purpose Behind This Paper

Blockchain as a supporting tool for European sustainability

This paper addresses the gap between blockchain's promising role in enhancing agri-food sustainability and the practical barriers to its widespread implementation, particularly as Europe pursues the ambitious targets of the Green Deal. Blockchain technology holds unexplored potential to support supply chain transparency, efficiency, and environmental accountability within the agri-food sector. However, despite its potential advantages, technology maturity in European agri-food remains low, with most implementations currently in the pilot or conceptual stages. The less commonly discussed but essential for the operation and broader adoption challenges to broader adoption include the lack of common standards, interoperability difficulties between blockchain and non-blockchain platforms, and the need for consistent data structures across a range of agricultural products. These issues create fragmented “blockchain islands” that limit the blockchain’s ability to drive sector-wide integration. We also acknowledge the key adoption barriers such as implementation costs, energy consumption, and the technical complexity that creates friction, especially for smaller agricultural producers, but this work is mainly presented through the angle leading to the discussion around standardisation and interoperability.

One prominent complication lies in the diversity of blockchain technologies themselves. These vary in structure, permissions, and applicability to different types of agri-food data, making it difficult for stakeholders to commit to specific solutions due to concerns about compatibility and longevity. Additionally, the complex and fragmented nature of agri-food supply chains suggests that no single blockchain solution can meet the needs of all stakeholders. Therefore, this paper advocates for a perspective that considers an agnostic approach to any single blockchain technology. By connecting these “blockchain islands” into a more synergetic ecosystem, the agri-food sector can benefit from blockchain’s potential in areas like traceability, ESG (Environmental, Social, and Governance) reporting, and climate resilience, which align with key objectives under the European Green Deal.

Specifically, the European Union’s Green Deal has outlined concrete goals to position Europe as the first climate-neutral continent by 2050, stressing sustainability, climate action, and environmental responsibility. These policy goals offer strong incentives for integrating blockchain-based solutions across the agri-food sector for applications that support low-carbon farming, comprehensive traceability, and responsible resource use. If supported by defined standards and interoperability aspects, blockchain can contribute to climate goals. For example, in climate change adaptation, blockchain’s capacity for secure data handling could support carbon trading systems, providing verified incentives for sustainable practices like carbon farming. In smart farming, blockchain enables secure integration of data from IoT devices, satellite monitoring, and other digital agriculture tools, helping farmers to adopt efficient and resource-conscious practices. Through these examples, the paper illustrates how blockchain, underpinned by standards and interoperability specifics, could play a valuable supporting role in helping agri-food stakeholders align their practices with EU climate objectives.

What is this paper about

Each section of this paper contributes to a gradually built understanding of how blockchain can support the goals of the European Green Deal, with a focus on identifying areas where standards and interoperability can amplify blockchain’s positive impact or, in some cases, be positioned as the essential enablers.

Introduction to blockchain’s potential benefits applied to agri-food: The first section presents blockchain’s potential benefits, particularly in enhancing food safety, traceability, and environmental monitoring. This overview helps to establish a foundational understanding of how blockchain could improve transparency and efficiency across agri-food supply chains, aligning with the Green Deal’s objectives (i.e., reducing environmental impact and encouraging sustainable practices).

Analysis of research trends and pilot projects in European agri-food: By examining current trends in blockchain research and adoption within Europe’s agri-food sector, this paper sheds light on both advancements that were aimed to be explored within the European scale and ongoing challenges. This analysis also highlights EU-backed initiatives aimed at meeting specific industry needs, demonstrating Europe’s commitment to integrating digital solutions that support sustainability.

Emphasis on standards and interoperability in agri-food blockchain applications: This paper emphasises the critical role of standards and interoperability in enabling blockchain solutions across the agri-food sector. Through an exploration of existing standards and protocols, it highlights three key use cases, including supply chain management, climate change and farmer income, and smart farming, where blockchain, if supported by interoperable standards, could make a meaningful impact, particularly in alignment with EU regulations and the Green Deal’s goals. These cases illustrate blockchain’s potential to encourage sustainable practices, support ESG compliance, and ultimately enhance resilience against climate change.

Recommendations for supporting blockchain interoperability, standards, and adoption: In the third section, this paper gives a set of actionable recommendations aimed at accelerating the development and adoption of blockchain standards within the agri-food sector as well as positioning the role of interoperability within this context. These measures are tailored to support the European Commission and other stakeholders in fostering further a supportive ecosystem for blockchain exploration and integration that aligns with EU sustainability and regulatory objectives, but also accounts for the value and the balance of the benefits and challenges it brings if adopted.

Intended reader

The primary audience for this paper is **policymakers** and **regulatory bodies within the European Union**, who play a vital role in developing the regulatory framework needed for blockchain adoption in the agri-food sector. Through the discussion of current barriers and proposing actionable measures, the paper offers policymakers a clear, evidence-based perspective on how blockchain implementation can be approached and harmonised with the EU’s sustainability and regulatory priorities.

The secondary audience comprises **industry stakeholders**, including food producers, technology providers, supply chain managers, and sustainability professionals. For these groups, the paper provides a structured analysis of blockchain's potential, if facilitated by standards and interoperability, to deliver measurable value, offering insights that can inform strategic decisions regarding blockchain's exploration and application within their operations.

Academic researchers and **industry associations** are also among the intended readers, as the paper serves as a reference for understanding the regulatory and operational requirements specific to blockchain in agri-food through the use cases and practical examples discussed in the paper.

This paper advocates for an approach that emphasises standards and interoperability as essential enablers of blockchain's role in the agri-food sector, particularly in alignment with the Green Deal. Through the practical measures given, the paper seeks to empower and assist stakeholders, especially the European Commission, toward creating a supportive ecosystem for blockchain in agri-food. As blockchain doesn't go anywhere while it's fit for particular use cases and full potential has not been validated, such an ecosystem will be critical to maximising its potential to support Europe's environmental and social goals.

I. Blockchain in Agri-Food: Understanding the Value And European Trends

1.1 Understanding the value of the blockchain in the agri-food sector

Blockchain technology, which debuted with Bitcoin in 2008 [1], has grown far beyond its origins since then and now has a range of applications across many industries, including the agri-food sector. At its heart, blockchain is a digital record-keeping system or a digital ledger [2], but it differs from traditional databases following its distributed approach: rather than being stored in one central location, the information is shared across multiple computers, known as “nodes” [3]. This decentralised setup can make the data harder to tamper with.

The way blockchain works is by linking pieces of information, called “blocks”, into a chain that builds up over time. Each block connects securely to the one before through a cryptographic hash [2,4], forming an unbroken line that’s nearly impossible to change. If someone tried to alter one block, they’d have to go back and change all the blocks that follow it, which would require controlling most of the network's computing power and is therefore extremely challenging to execute. This makes blockchain a potentially valuable solution for industries where immutable records are important and where data integrity across the supply chain is essential, such as agri-food.

Another unique feature of blockchain is its use of self-executing programs known as “smart contracts” [5]. These contracts automatically enforce the rules of an agreement when certain conditions are met. For example, payment for a shipment of goods might be released automatically once the shipment is confirmed as delivered. However, it's important to note that current blockchain systems face scalability challenges and may not be suitable for all types of agricultural data or high-volume transactions.

Blockchain networks also rely on a process called consensus [6], where all nodes in the system agree on each new piece of information added to the chain. This helps to ensure that everyone in the network can trust the data without needing a central authority to verify it.

In the agri-food world, blockchain can help solve some significant problems, particularly around **transparency** and **traceability** [7]. Supply chains for food are often complex and involve many players, from farmers and processors to distributors and retailers. Traditionally, each of these parties keeps its own records, and there’s often no easy way to communicate and share this information across the chain. As a result, it can be challenging to get a complete and consistent view of a product’s journey from farm to fork. By using blockchain, all authorised participants in the agri-food supply chain can access the same verified information. Each step in the product’s journey is recorded as it happens, creating a single, shared source of truth that anyone involved can trust. For example, when produce is harvested and shipped, those actions are logged on the blockchain. This makes it easy for anyone, from farmers to consumers, to see where the product came from and how it’s been handled along the way, hence making the entire chain of events available and transparent.

In addition to boosting transparency, blockchain can also enhance traceability, which is a growing priority for many consumers today. People want to know more about the origins of their food, especially if it’s marketed as organic, sustainably sourced, or fair trade. Blockchain can link a product to its digital history with something as simple as a QR code [8] or an RFID tag [9]. This means anyone can scan the code and view the product’s history. Having this information available can help eliminate paper-based and time-consuming tracking processes while building trust with consumers. It also gives companies a straightforward way to show their commitment to quality and safety.

Having mentioned safety, blockchain is also beneficial when it comes to managing food safety issues concerning the **provenance** of the food's origins [10]. Suppose there's a problem, such as contamination. In that case, blockchain allows for quick tracing back to the source, enabling rapid action to mitigate mass pathogen outbreaks related to food and, as a result, prevent further harm. Also, in the event of a recall, products can be identified and removed from the supply chain with greater precision within hours rather than days, reducing the cost and effort required to handle the situation and eliminating worse public health consequences. This efficient response is a crucial benefit for businesses and human well-being.

Despite the benefits blockchain brings to the agri-food sector's table, it does come with some shortcomings [11]. Setting up a blockchain system *can be costly* and might require specialised training and equipment. In many cases, these systems consume more energy than traditional databases, which can drive up operational costs. While some of these expenses could lead to higher prices for the goods, studies show that consumers are willing to accept as high as a 17.8% price increase if that means that the product they buy comes with proven traceability and origin [12].

Beyond these internal challenges, which are likely to be addressed gradually over time, there are significant issues that originate outside the agri-food sector itself. Key among these are *regulatory uncertainties* (despite frameworks like MiCA addressing some crypto-asset concerns in the EU), the *lack of unified blockchain standards* specific to the sector, and *interoperability challenges* between different systems, factors that are critical for broader adoption [3] [10]. Our paper will explore these external influences, as they play a crucial role in shaping blockchain's long-term potential in agri-food. Nevertheless, it is evident that blockchain can already address some of the sector's most urgent issues, particularly those related to sustainability and food safety. These priorities are central to the European agenda, and they underscore why EU countries are increasingly investigating blockchain solutions in agri-food, recognising the technology's potential to foster a more secure and transparent supply chain.

1.2 The evolution of blockchain research and adoption in European agri-food

As globalisation and decentralisation reshape food supply chains, the need for robust traceability and security mechanisms has become increasingly urgent. Blockchain has been widely discussed as a potential solution to these challenges, particularly for managing the complex agri-food supply chains that demand transparency and data integrity. While blockchain's role in agri-food is still emerging, its potential to address issues like food fraud, safety, and sustainability has drawn significant interest in Europe.

The early years following blockchain's debut in 2008 saw little focus on agri-food applications. Initial studies were sporadic, with just a handful of publications by 2013 [13]. However, interest in applying blockchain to agri-food began to build around 2014. From 2017 to 2018, the sector saw a surge in research and pilot projects, with around 271 projects launched by 2020 (Figure 1). Many of these initiatives were aimed at exploring blockchain's potential to improve transparency and traceability within the food supply chain, with about half progressing to pilot testing (Figure 2).

Although fewer projects made it to full production, this period marked an essential phase of exploration and experimentation.

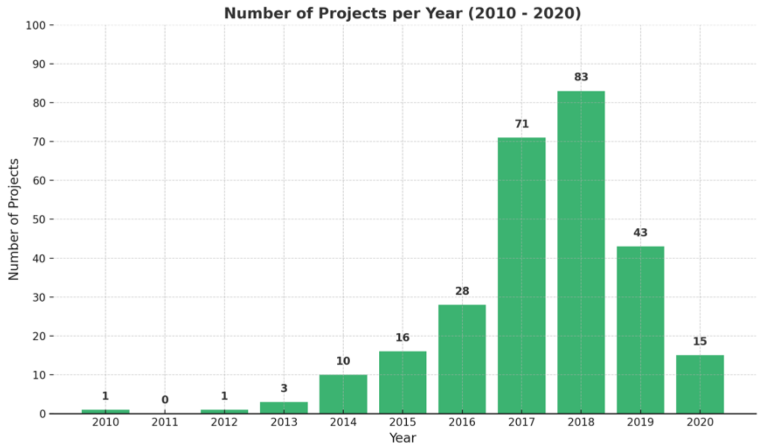

Figure 1. The number of blockchain projects disseminated between 2010-2020 [13].

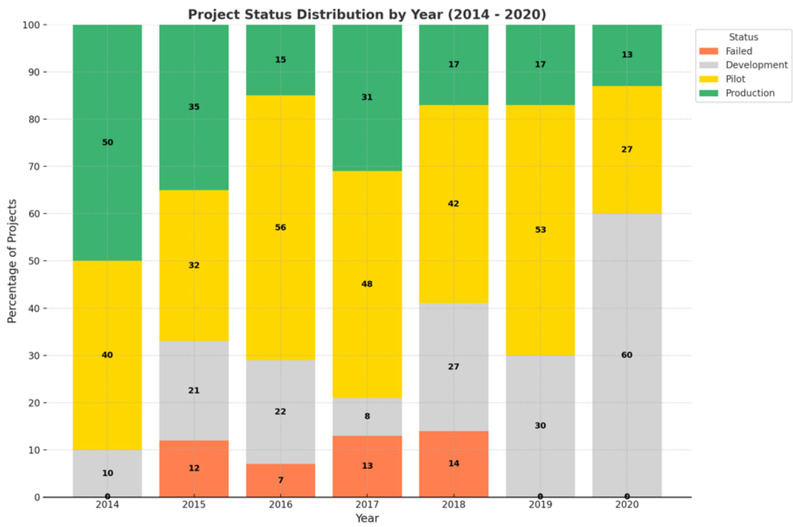

Figure 2. Distribution of implementation stages across projects disseminated between 2014-2020 [13].

In terms of stakeholder involvement, the early blockchain projects in agri-food were largely driven by private companies, including tech startups focused on digital solutions. As awareness grew, government bodies, consortia, and larger corporations began to engage (Figure 3). Today, blockchain projects in agri-food are more collaborative, with initiatives often involving multiple stakeholders. This trend reflects a growing understanding that blockchain's potential impact extends beyond any single entity and requires cross-sector collaboration to maximise impact.

Figure 3. Distribution of project types disseminated between 2014-2020 [13].

Since 2020, the pace of blockchain research in agri-food has shifted. Recent studies have moved from general explorations of blockchain's applicability to more focused examinations of specific benefits and barriers to adoption [14][15]. Much of the current literature investigates how blockchain can address pressing issues such as food security, supply chain efficiency, and environmental impact [16]. Many studies now centre on using blockchain for transparency and logging purposes, showing a slight shift from earlier emphases on food integrity to guarantee safety, authenticity and quality [17] (Figure 4).

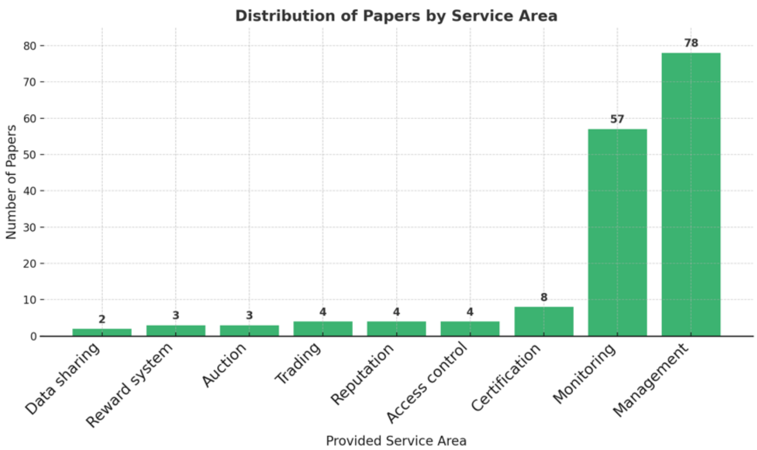

Figure 4. Top processes in agri-food supported by the blockchain [17].

Yet, the maturity of the proposed solutions, and hence their complete adoption in the agri-food sector, is rather low [17]. Many solutions are still conceptual, with only a small number progressing to pilot testing or full-scale adoption. Most active blockchain projects are concentrated in Asia, with fewer initiatives seen across Australia, Europe, and South America. This disparity suggests that, while Europe is engaged in blockchain exploration, significant work remains to bring these solutions to maturity and broader adoption.

Nonetheless, Europe has seen some noteworthy blockchain projects in the agri-food sector, led by companies like TE-FOOD and Provenance. ***TE-FOOD*** [18], for instance, has collaborated with organisations like ***Deloitte*** and ***HALAL TRAIL*** to deliver blockchain-based food traceability solutions. These projects illustrate how blockchain can be applied to improve transparency and traceability across the entire supply chain, from production to consumption [19][20]. ***Provenance*** [21], a UK-based company, has also made strides in this area by working with NGOs and local partners in South Asia to track tuna supply chains, bringing transparency from fishing to export stages [22]. It then collaborated with Princes Group to provide a blockchain-based transparency system for sourcing tuna [23]. This European focus on blockchain applications reflects a keen interest in enhancing food safety and supporting sustainable practices within the EU.

In comparison, the US has also made significant advances in blockchain applications within the agri-food sector. ***IBM*'s** collaboration with ***Walmart*** is a prime example, where they've built a permissioned blockchain network to connect farmers, distributors, and retailers in a secure and transparent system [24]. The platform includes various modules for tracking, data management, and access control, all designed to boost efficiency and integrity across the supply chain. While IBM's model offers an insightful look at how large-scale blockchain solutions can function, European projects tend to focus more on sustainable practices and alignment with the EU's stringent food safety regulations.

The adoption of blockchain in Europe's agri-food sector is still in the early stages. A significant portion of European projects are still experimental, with full-scale implementations limited due to challenges like high costs, complexity, lack of regulatory base, and the need for specialised knowledge. Additionally, while some EU countries are actively pursuing blockchain solutions, much of the activity is concentrated outside Europe. However, the collaborative nature of recent projects suggests that blockchain's role in agri-food is being taken seriously, with promising potential for growth as solutions mature. Moreover, by addressing these external factors and barriers, the agri-food sector can leverage blockchain to build more resilient, transparent, and sustainable supply chains, ultimately aligning with EU objectives for food safety and environmental sustainability [25].

II. The Role of Blockchain Standards and Interoperability Across Agri-Food Key Sector Innovations

2.1 The importance of standards and interoperability in agri-food supply chains and the role of blockchain

As agri-food supply chains grow more complex, involving numerous stakeholders and increasingly advanced systems, the need for seamless communication, traceability, and security has become more critical. Standards and interoperability are critical to ensuring efficient data exchange and cooperation between various platforms, devices, and actors within the sector [26]. These standards define data formats, protocols, and communication methods, enabling systems to exchange and process data consistently. These elements are vital for maintaining food safety, ensuring transparency, and building trust across the entire supply chain, from production to retail.

In the agri-food sector, where supply chains are very fragmented, international standards like GS1 play a fundamental role. ***GS1*** standards, including the ***Global Trade Item Number** (**GTIN**)* [27] and the ***Global Traceability Standard** (**GTS**)* [28], enable traceability, promote food safety, and ensure a flow of information across global supply chains [29]. For example, GS1 standards assign each product a unique identifier, allowing stakeholders to track its movement and status throughout the supply chain. This is particularly valuable in managing food safety issues, such as product recalls, where swift and effective responses are essential [30]. Without such standards, supply chain data can become even more fragmented, siloed, or incompatible, making it difficult to achieve the transparency and traceability required.

Interoperability is closely linked to standards and refers to the ability of different systems or platforms to exchange data and work together [31]. Achieving interoperability within the agri-food sector is critical because it allows stakeholders, ranging from producers to distributors and retailers, to share information, enabling a smooth flow of goods and data through the supply chain. Interoperability relies heavily on established standards but also requires aligned workflows and consistent data handling across different platforms. For instance, differing operational contexts, proprietary systems, or customised standards can limit the effectiveness of data exchange and reduce overall transparency [32].

In a global context, ensuring interoperability within supply chains is essential for preventing issues such as counterfeiting, food fraud, or defects in products. EU countries are already embracing open standards for open data and building an ecosystem of interoperability across Europe [33]. This highlights the essential role that *governments* play by offering incentives and updating regulations to support interoperability and improve sector-wide efficiency.

Blockchain technology may offer additional capabilities in some specific areas by providing a decentralised and tamper-proof platform for recording and sharing data. Blockchain ensures that all participants can access and verify accurate, secure records, thereby enhancing traceability and facilitating smoother data exchange [34] [35]. In specific use cases where additional data verification is needed beyond traditional systems, blockchain may complement existing interoperability frameworks by providing an additional layer of data validation, though this requires careful integration with established standards like GS1. While these traditional standards and systems effectively support most supply chain interoperability needs, blockchain may offer additional value in specific scenarios requiring enhanced verification [36], such as premium product authentication or complex multi-party transactions where trust between parties is limited.

Blockchain may provide additional verification capabilities for data exchange, though integration with existing systems requires careful planning. In practice, such multi-stakeholder blockchain implementations typically emerge through several models: technology provider-financed consortiums; authority-offered services; industry-led consortiums where competitors jointly invest; non-profit foundation initiatives; or through adoption of existing public blockchain infrastructure. These various approaches address the challenge of stakeholder alignment on technology adoption. Blockchain's decentralised ledger also ensures that all recorded data is immutable, which builds trust across the supply chain but also requires careful consideration of data governance and regulatory compliance. As a result, this approach specifically addresses the trust gap identified in cross-border food trade scenarios.

Emphasis on the importance of interoperability and standards, with the use of blockchain technology, is given by the European Commission's blockchain strategy, while the creation of a set of supporting standards is one of the key goals and challenges to ensure interoperability between different blockchain platforms and legacy systems [37]. However, the effective implementation of blockchain in agri-food depends on harmonised standards and consistent regulatory frameworks. Blockchain enhances existing standards by ensuring that data recorded using these standards is accurate, traceable, and secure. An example of this can be seen in the U.S. egg supply chain, where blockchain has been successfully implemented to provide a transparent and immutable record of product origins, enhancing traceability and consumer trust [38]. However, without standardised processes and harmonised protocols, issues such as data capture inconsistency, scalability, and governance fragmentation can limit the success of blockchain systems [39][40].

Recognising the importance of these issues, the European Commission (EC) has prioritised blockchain standards and interoperability in its blockchain strategy, aiming to establish a harmonised framework that supports cross-platform compatibility and widespread adoption of blockchain technology across the European Union [37]. Moreover, the EC is actively promoting the standardisation of blockchain technologies through initiatives such as the ***European Blockchain Partnership*** and the ***European Blockchain Services Infrastructure** (**EBSI**).* These initiatives aim to create interoperability across blockchain platforms and ensure more seamless integration with existing systems. The EC is also engaging with global standards bodies like ISO, ETSI, and IEEE to encourage the development of standardised blockchain protocols that can be adopted across various industries, including agri-food. Yet, the agri-food sector continues to await more concrete regulatory guidelines being established.

2.2 Review of blockchain standards and their relevance to agri-food

The lack of common blockchain standards in agri-food or any other sector involving large volumes of data across numerous stakeholders can cause problems in adopting a common framework and data exchange schema. This often leads to interoperability issues, especially when such systems are developed for different kinds of agricultural products, where the required information for each type of product might differ, or when the blockchain systems developed by different companies or even countries use different blockchain technologies.

These issues have prompted national and international committees and standardisation bodies to work on producing standards aiming to harmonise the use and exchange of data within supply chains and beyond, facilitating smoother integration and enhanced interoperability between blockchain platforms.

In this section, we explore the most significant blockchain standards developed by key global organisations and promoted by the European Commission [37], including ISO, ITU-T, ETSI, CEN-CENELEC, and IEEE, and analyse their relevance to the agri-food sector.

2.2.1 ISO/TC 307

International Organization for Standardization (ISO) established the ISO/TC 307 [41] committee in 2016 with the goal of creating standards to enhance security and better interoperability when working with blockchain technologies, especially when it comes to a number of Small-Medium Enterprises (SMEs) that develop their own blockchain solutions. ISO/TC 307 main purpose is the "standardization of blockchain technologies and distributed ledger Technologies"; thus, it aims to cover a variety of aspects relevant to blockchain technology, including terminology, security and privacy, the application of smart contracts, governance, and interoperability.

Relevance to agri-food: The ISO/TC 307 standards play a crucial role in enabling effective communication between different technologies, or in other words **interoperability**, such as Internet of Things (IoT) devices and cloud-based systems, which are commonly used in modern agri-food operations. Additionally, ISO's work on smart contracts offers a secure and standardised solution for **automating key processes** like payments and quality checks. By reducing delays and minimising errors, smart contracts enhance both operational efficiency and transparency within the supply chain. Moreover, the **governance** standards set by ISO/TC 307 are vital for managing data and platform usage across multiple stakeholders, ensuring that agri-food companies can navigate complex compliance and regulatory environments effectively.

One practical application is the ***R.O.U.G.E project*** in Sicily, Italy, where these standards were adopted to ensure the traceability of the Sicilian Blood Orange PGI [42]. This use case highlights how ISO/TC 307 standards can enhance transparency and product integrity across agri-food supply chains.

2.2.2 ITU-T Focus Group on Application of Distributed Ledger Technology

The International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) Focus Group on Application of Distributed Ledger Technology (FG DLT) [43], launched in 2017 and closed in 2019, focused on best practices and proper guidance when designing and implementing applications based on DLT while attempting to assist standardisation actions within the ITU-T landscape [43]. Its work on architecture and regulatory frameworks provides a solid foundation for industries, helping them to implement blockchain solutions that meet the specific demands of their sector.

Relevance to agri-food: The ITU-T standards may provide some **architectural guidance** for organizations considering blockchain implementation, though these telecommunications-focused frameworks require significant adaptation for agricultural contexts. While blockchain could potentially supplement existing compliance systems in specific scenarios where **additional verification** is needed, the practical benefits over established regulatory reporting mechanisms remain to be demonstrated. ITU-T's work on DLT architecture may inform blockchain deployment decisions, though integration with existing agricultural systems typically involves significant complexity and costs that require careful evaluation against simpler alternatives.

2.2.3 ETSI Industry Specification Group on Permissioned Distributed Ledger

European Telecommunication Standards Institute (ETSI) Industry Specification Group on Permissioned Distributed Ledger (ISG PDL) [44] focuses on Permissioned Distributed Ledgers (PDL), which are designed for enterprise applications where privacy and security are essential. Its role is to delve into the foundational layer of PDLs, aiming to create a set of solutions, mainly addressed to industries across different sectors, that can encourage the adoption of such technologies and help establish trust towards them. The group makes efforts to avoid covering work, carried out by other efforts on standardisation activities, and puts its focus on analysing architectural and infrastructure-related aspects of PDLs.

Since 2019, ETSI's work in this area has resulted in a number of deliverables that cover numerous topics, including interoperability, smart contracts, distributed data management, consensus, and others [45] [46]. An example of work related to agri-food supply chain is *PDL-022 - PDL use in supply chain management*, which specifically addresses blockchain's role in supply chain management, where traceability is key.

Relevance to agri-food: ETSI's work on permissioned distributed ledgers may be relevant for agri-food organizations handling particularly sensitive data that requires **additional verification layers** beyond traditional security measures. While most agricultural supply chain data is effectively managed through existing secure databases and APIs, permissioned blockchain systems could potentially add value in specific scenarios such as **high-value product authentication** or **complex multi-party contracts** where traditional trust mechanisms are insufficient. Yet, the added complexity and costs of implementing permissioned ledger systems require careful evaluation against existing data management solutions that already provide security and traceability for most agricultural applications.

2.2.4 CEN-CENELEC JTC 19

CEN-CENELEC JTC 19 (European Committee for Standardization and European Committee for Electrotechnical Standardization Joint Technical Committee) [47] was created to focus on European-specific blockchain standardisation needs. This group collaborated closely with ISO/TC 307 with the goal of supporting its standardisation activities, identifying missing needs for standardisation in the EU premises, and later connect these needs to work performed under ISO/TC 307, while at the same time encourage participation to the latter [48]. While it works closely with ISO/TC 307, it also takes into account European legislative and policy requirements, placing particular emphasis on sustainability and interoperability with two standards being under preparation – *Environmental and sustainability classification methodology of consensus mechanisms of Blockchain and DLTs* and *Decentralised Identity Management Model based on Blockchain and other Distributed Ledgers Technologies. – Part 1: Generic Reference Framework.*

Relevance to agri-food: Sustainability is becoming increasingly important in the agri-food sector as companies face growing pressure to reduce their **environmental footprint**. CEN-CENELEC's focus on this issue is particularly relevant, with a forthcoming standard on the **environmental classification of blockchain consensus mechanisms**. This standard can be helpful for agri-food companies in assessing the energy impact of the blockchain systems they use, which may facilitate them to make more sustainable choices. Additionally, for agri-food companies operating within the European Union, aligning with CEN-CENELEC standards ensures **compliance with both EU regulations** and broader international standards like ISO, making it easier to navigate the regulatory landscape while maintaining sustainable practices.

2.2.5 IEEE Computer Society Blockchain and Distributed Ledger Standards Committee

IEEE CTS/BSC (Computer Society Blockchain and Distributed Ledger Standards Committee) [49] involves a number of various stakeholders, including companies, academic institutes and other organisations worldwide. This committee is tasked with developing standards for the blockchain and DLT domain, as well as standards for the application of blockchain technologies and DLTs across different sectors and industries. As of now, two standards – *IEEE Standard for the Use of Blockchain in Supply Chain Finance (IEEE 2418.7-2021) and IEEE Standard for Data Format for Blockchain Systems (IEEE 2418.2-2020)* have been published, and two are under review – *P3207 Standard for Blockchain-based Digital Asset Identification* and *P3218 Standard for Using Blockchain for Carbon Trading Applications*. Yet, the group is currently working on 27 more standards.

Relevance to agri-food: IEEE's supply chain finance standards may provide frameworks for blockchain implementation where traditional payment systems face specific challenges, such as international transactions with limited trust between parties. In that regard, blockchain has the potential to **complement existing financial processes** within agri-food supply chains. Another significant initiative from IEEE, P3218, focuses on the role of blockchain in **carbon trading**. This is particularly important for agri-food companies looking to reduce their carbon footprints and adopt more sustainable farming practices, as it provides a framework for engaging in carbon trading and meeting environmental targets.

2.2.6 Summary of standards analysed

The blockchain standards developed provide a valuable framework for addressing the specific challenges faced by the agri-food sector. These standards are crucial for enhancing interoperability, security, and traceability, all of which play a key role in improving transparency, reducing fraud, and building consumer trust. However, while these standards offer strong guidance for blockchain adoption, better alignment between current industry practices and these standards is essential to achieve more widespread adoption within the agri-food sector.

For example, the successful implementation of ISO/TC 307 standards in the R.O.U.G.E project highlights blockchain's potential for improving traceability in agri-food supply chains. Nevertheless, broader adoption across various agricultural sectors is still required. Similarly, the standards developed by ETSI ISG PDL and IEEE present promising solutions for advancing supply chain finance and environmental sustainability, though their practical application in agri-food remains limited.

As the regulatory landscape continues to evolve, especially within the European Union, these standards will play a crucial role in shaping blockchain's future in agri-food, ensuring that it can meet the sector's growing demands for security, interoperability, and sustainability. Therefore, it is critical that these standards are translated into actionable agri-food use cases, starting with areas that stand to benefit most from the integration of blockchain technology. Table below briefly outlines key elements of each standard analysed in this paper.

Standard	Focus	Key contributions	Relevance to Agri-food sector	Examples of practical application in AF sector
ISO/TC 307	Standardization of blockchain and distributed ledger technologies	Establishes standards for terminology, security, privacy, governance, interoperability, and smart contracts Enhances secure and efficient blockchain adoption	May enable interoperability between IoT devices, blockchain systems, and cloud-based platforms Could support processes like payments and quality checks	R.O.U.G.E. project: traceability for Sicilian Blood Oranges PGI
ITU-T Focus Group on Application of DLT	Best practices and regulatory frameworks for designing and implementing DLT applications	Provides a foundation for architecture and regulatory compliance Guidelines to align blockchain applications with sector-specific demands	May provide architectural guidance for blockchain implementation; frameworks require adaptation for agricultural contexts	No specific agri-food applications identified*
ETSI Industry Specification Group on Permissioned Distributed Ledger (ISG PDL)	Permissioned Distributed Ledgers (PDL) for secure enterprise applications	Deliverables on interoperability, smart contracts, distributed data management, and consensus Prioritises secure and private blockchain systems for industry-wide adoption	May complement existing data security measures for particularly sensitive applications Could support specific use cases requiring additional verification Addresses blockchain's role in supply chain management (PDL-022)	No specific agri-food applications identified*
CEN-CENELEC JTC 19	European-specific blockchain standardisation with a focus on sustainability and interoperability	Collaboration with ISO/TC 307 to address missing standardisation needs within the EU Standards for environmental sustainability (e.g., energy classification for blockchain consensus mechanisms) Addresses European legislative and policy-specific blockchain needs (e.g., identity management and sustainability compliance)	Supports sustainability efforts in the agri-food sector by providing methodologies to assess and minimise blockchain systems' energy impact Helps companies align with EU regulations and international standards (ISO) for compliance Emphasises the importance of interoperability and sustainability in reducing the environmental footprint of blockchain applications	No specific agri-food applications identified*

Standard	Focus	Key contributions	Relevance to Agri-food sector	Examples of practical application in AF sector
IEEE Computer Society Blockchain and Distributed Ledger Standards Committee	Development of standards for blockchain technologies and distributed ledger applications across industries	Published standards IEEE 2418.7-2021 for supply chain finance (e.g., reducing fraud, improving transparency, and minimising delays in payment processes) Published IEEE 2418.2-2020, standardising data formats to support interoperability and consistency in blockchain implementation across industries Upcoming standards under review include P3207 for digital asset identification and P3218 for blockchain use in carbon trading and environmental accountability	May provide frameworks for financial processes in agri-food supply chains May support sustainability through frameworks for carbon trading, helping agri-food companies reduce their carbon footprint	No specific agri-food applications identified*

***Note**: At the time of writing this report, to the best of our knowledge and according to the extensive desk research we performed, we did not come across any available evidence or other credible source(s), we could rely on, to support a different claim.

2.3 Key agri-food use cases powered by blockchain standards and interoperability

Blockchain technology may offer potential solutions for specific challenges across the agri-food sector, offering solutions that go beyond improving supply chain processes. It has the potential to enhance traceability, data sharing, sustainability, and overall efficiency in different areas of agri-food. By encouraging interoperability between platforms and stakeholders, blockchain standards may facilitate integration in specific use cases. In this section, we explore several key areas where blockchain interoperability can make a real difference.

2.3.1 Supply chain management: data sharing and traceability

Blockchain technology has been proposed as one approach to enhance food integrity in the agri-food sector. Numerous stakeholders along the food supply chain generate vast amounts of data, including information on land, soil, seed, crop health, weather conditions, pests, product quality, market conditions, and logistics. These data points are collected from diverse sources, such as mobile devices, IoT sensors, and satellite imagery. Integrating these various data types and sources to enable end-to-end traceability is the key challenge. Currently, significant barriers include the fragmentation between information systems and the legal frameworks governing data sharing in digital agriculture [50], as well as the need for common data architecture standards and cross-platform interoperability. These issues present obstacles to farmers and other agri-food stakeholders seeking to adopt new technologies like blockchain [51][52].

Data sharing has immense potential to transform agricultural systems, particularly in the agri-food sector. However, data-sharing ecosystems remain at an early stage, primarily due to the lack of an enabling infrastructure that facilitates collaboration between stakeholders. As illustrated in Figure 5, the path forward for enabling these ecosystems focuses on the creation of standards and interoperability [53]. This includes establishing standardised data structures and terminology to promote interoperability, along with standardised methods for data collection. From a governance perspective, agreed-upon policies and regulatory frameworks are also essential to managing and coordinating the data generated.

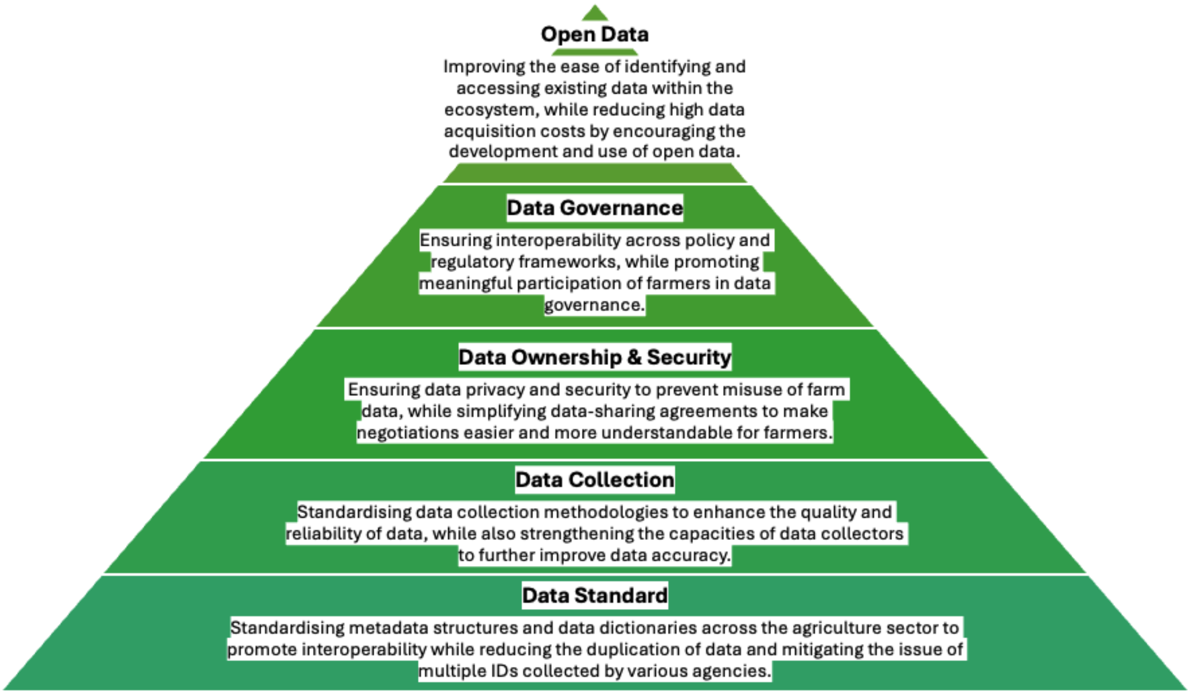

Figure 5. Suggested pathways for enabling data sharing ecosystem in AFS [53]

The challenge of developing data standards for cross-platform interoperability in the agri-food sector is being addressed by initiatives such as the Digital Integration of Agricultural Supply Chains Alliance (DIASCA). DIASCA is developing open standards to support interoperability between traceability systems in agriculture. Led by the Deutsche Gesellschaft für Internationale Zusammenarbeit (German Development Cooperation), it focuses on facilitating due diligence reporting, as required by the EU Deforestation Regulation (EUDR) and the Corporate Sustainability Due Diligence Directive (CSDDD) [54]. DIASCA's work is focused on establishing digital standards for product traceability to create a foundation for data exchange and reliable documentation of corporate due diligence obligations.

The resulting interoperability between traceability systems, from the start of the agri-food supply chain to the end-consumer, would significantly enhance transparency. This transparency can be leveraged to support efforts to mitigate deforestation or ensure fair income for farmers. Thus, it would be valuable to explore how blockchain may complement existing interoperability efforts in supply chain scenarios addressing Environmental, Social, and Governance (ESG) compliance issues [55].

2.3.2 Climate change and farmer income

The income of farmers largely depends on the **yield** they achieve [56] [57]. However, challenges posed by **climate change**, such as rising temperatures and shifting rainfall patterns, are having a notable impact on crop yields [58]. Additionally, increasing farmland prices are pressuring farmers to intensify their production practices to maximise yields, often leading to long-term consequences such as degrading soil health, which ultimately results in soil depletion and a further reduction in yield potential [59][60].

In response to these challenges, **regenerative agriculture** has gained attention as a sustainable alternative that benefits both the environment and society. Regenerative agriculture aims to mitigate climate change by adopting a holistic approach focused on improving soil health, enhancing biodiversity, managing water resources, and promoting climate resilience [60]. This approach not only supports farmers' livelihoods by helping them maintain productive land but also contributes to **carbon sequestration** and the reduction of greenhouse gas emissions – key components of what is often termed "carbon farming" [61]. While regenerative agriculture is widely recognised for these advantages, the primary obstacle remains the **financial burden** associated with transitioning to these practices. Current estimates suggest that achieving global regenerative goals would require an annual investment of US dollar $200 billion to $450 billion over the next decade, yet current funding levels are only a fraction of this estimated need [62].

To help bridge this **funding gap**, **market-based solutions** like voluntary carbon markets tailored to agriculture are emerging. These carbon markets offer financial incentives to farmers for adopting environmentally beneficial practices, such as those that reduce carbon emissions [63]. For many, **carbon farming** could represent a new revenue stream, turning carbon sequestration into a viable business model [64]. However, recent studies highlight that additional funding for research and the development of standards specific to carbon farming is essential [65].

The **need for standards** extends beyond agricultural systems; it also applies to the blockchain technologies that support carbon markets. At present, the absence of coordinated standards across key international organisations hinders the entire blockchain ecosystem for carbon markets, creating challenges in establishing consistent terminologies and data quality expectations. Standards play a vital role in ensuring that high-quality, reliable data can be verified and tracked through blockchain systems, which is especially critical for tracking carbon credits [66].

Furthermore, **tokenising carbon credits** on blockchain introduces additional complexity. Tokenized carbon credits vary significantly depending on characteristics such as the blockchain platform used, whether the credits are fungible (exchangeable with similar assets [67]), whether they are retired or active, and if they can be traded on secondary markets. Developing standards for these aspects, along with interoperability standards that allow applications to integrate effectively with carbon credit systems, will be crucial for building a transparent **carbon market infrastructure** for agriculture [68].

2.3.3 Smart farming

Driving digital transformation in agriculture

Smart farming refers to the use of modern information and communication technologies in agriculture, paving the way for more data-driven and precise agricultural practices. Practical applications of smart farming include satellite-guided machinery, automated feeding systems, and machine learning for optimising seed application. Each of these technologies, such as sensors, drones, satellite systems, and smart software, works together to improve efficiency and reduce resource use across farming operations.

However, to truly unlock the potential of smart farming, these different technologies need to communicate with one another effectively. For instance, data from a drone monitoring crop health should be able to integrate with the data from automated irrigation systems or machinery in the field. To achieve this level of integration, **open interfaces and standardised data formats are essential**. Standards create a "common language" that makes it possible for all stakeholders (i.e., farmers, suppliers, technology providers) to access and share data with reduced barriers [69] [70]. In combination with AI models, standardised data can also help farmers make informed decisions, providing a clearer picture of past activities and supporting real-time decision-making to optimise yields and reduce waste [71].

The role of Digital Infrastructure and Data Standards

Creating an effective digital infrastructure is essential for capturing and sharing data across different technologies in a transparent, reliable, and privacy-compliant manner. This infrastructure should allow agri-food stakeholders, from farmers to retailers, to collaborate efficiently by sharing data and insights that benefit the entire chain [72].

A robust digital infrastructure in agriculture relies on Internet of Things (IoT) devices and emerging frameworks like Decentralized Physical Infrastructure Networks (DePIN). These networks, also powered by blockchain, establish reliable systems of connected IoT devices that can gather and even monetise data. For example, ***Farmsent*** is an initiative that uses DePIN to enhance transparency in agricultural supply chains, connecting farmers with global businesses and creating new opportunities through a marketplace model. Yet, despite this potential, the absence of clear standards for data collaboration and monetisation limits the full utility of DePIN and similar technologies [73][74]. Establishing **standards and frameworks** that outline how data is collected, shared, and valued can **open up new avenues for smart farming applications**, making it easier for stakeholders to participate in and benefit from digital agriculture on a global scale.

III. Measures to Support Interoperability and Standards Adoption

Our analysis of blockchain applications in agri-food has revealed a landscape characterised by promising initiatives but limited by fragmentation, "blockchain islands," and inconsistent implementation approaches. While Sections I and II have outlined the value proposition of blockchain and examined existing standards, this section provides strategic recommendations to overcome the identified barriers and accelerate meaningful adoption across the European agri-food sector.

The following table maps our recommendations to the key challenges identified throughout this paper.

Recommendation	Addresses challenges
Treat standards and interoperability as distinct needs	Fragmentation, inconsistent implementation approaches
Define core infrastructure	"Blockchain islands," limited cross-platform compatibility
Build guiding framework	Sector-specific requirements, low maturity levels
Focus on key use cases	Practical implementation, unclear value proposition
Create task forces	Stakeholder coordination, regulatory alignment

3.1 Treat standards and interoperability as distinct, complementary needs

Standards and interoperability often overlap, but they're **not the same**. Standards provide best practices and consistency in areas like data quality, privacy, and security. Interoperability, however, is specifically about making systems compatible so they can exchange data.

This distinction is crucial because it enables flexibility. For instance, while a blockchain solution might follow ISO/TC 307 standards on data security and privacy, the protocols for sharing data with IoT or cloud systems can be tailored to meet specific needs, similar to ETSI ISG PDL's approach to permissioned blockchain systems (Section 2.2.3). With this dual approach, blockchain systems can be rigorous in areas that need it while remaining flexible enough to connect with a range of agri-food technologies.

The blockchain landscape in agri-food suffers from *fragmentation*, as evidenced by our analysis of inconsistent approaches and implementation methods that have hindered widespread adoption. As shown in the evolution of blockchain projects (Section 1.2, Figure 3), the agri-food sector encompasses diverse stakeholders (from farmers to retailers to technology providers) each with unique requirements that cannot be served by a one-size-fits-all approach. Treating standards and interoperability as complementary allows us to balance quality control with the adaptability needed for real-world integration, though such integration typically involves significant coordination and planning.

3.2 Define a core infrastructure for blockchain interoperability

A critical step for the sector is developing a conceptual foundation for interoperability. Instead of aiming to make every solution compatible, which is a nearly impossible goal, the focus should be on **identifying what specific areas and data need to be interoperable** across systems. For example, data on product traceability, compliance records, and sustainability certifications are areas where interoperability is essential.

The *"blockchain islands"* problem identified in the introduction emphasises that isolated blockchain implementations fail to communicate effectively with each other or with traditional systems. By establishing core interoperability approaches, we can bridge these islands, creating connections between previously isolated implementations and enabling a more cohesive blockchain ecosystem. Let's consider an actual use case – organic certification. For this data to flow from farm records to retail, we need to ensure key components across different blockchain solutions can 'talk' to each other. This reflects the data sharing ecosystem pathways illustrated in Figure 5 (Section 2.3.1), which emphasises standardised data structures and terminology as foundational elements for interoperability.

This recommendation aligns with initiatives like DIASCA (Section 2.3.1), which focuses on developing open standards for interoperability between traceability systems in agriculture. DIASCA's work on establishing digital standards for product traceability to support EU regulatory compliance provides a model for identifying critical interoperability points. Moreover, the European Blockchain Services Infrastructure (EBSI) (Section 2.1) offers a potential foundation upon which agri-food-specific interoperability protocols could be built. By leveraging this existing EU initiative while focusing on agri-food's specific needs, the sector can avoid duplication of effort while ensuring solutions that address the practical requirements of European food supply chains.

3.3 Build an agri-food framework for blockchain standards

Standards exist, but there isn't yet a framework that shows agri-food companies how to apply them specifically to their sector. Without such a framework, adoption may remain scattered. **Developing a guiding framework that links general blockchain standards to agri-food needs** (e.g., covering traceability, food safety, and environmental impact) would help address this gap.

This framework is drawn upon the comprehensive standards analysis presented in Section 2.2.6, identifying which standards (ISO/TC 307, ETSI ISG PDL, IEEE standards) are most relevant for *specific agri-food applications*. For instance, ISO/TC 307's work on security and privacy could form the basis for handling sensitive farm data, while IEEE's standards for supply chain finance could guide payment systems between producers and distributors. The framework should provide guidance on which standards to apply at different points in the supply chain, making it easier for businesses to integrate blockchain into their current operations.

Such a guiding framework aligns with the European Union's Green Deal objectives by providing clear pathways for implementing blockchain solutions that enhance transparency, sustainability reporting, and environmental accountability. Critically, it would directly address the *low maturity levels* identified in Section 1.2, where many blockchain applications remain at conceptual or early pilot stages. By offering sector-specific guidelines towards existing standards adaptation, the framework would provide the structure and hands-on experience needed to move projects from experimental to operational stages.

3.4 Focus on key use cases with stronger value proposition

Rather than pushing for widespread adoption, it makes sense to **focus on specific use cases where blockchain shows higher potential for benefits**. This technology is not a one-size-fits-all solution, so its application should be purposeful and aligned with the areas where it can deliver the most value in agri-food.

Building on the three key use cases detailed in Section 2.3, we recommend prioritising:

1. *Supply chain traceability for food safety* – As demonstrated by examples like TE-FOOD and Provenance (Section 1.2), blockchain has a potential to reduce product recall times from days to hours and enable farm-to-fork visibility. This aligns with the EU's food safety objectives and consumer demand for transparency.
2. *Carbon credits for climate adaptation* – The carbon farming initiatives (Section 2.3.2) show potential for blockchain to support the €200-450 billion annual investment needed for regenerative agriculture. These applications directly support the Green Deal's climate neutrality goals.
3. *Smart farming integrations with IoT devices* – Section 2.3.3 highlights how blockchain can enhance the security of data from various digital farming technologies, supporting precision agriculture and resource optimisation.

Each of these aligns with blockchain's strengths in transparency and data integrity while directly supporting EU policy objectives for sustainability, climate action, and digital transformation. Focusing on these cases first will drive practical implementation by addressing concrete, well-defined problems with clear value propositions. Rather than attempting to solve all blockchain implementation challenges simultaneously, this targeted approach creates demonstrable successes that demonstrate the technology's potential benefits for stakeholders. Through building a foundation of practical implementations, we establish models for other applications to follow.

3.5 Create practical task forces to drive standards and interoperability in key agri-food use cases

To maximise blockchain's impact in agri-food, **dedicated task forces** should be formed, drawing from a cross-section of stakeholders, including food producers, regulators, technology providers, and standards bodies. These groups would focus on specific, high-potential use cases (e.g., traceability, carbon credits, and data sharing) and **assess where standards and interoperability are most needed** for effective blockchain adoption.

These task forces could be coordinated by European industry associations with support from the European Commission, ensuring both industry relevance and policy alignment. A governance structure with rotating leadership among stakeholders would help maintain balanced representation of interests. For instance, a task force focused on traceability and food safety could explore how blockchain can standardise documentation across regions, enabling the data flow for compliance and quality assurance. Another group focused on carbon credit trading might assess interoperability requirements for blockchain systems to facilitate accurate carbon tracking and reporting, benefiting both farmers and environmental regulatory bodies. Each task force should operate with clear deliverables and timelines, producing initial recommendations within 12 months and implementation guidelines within 18 to 24 months. The success of these task forces should be measured through concrete outcomes (e.g., publication of specific interoperability protocols for priority data types, development of reference implementations that demonstrate cross-platform data exchange).

This recommendation lines up with the European Commission's blockchain strategy referred to in Section 2.1, which emphasises the importance of creating a common standard for interoperability between different blockchain platforms and legacy systems. By engaging stakeholders from across the ecosystem in focused, use-case specific task forces, we can develop or adapt standards and interoperability solutions that ensure regulatory alignment with both existing frameworks (such as MiCA, EUDR, and CSDDD (Section 2.3.1) and emerging EU policies related to digital agriculture and sustainability.

Concluding Remarks

The aim of this paper is to build a **narrative around the importance of interoperability** and standards in the adoption of blockchain technology within the European agri-food sector. Blockchain offers promising tools for enhancing transparency, traceability, and accountability across agri-food supply chains. As the EU pursues its Green Deal objectives, setting Europe on a path toward climate neutrality by 2050, these capabilities could play a vital role in supporting sustainable practices and improved resource management. However, for blockchain to realise this potential, there is a pressing need to address the fragmented "blockchain islands" that currently limit its broader adoption and integration.

Our findings underscore the importance of standards and interoperability as essential foundations for blockchain's effective application in agri-food. Standards establish best practices for data quality, privacy, and security, while interoperability ensures that different systems can communicate effectively. Together, these components are vital for building trust, transparency, and operational efficiency. However, current approaches to standardisation and interoperability remain inconsistent, creating barriers to the broader adoption of blockchain. While organisations such as ISO, ITU-T, ETSI, and IEEE have established relevant standards, a sector-specific guiding framework that directly addresses the unique requirements of agri-food is still needed.

To fully leverage blockchain's capabilities in agri-food, we need a targeted approach that prioritises practical, interoperable solutions tailored to the sector's specific needs.

First, a clear **distinction** must be made **between standards and interoperability**. While standards define best practices, interoperability is specifically about enabling systems to exchange data effectively. Recognising these as distinct but complementary needs allows for a blockchain ecosystem that balances quality and connectivity, making it flexible enough to accommodate diverse applications while maintaining rigorous standards.

Establishing a **core infrastructure for interoperability** within agri-food blockchain applications is another critical step. Rather than attempting to make all solutions universally compatible, which is unrealistic, stakeholders should identify and prioritise key areas, such as traceability, compliance, and sustainability certifications, where interoperability can have the most impact. By focusing on these critical components, the sector can develop a foundational framework for integrating blockchain effectively across different use cases.

Additionally, developing a **tailored guiding framework** for blockchain standards **specific to agri-food** would support companies in navigating the sector's regulatory and operational complexities. This framework would link existing standards to the unique needs of agri-food, providing clear guidance on how to apply blockchain in ways that enhance traceability, food safety, and environmental accountability. Such a framework would help create consistency across the sector, fostering more widespread and effective adoption.

Focusing on **high-impact use cases** will also be key. Rather than pursuing broad, generalised applications, stakeholders should concentrate on areas where blockchain's benefits are most evident, such as supply chain traceability, carbon credits for climate resilience, and smart farming. By beginning with these high-value use cases, we can establish a robust foundation for other applications, building a blockchain ecosystem that delivers practical value in the agri-food sector.

Last but not least, **creating collaborative task forces** dedicated to standards and interoperability within agri-food blockchain applications will be essential. By bringing together stakeholders from across the industry, including policymakers, technology providers, and standards organisations, these task forces can provide sector-specific insights, recommend adjustments to standards, and help shape a blockchain ecosystem that meets the diverse needs of the agri-food sector. Through such collaboration, the sector can create solutions that not only address regulatory and operational requirements but also support long-term sustainability goals.

These recommendations align with and could be implemented through several existing EU policy frameworks. The European Data Strategy, the Digital Europe Programme, and initiatives under the Farm to Fork Strategy all provide potential channels for advancing blockchain standardization and interoperability. Implementation could leverage existing mechanisms such as the European Multi-Stakeholder Platform on ICT Standardisation or the Digital Innovation Hubs focused on agri-food. Regulatory sandboxes created under these frameworks could provide safe environments for testing blockchain applications that adhere to the standards and interoperability guidelines proposed in this paper.

This paper calls for a focused, coordinated approach to blockchain adoption in agri-food. By addressing standards, interoperability, and targeted applications, stakeholders can create a blockchain ecosystem that aligns with the EU's Green Deal objectives and supports a more sustainable, resilient, and transparent food system in Europe. The recommendations presented here, if implemented, could transform blockchain from a promising but fragmented technology into a powerful enabler of digital transformation across European agri-food supply chains, ultimately contributing to a more sustainable, competitive, and resilient European food system for generations to come.

Finally, the analysis presented in this paper indicates that blockchain's most significant contribution to European agri-food systems lies not in the current infrastructure replacement or new invention, but in addressing particular challenges where its distinctive capabilities, such as transparency and decentralized verification, enhance existing infrastructures within the sector. The sector's path forward requires pragmatic implementation supported by robust standards and interoperability frameworks. While blockchain will not resolve every agricultural challenge, the evidence indicates it can serve a meaningful supporting role in developing more transparent, accountable, and sustainable food systems. Success will depend on the sector community's commitment and stakeholders of interest to collaborative standards development, focused pilot implementations, and realistic evaluation of both benefits, limitations, and the work of particular value propositions. The recommendations presented here provide a framework for realizing this potential further while avoiding the pitfalls of unfocused and not well-justified, and hence, inappropriate, technology adoption.

References

[1] *Nakamoto, S., 2008. Bitcoin: A peer-to-peer electronic cash system.*
[2] *https://www.synopsys.com/glossary/what-is-blockchain.html, Last accessed at: 9/7/2024*
[3] *Patelli, N. and Mandrioli, M., 2020. Blockchain technology and traceability in the agrifood industry. Journal of food science, 85(11), pp.3670-3678.*
[4] *https://www.investopedia.com/terms/b/blockchain.asp*, Last accessed at: 9/7/2024
[5] *https://www.investopedia.com/terms/s/smart-contracts.asp.,* Last accessed at: 9/7/2024
[6] *https://www.investopedia.com/terms/c/consensus-mechanism-cryptocurrency.asp*, Last accessed at: 9/7/2024
[7] *Tripoli, M. & Schmidhuber, J. 2018. Emerging Opportunities for the Application of Blockchain in the Agri-food Industry. FAO and ICTSD: Rome and Geneva. Licence: CC BY-NC-SA 3.0 IGO*
[8] *M. Fiore and M. Mongiello, "Blockchain Technology to Support Agri-Food Supply Chains: A Comprehensive Review," in IEEE Access, vol. 11, pp. 75311-75324, 2023, doi: 10.1109/ACCESS.2023.3296849.*
[9] *Guoqing Zhao, Shaofeng Liu, Carmen Lopez, Haiyan Lu, Sebastian Elgueta, Huilan Chen, Biljana Mileva Boshkoska, Blockchain technology in agri-food value chain management: A synthesis of applications, challenges and future research directions, Computers in Industry, Volume 109, 2019, Pages 83-99, ISSN 0166-3615, https://doi.org/10.1016/j.compind.2019.04.002.)*
[10] *Jie Xu, Shuang Guo, David Xie, Yaxuan Yan, Blockchain: A new safeguard for agri-foods, Artificial Intelligence in Agriculture, Volume 4, 2020, Pages 153-161, ISSN 2589-7217, https://doi.org/10.1016/j.aiia.2020.08.002.*
[11] *Blockchain in Agriculture Solving Agri-Food Supply Chain Issues with New-Tech, Philip B. Farelly, https://farrellymitchell.com/wp-content/uploads/2024/02/Blockchain-The-latest-agtech-solution-to-supply-chain-issues-MAIN37.pdf, Last accessed at: 29/7/2024*
[12] *Violino, S., Pallottino, F., Sperandio, G., Figorilli, S., Antonucci, F., Ioannoni, V., Fappiano, D. and Costa, C., 2019. Are the innovative electronic labels for extra virgin olive oil sustainable, traceable, and accepted by consumers?. Foods, 8(11), p.529.*
[13] *Vadgama, N. and Tasca, P., 2021. An analysis of blockchain adoption in supply chains between 2010 and 2020. Frontiers in Blockchain, 4, p.610476.*
[14] *Akella, G.K., Wibowo, S., Grandhi, S. and Mubarak, S., 2023. A systematic review of blockchain technology adoption barriers and enablers for smart and sustainable agriculture. Big Data and Cognitive Computing, 7(2), p.86.*
[15] *Mohammed, A., Potdar, V., Quaddus, M. and Hui, W., 2023. Blockchain adoption in food supply chains: A systematic literature review on enablers, benefits, and barriers. IEEE Access, 11, pp.14236-14255.*
[16] *Kamilaris, A., Fonts, A. and Prenafeta-Boldú, F.X., 2019. The rise of blockchain technology in agriculture and food supply chains. Trends in food science & technology, 91, pp.640-652.*
[17] *Sendros, A., Drosatos, G., Efraimidis, P.S. and Tsirliganis, N.C., 2022. Blockchain applications in agriculture: A scoping review. Applied Sciences, 12(16), p.8061.*
[18] https://te-food.com/, Last accessed at: 31/07/2024
[19] *https://medium.com/te-food/te-food-cooperates-with-deloitte-to-implement-blockchain-based-traceability-projects-815d0ff495f7*, Last accessed at: 31/07/2024
[20] *https://halalfocus.net/te-food-collaborates-with-halal-trail-to-bring-halal-food-companies-to-blockchain/*, Last accessed at: 31/07/2024
[21] *https://www.provenance.org/*, Last accessed at: 31/07/2024
[22] *https://www.provenance.org/news-insights/tracking-tuna-catch-customer*, Last accessed at: 31/07/2024
[23] *https://www.provenance.org/case-studies/princes-tuna*, Last accessed at: 31/07/2024
[24*] https://www.ibm.com/products/supply-chain-intelligence-suite/food-trust*, Last accessed at: 31/07/2024
[25] *Antonucci, F., Figorilli, S., Costa, C., Pallottino, F., Raso, L. and Menesatti, P. (2019), A review on blockchain applications in the agri-food sector. J. Sci. Food Agric., 99: 6129-6138. https://doi.org/10.1002/jsfa.9912*
[26] M. I. H. Hafizur Rahman, "A comprehensive survey on semantic interoperability for Internet of Things: State-of-the-art and research challenges," *Transactions on Emerging Telecommunications Technologies,* vol. 31, no. 12, 2020.
[27] *https://www.gs1.org/standards/id-keys/gtin*, Last accessed at: 15/07/20254
[28] *https://www.gs1.org/standards/gs1-global-traceability-standard/current-standard,* Last accessed at: 15/07/20254
[29] *J. G. Keogh, A. Rejeb, N. Khan, K. Dean and K. J. Hand, "Blockchain and GS1 standards in the food chain: A review of the possibilities and challenges," Building the future of food safety technology, vol. 171, 2020.*
[30] *A. Bozhko and S. Usatyuk, "IMPLEMENTATION OF THE GS1 GLOBAL TRACEABILITY STANDARD BY MARKET OPERATORS FOR THE PRODUCTION OF FLOUR CONFECTIONERY PRODUCTS USED USE OF CAROB POWDER," Věda a perspektivy, vol. 6, no. 13, pp. 303-316, 2022.* [31]
[31] *T. Burns, D. J. Cosgrove and F. Doyle, "A Review of Interoperability Standards for Industry 4.0.," in 29th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2019), Limeric, Ireland, 2019*
[32] *K. N. Molholm, "Standards and interoperability," Information Services & Use, vol. 26, no. 1, pp. 29-37, 2006.*
[33] *https://data.europa.eu/en/news-events/news/embracing-open-standards-open-data-ecosystem-interoperability-across-europe*, Last accessed at: 17/11/2024
[34] *K. Wasnik, I. Sondawle, R. Wani and N. Pulgam, "Detection of Counterfeit Products using Blockchain," in ITM Web of Conferences, Nerul, Navi Mumbai, India, 2022.*
[35] *S. A. Bhat, N.-F. Huang, I. B. Sofi and M. Sultan, "Agriculture-Food Supply Chain Management Based on Blockchain and IoT: A Narrative on Enterprise Blockchain Interoperability," Agriculture, vol. 12, no. 1, 2022.*

[36] *J. Qian, W. Wu, Q. Yu, L. Ruiz-Garcia, Y. Xiang, L. Jiang, Y. Shi, Y. Duan and P. Yang, "Filling the trust gap of food safety in food trade between the EU and China: An interconnected conceptual traceability framework based on blockchain," Food Energy Security, vol. 9, no. 4, 2020.*
[37] *U. European, "Shaping Europe's digital future," Directorate-General for Communications Networks, Content and Technology, 27 02 2023. [Online].* Available: https://digital-strategy.ec.europa.eu/en/policies/blockchain-strategy, Last accessed at: 29/08/2024
[38] *S. Menon and K. Jain, "Blockchain Technology for Transparency in Agri-Food Supply Chain: Use Cases, Limitations, and Future Directions," IEEE Transactions on Engineering Management, vol. 71, pp. 106-120, 2024.*
[39] *R. L. Rana, C. Tricase and L. D. Cesare, "Blockchain technology for a sustainable agri-food supply chain," British Food Journal, vol. 123, no. 11, pp. 3471-3485, 2021.*
[40] *K. Behnke and M. F. Janssen, "Boundary conditions for traceability in food supply chains using blockchain technology," International Journal of Information Management, vol. 52, 2020.*
[41] https://www.iso.org/committee/6266604.html, Last accessed at: 9/7/2024
[42] *Villari, E.R., Mertoli, F., Tripi, G., Matarazzo, A. and Albertini, E., 2020. Innovative tools of smart agriculture to protect the supply chain of Sicilian blood orange PGI. Procedia environmental science, Engineering and Management, 7(2), pp.175-184.*
[43] https://www.itu.int/en/ITU-T/focusgroups/dlt/Pages/default.aspx, Last accessed at: 9/7/2024
[44] https://www.etsi.org/committee/1467-pdl, Last accessed at 9/7/2024
[45] https://www.etsi.org/technologies/permissioned-distributed-ledgers, Last accessed at: 9/7/2024
[46] https://www.etsi.org/committee-activity/activity-report-pdl, Last accessed at: 9/7/2024
[47]https://standards.cencenelec.eu/dyn/www/f?p=205:7:0::::FSP_ORG_ID:2702172&cs=148F2B917E4B67BCFD6FE36CE0EA923AC, Last accessed at: 9/7/2024
[48] https://joinup.ec.europa.eu/collection/rolling-plan-ict-standardisation/blockchain-and-distributed-digital-ledger-technologies-rp2020, Last accessed at: 9/7/2024
[49] https://sagroups.ieee.org/bdlsc/, Last accessed at: 12/7/2024
[50] https://publica-rest.fraunhofer.de/server/api/core/bitstreams/68fb5b65-b013-4475-82e0-6f9f601bc05b/content, Last accessed at: 12/7/2024
[51] https://www.weforum.org/agenda/2023/01/here-s-how-agricultural-sector-data-problem-davos2023/, Last accessed at: 12/7/2024
[52] https://www.mckinsey.com/industries/agriculture/our-insights/agtech-breaking-down-the-farmer-adoption-dilemma, Last accessed at: 12/7/2024
[53] https://www.idhsustainabletrade.com/uploaded/2024/01/Unlocking-Data-Sharing-in-Agriculture-January-2024.pdf, Last accessed at: 12/7/2024
[54] https://www.sustainable-supply-chains.org/topics/digitalisation-traceability/diasca, Last accessed at: 10/3/2025
[55] https://www.nachhaltige-agrarlieferketten.org/en/in-practice/diasca-interoperability-between-traceability-solutions, Last accessed at: 12/7/2024
[56] https://www.nachhaltige agrarlieferketten.org/fileadmin/INA/diasca/20230628_DRAFT_DIASCA_Farmer_Income___COP_Working_Group_Indicators.pdf, Last accessed at: 12/7/2024
[57] https://www.fairtrade-deutschland.de/fileadmin/DE/01_was_ist_fairtrade/05_wirkung/studien/study_true_cost_cocoa_farmer_income_2018.pdf, Last accessed at: 12/7/2024
[58] https://www.mdpi.com/2071-1050/13/3/1318, Last accessed at: 12/7/2024
[59] https://www.dnb.nl/media/adjnzhdz/web-financing-regenerative-agriculture-final.pdf, Last accessed at: 12/7/2024
[60] https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2021.699147/full, Last accessed at: 12/7/2024
[61] https://www.wbcsd.org/wp-content/uploads/2023/09/Cultivating-farmer-prosperity_Investing-in-regenerative-agriculture.pdf, Last accessed at: 12/7/2024
[62] https://www.rockefellerfoundation.org/wp-content/uploads/2024/06/Financing-for-Regenerative-Agriculture-Final.pdf, Last accessed at: 13/7/2024
[63] https://fsr.eui.eu/agricultural-voluntary-carbon-markets-challenges-and-recommendations/#:~:text=Voluntary%20Carbon%20Markets%20(VCMs)%20are,from%20various%20sectors%2C%20including%20agriculture., Last accessed at: 13/7/2024
[64] https://www.dinmedia.de/de/themenseiten/smart-farming/carbon-farming?registrationStep=CANCEL, Last accessed at: 13/7/2024
[65] https://www.sae.org/publications/technical-papers/content/epr2023026/, Last accessed at: 13/7/2024
[66] *Baiz, P., 2024. Blockchain and Carbon Markets: Standards Overview. arXiv preprint arXiv:2403.03865.* Avaialble: https://arxiv.org/html/2403.03865v1#S4
[67] https://www.heg-fr.ch/media/lbdfnyd1/schueffelgroenewegbaldegger2019_crypto-encyclopedia_eng.pdf, Last accessed at: 13/7/2024
[68] *Sorensen, Derek. (2023). Tokenized Carbon Credits. Ledger. 8. 10.5195/ledger.2023.294.*
[69] https://www.din.de/en/din-and-our-partners/press/press-releases/global-standards-for-digital-agriculture-852088, Last accessed at: 15/7/2024
[70] https://www.din.de/en/smart-farming-needs-standards-and-specifications--827472, Last accessed at: 15/7/2024
[71] *Klerkx, L., Jakku, E. and Labarthe, P., 2019. A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS-Wageningen journal of life sciences, 90, p.100315.*
[72] https://www.iese.fraunhofer.de/en/trend/digital-farming.html, Last accessed at: 15/7/2024

[73] *https://www.ccn.com/opinion/technology/standardization-effective-depin-monetization/*, Last accessed at: 15/7/2024
[74] *https://cointelegraph.com/news/de-pins-connecting-farmers-businesses-blockchain*, Last accessed at: 15/7/2024