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SPECIAL SECTION

BLOCKCHAIN IN AGRIFOOD SUPPLY CHAIN

Achieving traceability and sustainability under the UN 2030 agenda

Abstract

A comprehensive social and regulatory framework could incentivise States to pursue a balanced integration between digital transformation, ecological transition, and agricultural development. Within this context, it is increasingly feasible to design trustless, intermediary-free production chains that reduce critical inefficiencies, foster innovative forms of competition, and promote new models of sustainability.

Blockchain technology emerges as a trusted infrastructure for certification and data storage, providing guarantees of certainty, transparency, and security. These features not only enhance consumer awareness but also provide a potential solution to the persistent issue of counterfeiting.

This study aims to examine how this infrastructure can adapt to the diverse requirements established by European, national, and regional legislators, particularly about food safety, traceability, and eco-sustainability. Rethinking blockchain integration within supply chains could thus mark a turning point in reshaping the current bioeconomy, transitioning from a traditionally linear economic model to a truly circular economy. In such a system, waste materials are either reintegrated into other production cycles or responsibly disposed of in an environmentally responsible manner.

To achieve a genuinely sustainable and circular economy, the integration of blockchain with digital twin technology could enable comprehensive, qualitative tracking and monitoring of products throughout their entire lifecycle — from production to disposal — ensuring their reusability.

While technology can efficiently address challenges related to traceability and counterfeiting, it cannot replace the subjective evaluations required for issuing certifications such as P.D.O. (Protected Designation of Origin) and P.G.I. (Protected Geographical Indication), which remain essential in the context of supply chain economies.

It is important to underscore, however, that certifying a product is not equivalent to certifying its entire supply chain. By enhancing the reliability and efficiency of the information it processes, blockchain could improve supply chain management and overall profitability. In turn, this would promote a more balanced and transparent B2C (business-to-consumer) relationship, reducing informational asymmetries and strengthening contractual trust.

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SUMMARY

1 Digital innovation in the agri-food sector under UN 2030 goals

To promote the sustainability of the agri-food supply chain, the UN 2030 Agenda has set as a goal 2.4, which aims to "...implement resilient agricultural practices that increase productivity and production and that help protect ecosystems...". However, it does not specify the tools needed to achieve these goals; a review of numerous international reports on the point reveals that 'increasing productivity' and 'implementing agricultural practices' are well known concepts[1].

The FAO 2018 report already indicated several preliminary ways to achieve these goals, including precisely the use of distributed ledger-based technologies, which are considered "...a unique opportunity for the agricultural sector".

The potential of this phenomenon could bring unlimited benefits to the agri-food sector through increased information symmetry, certainty in product traceability and easy control of the environmental impact of the entire production chain.

In this regard, last European Union legislative interventions on corporate sustainability have focused precisely on this aspect: the "Corporate Sustainability Reporting Directive" (Directive 2022/2464) addresses corporate sustainability reporting, aiming to improve the transparency of environmental, social, and governance information, ie, ESG rating. This Directive targets the actors involved in the production chain through two distinct action modes: the identification of disclosures along the chain and the dissemination of best practices inspired by sustainability[2], which is expected to have an economic impact as well[3].

In general, technological advances could provide the supply-chain with automation of production lines and productivity gains, giving new life to what has been dubbed 'Industry 4.0'.

[1] For example see: Food and Agriculture Organization of United Nations, International Telecommunication Union, Status of Digital Agricolture in 18 countries of Europe and Central Asia (ITU Publications 2020) <https://openknowledge.fao.org/server/api/core/bitstreams/29c2830e-8560-48ff-b636-06af2a1bb778/content> accessed 20 June 2025; Word Economic Forum 'Shaping of Global Food Systems: A Scenarios Analysis' (2017) <https://www3.weforum.org/docs/IP/2016/NVA/WEF_FSA_FutureofGlobalFoodSystems.pdf> accessed 20 June 2025; Food and Agriculture Organization of the United Nations, Environmental Sustainability in Agriculture (OEDC 2023) <https://openknowledge.fao.org/server/api/core/bitstreams/32da2942-3854-4736-af19-877b3ab22d35/content> accessed 20 June 2025.

[2] Mia Callegari, 'Sostenibilità, supply chain e intelligenza artificiale' (2024) 5 Giurisprudenza Italiana 1211.

[3] European Parliament and Council Directive (2022/2464) as regards corporate sustainability reporting [2024] OJ L 322/15 paragraph 8.

This trend enables supply chains to achieve significant performance improvements through a multitude of applications. Specifically, by analysing a series of case studies, it emerges that the technologies most commonly used in the agri-food sector are those focused on monitoring and controlling resources — particularly IoT and sensors for data transmission and processing — as well as those involved in product identification and tracking, with blockchain playing a key role in this regard[4]. In this context blockchain could act as a privileged system for certification and archiving, valued for its inherent guarantees of certainty, transparency and security and these qualities must be applied to ensure *end-to-end* traceability, quality assurance and reduction of food waste.

The combination of technology and agriculture finds its concrete application in several projects: in Italy, the three-year framework project 2019-2021 of Mi.p.a.s, together with Microsoft, has created 'AgriDigit'[5], a cloud that enables technological development in agriculture, offering greater capillarity in traceability and giving further guarantees to consumers in terms of food safety and transparency of information; in Spain, the Council of Ministers approved in November 2021, at the proposal of the Ministry of Agriculture, Fisheries and Food (MAPA), investments for the environmental and digital transformation of the agricultural sector between 2021 and 2023, with the aim of adopting structural reforms necessary to promote a change in the agricultural production model that improves its sustainability in environmental, economic and social terms.

2 The role of blockchain in data management and security

Blockchain is a form of Distributed Ledger Technology (DLT) based on a shared, decentralised, distributed and transparent database[6]. It functions as a public ledger of information that is, in principle, irreversible and tamper-proof, where a transaction can only be validated once it has been approved by all nodes in the network. Owing to these features, blockchain can be conceptualised as a “public blackboard” on which all transactions executed up to that point can be read, along with the identities of the asset holders and the traceability of each transfer[7].

This digital architecture is organised into smaller, fixed-size sets of data known as blocks. The link between each block and the next is ensured by a cryptographic function called a ‘hash’, which compresses information of arbitrary length into a unique alphanumeric code. As the chain grows, each block contains the hash of the previous ones,

[4] Livio Cricelli, Roberto Mauriello, Serena Strazzullo, ‘Technological innovation in agri-food supply chains’ (2022) 5 British Food Journal 1852.

[5] Agridigit is a project, divided into six sub-projects, which deals with - among other things - testing which technological mechanisms enable greater efficiency in the world of agriculture. To can find out more about what the whole project consists of at: <https://www.crea.gov.it/-/agridigit> accessed 20 June 2025.

[6] Andrea Stazi, *Automazione contrattuale e “contratti intelligenti”. Gli smart contract nel diritto comparato* (Giappichelli 2019) 100.

[7] Maria Rosaura Maugeri, *Smart Contracts e disciplina dei contratti* (Il Mulino 2021) 21.

thereby creating an immutable chain—or, more precisely, a chain in which any alteration would immediately reveal evidence of tampering[8].

One of the main issues associated with distributed ledger technology is the management of consensus, which refers to the process by which nodes reach an "agreement" to approve individual transactions. This mechanism serves as a validity guarantee for the ledger among the nodes and is implemented through computational protocols. The most widely used protocol is proof of work, where, to find the solution necessary to validate the transaction, nodes must solve a complex mathematical problem. Once the correct solution is found, for the transaction to be added to the most recent block, other nodes must understand and verify it as quickly as possible, but the system appears efficient because the mathematical problem is extremely difficult to solve, but once the solution is found, it is easily verifiable by anyone[9].

Nowadays, in the European system, the quality of agrifood products is ensured by strict regulations and, for this reason, data from logistics, transportation and product conformity management processes are verified by different bodies, depending on the country and are stored in paper records, centralised databases or non-automated channels. However, as there is still no connection between companies operating in a given product sector, either locally or at EU level, there is no shared *framework for* the digital management of this information[10].

Fragmentary, incomplete or contradictory data do not offer sufficient certainty as to the reliability of each individual product, nor do they allow timely action to be taken in the event of malfunctions, food contamination or more general irregularities.

For this reason, the current major concern of players within the food supply chain has shifted to the problem of integrity, ie, the 'fairness and authenticity of food in food value chains'[11] a challenge that could find fertile ground through the application of blockchain technology. Yet, it should be considered that, in the light of the sectoral regulations in force, it is not possible to replace a state certifying body; at most, the way in which the data processed within the supply chain, which is the subject of subsequent audits, can be improved.

[8] Lorenzo Parola, Paola Merati, Giacomo Gavotti, 'Blockchain e smart contract: questioni giuridiche aperte' (2018) 6 I Contratti 681.
[9] Andrea Visconti, Andra Frisoni, 'Consenso e mining nella blockchain' in Laura Ammanati e Allegra Canepa (eds), *Tech Law. Il diritto di fronte alle nuove tecnologie* (Editoriale Scientifica 2021) 182; Christian Cachin, Marko Vukolic, 'Blockchain Consensus Protocols in the Wild' in 31st International Symposium on Distributed Computing (DISC 2017), Leibniz International Proceedings in Informatics (LIPIcs), Volume 91 (Leibniz 2017) 1:1.
[10] Ministry of Economic Development, 'Blockchain for Made in Italy traceability: Origin, Quality, Sustainability. Case study applied to the textile sector' (2019) <www.mimit.gov.it/index.php/it/normativa/notifiche-e-avvisi/blockchain-per-la-tracciabilita-del-made-in-italy> accessed 20 June 2025.
[11] Eloisa Marchesoni, 'La blockchain per la tracciabilità del made in Italy: Origine, Qualità, Sostenibilità. Caso di studio applicato al settore tessile' (Ministero dello sviluppo economico & Ibm. 2019) <https://www.agendadigitale.eu/documenti/blockchain-per-lagrifood-rivoluzione-smart-contract-ecco-vantaggi-e-limiti/> accessed 20 June 2025.

Having identified the limitations of the current supply-chain system, the key feature of blockchain for the agri-food supply chain is the ability of collecting a substantial amount of information[12].

The blockchain is a type of Distributed Ledger Technologies, characterised by the fact that there is a well-defined sequence of data, in which several pieces of information are linked together in such a way as to form a chain whereby the next block of data is added at the end of the structure itself, in strict chronological order[13].

In this technology, as in all DLT's, there is no central database, which is replaced by the individual nodes of the network forming a decentralised, distributed, encrypted and transparent one, which acts as a public repository of information that tends to be irreversible and incorruptible in which, before a transaction can be added, all nodes must approve it[14] and which, once approved, is 'branded' through *time stamping*[15], thus making it legally enforceable against third parties[16]. At this point, it is straightforward to draw a comparison between a *block-chain* and a *supply-chain* whereby each block could be the representation of a *player* operating within a supply chain and the link between the 'on-chain' and 'off-chain' worlds could be ensured using *smart contracts*.

The characteristics of the blockchain that could guarantee the product traceability and the clarity of information in the supply chain are immutability, secured by the cryptographic hash function and transparency.

Indeed, before data can be considered immutably recorded on the blockchain, at least six subsequent blocks must be validated, as only after this point does any alteration to the most recent block become economically unfeasible for an attacker. This is because one would need to generate a new block containing the exact same hash as the altered block, thereby replicating the computational effort required to validate all preceding blocks.

For this reason, some scholars argue that blockchain should be regarded as "virtually" irreversible. In fact, information could theoretically be modified if consensus for such a change were achieved by a majority of nodes in the network[17].

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[12] Most international regulations that have attempted to give a definition of blockchain identify as their starting point exactly the function of DLT, which enables the collection of an immense amount of information. This choice of legal policy seems audacious, since the main and best-known function of blockchain is instead to avoid so-called *double spending* in the exchange of cryptocurrencies.

[13] Kelvin Low, Eliza Mik, 'Pause the Blockchain Revolution' (2020) 69 (1) International & Comparative Law Quarterly 135; Stéphane Blemus, 'Law and the Blockchain: A legal Perspective on Current Regulatory Trends Worldwide' (2017) 4 Revue de Droit Financier 1; Cristina Poncibò, *La blockchain il diritto privato comparato* (Edizioni Scientifiche Italiane 2021); Massimo Giuliano, 'La blockchain e gli smart contracts nell'innovazione del diritto del terzo millennio' (2018) 34 (6) Il diritto dell'informazione e dell'informatica 989, 1100.

[14] Reggie O'Shields, 'Smart Contracts: Legal Agreements for the Blockchain' (2017) 21 (1) Banking Institute Journal 177.

[15] Paolo Lessio, 'Blockchain e tracciabilità della filiera' in Roberto Battaglini, Massimiliano Giordano (eds), *Blockchain e Smart Contract: funzionamento, profili giuridici e internazionali* (Giuffrè Francis Lefebvre 2019) 514.

[16] The cryptographic key used to approve transactions on the blockchain, together with its exact time identification, in fact allows compliance with the digital signature requirements of the European Eidass regulation.

[17] Ettore Battelli, 'Le nuove frontiere dell'automazione contrattuale tra codici algoritmici e big data: gli smart contract in ambito assicurativo, bancario e finanziario' (2020) 4 Giustizia Civile 671; Sara Saberi, Mathab Kouhizadeh, Joseph

Future technological developments could potentially enable a malicious actor to match or surpass the computational power of 50 % +1 of the nodes, thereby gaining control of the entire chain.

Nonetheless, even if data were tampered with, all subsequent blocks would be identifiable, allowing the remaining nodes to detect the manipulation and, crucially, to pinpoint the exact moment at which the fraudulent alteration occurred.

Another potential avenue for modification lies in the blockchain's source code itself. Programmers may assign certain nodes the authority to retroactively cancel or alter transactions. However, while this approach introduces greater flexibility, it simultaneously compromises the security of the system, as an attacker could gain control by accessing only the so-called "privileged nodes"[18].

Read in conjunction, these features ensure the overall integrity of the data[19]: information is connected to other data in a sequential, validated manner that makes it immutable, identified at a given space-time moment and so legally enforceable against third parties. This system allows for the widespread management of all data, transformations or certifications associated with the product. Therefore, *Industry 4.0* refers also to a way of doing business, based on new production paradigms[20], the harmonious use of new technologies, and which tends to improve crop yields and production quality[21].

3 Evolving food traceability. Legal frameworks and challenges from Europe to United States

In Europe, traceability, as a nuance of the principle of food safety, finds its legal basis in European Regulation n 178/2002 which, in Article 18, prescribes the obligation to trace every stage of production, providing for adequate control systems.

The reasoning of this approach is well identified in recital 28 of this Regulation EC/178/2002: '*Experience has shown that the inability to trace food and feed products can jeopardies the functioning of the internal market in these products. It is therefore necessary to establish a general system for traceability of products covering both the feed and food sectors to be able to carry out targeted and accurate withdrawals or to provide information to consumers or control officials, thereby avoiding greater and unjustified inconvenience when the safety of foodstuffs is endangered*'.

Sarkis, Lejia Shen, 'Blockchain technology and its relationships to sustainable supply chain management' (2018) 57(7) International Journal of Production Research 2117.

[18] Nathan Fulmer, 'Exploring the Legal Issues of Blockchain Applications' (2019) 52 (1) Akron Law Review 170.

[19] H L Gururaj, Ravi Kumar, Sam Goundar (eds), *Convergence of Internet of Things and Blockchain Technologies* (Springer 2022) 249.

[20] Wanda D'Avanzo, 'Blockchain e smart contracts per la gestione della filiera agroalimentare' (2021) 1 Diritto Agroalimentare 93.

[21] Claudio Gagliardini, Franz Russo, *I.o.T. e nuovo marketing. Come e perché le aziende devono utilizzare l'internet delle cose nelle loro strategie di marketing* (Dario Flavocchio Editore 2019).

‘Traceability’ was response to the growing demand from consumers for reliable and transparent information and reflected an increasing information asymmetry between producer and consumer, also due to an expansion of the production chain[22].

In fact, it served as a crucial risk management tool, enabling the swift removal of harmful food products and providing consumers with specific, accurate information about the items they purchase.

Nowadays, the problem is complex from a twofold point of view: on the one hand, there is no traceability obligation for the packaging of agricultural products, even though they form the basis of most processed products; on the other hand, processors of raw materials are hardly ever in a technical position to be able to operate an efficient *tracing* operation[23].

For this reason, the food system had to manage a large amount of information, leading to significant challenges in legal certification, due to the obsolescence of any other traditional system[24].

This system allows industry operators to quickly identify both suppliers and customers, ensuring greater accountability throughout the supply chain[25].

Moreover, thanks to globalisation and the immense lengthening of production chains, the problem of traceability in the agri-food chain has taken on global dimensions, with the need to investigate whether the problems encountered so far can also be found in non-European legal experiences.

In the United States, food safety activities have been defined as those designed to decrease the likelihood of a food causing harm to consumers[26], while traceability of the supply chain is discussed in more detail in terms of the amount of information, the ubiquity of control to which the supply chain is subjected, and the detail of information[27].

In 2011, with the enactment of the *Food Safety Modernization Act* (FSMA)[28], the US food traceability system was fundamentally changed[29].

[22] Defined as ‘the ability to trace and follow a food, feed, food-producing animal or substance intended to be, or expected to be incorporated into a food or feed through all stages of its production, processing and distribution’ Regulation EC/178/2002, Art 3.

[23] Luigi Costato, ‘Le regole di produzione e di commercializzazione dei prodotti alimentari’ in Luigi Costato, Paolo Borghi, Sebastiano Rizzioli, Valeria Paganizza, Laura Salvi (eds), *Compendio di diritto alimentare* (8th edn, Wolters Kluwer 2017) 275.

[24] Lessio (n 15) 520.

[25] Isabel Hernandez San Juan, ‘The Blockchain Technology and the Regulation of Traceability: The Digitization of Food Quality and Safety’ (2020) 15(6) European Food and Feed Law Review 563.

[26] Elis Golan, ‘Traceability in the Us Food Supply: Economic Theory and Industries Study. Us Department of Agriculture, Economic Research Service’ Washington DC Agricultural Economic Report No 3 (2004).

[27] Diego Souza-Monteiro, Neal Hooker, ‘Food safety and traceability’ in Walter Armbruster and Ronald Knutson (eds), *US Programs Affecting Food and Agricultural Marketing* (Springer 2013) 249.

[28] The full text of FSMA: <https://www.fda.gov/food/food-safety-modernization-act-fsma/full-text-food-safety-modernization-act-fsma> accessed 20 June 2025.

[29] John Scharff, David Decker, Marc Riedl, *Food Safety Law* (Wolters Kluwer 2020); Neal Fortin, *Food Safety Modernization Act: Law, Policy, and Practice* (Wiley-Blackwell 2018).

The FSMA has imposed a wide range of new food safety obligations on the FDA[30] addressed to food producers, farms, operators and others involved in the supply chain[31].

Section 103 requires all operators in the food chain, with the exception of small establishments, to equip themselves with risk prevention and protection control systems during the production, processing and packaging of the product, with the aim of creating a link between traceability and food safety.

This was implemented through the *Food* Traceability *Final Rule*[32], which established new traceability requirements for persons producing, processing, packaging or holding food, if included in the *Food Traceability List* (FTL), obliging them to maintain records containing key data elements associated with specific critical traceability events and to provide information to the FDA.

Since the *Food Traceability Final* Rule requires entities in the same supply chain to share information with each other, it was felt that the most effective and efficient way to implement this rule was to oblige all stakeholders to comply by the same date, 20 January 2026.

Some states have already begun working on the proper implementation of Section 103 to achieve initial results; one example is the *California Leafty Green Products Handler Marketing Agreement*, which provides for the creation of a state-wide traceability system.

However, this regulatory apparatus has been widely criticised for focusing only on producers, without considering the need to think about an integrated production chain[33].

Also deserving of attention is Section 204, which calls on food control agencies[34] to implement technological systems for collecting and storing data.

From the US perspective, even though it is based on a very different legislative framework, the same challenges faced in Europe can be observed — namely, the difficulty of managing large volumes of information and the challenge of thinking in terms of an integrated production chain.

In both contexts, there is a significant reliance on new technologies. For instance, it would be possible to record information about key stages of the food supply chain on a blockchain, automating agreements between the various stakeholders and achieving substantial cost savings by eliminating electronic data interchange and paper-based systems, while also reducing inefficiencies, vulnerabilities, inconsistencies, and other shortcomings.

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[30] The Food and Drug Administration, the most important US federal food safety agency.

[31] Arthur Stansbury, 'U.S. Food Safety Modernization Act: Implications for Exporters of Food to the United States' [2014] LMuR 237.

[32] Miriam Guggenheim, Cory Trio, *FSMA Final Rule on Requirements for Additional Traceability Records for Certain Foods* (IFDA 2020) <https://www.ifdaonline.org/wp-content/uploads/2024/02/IFDA-Manual-on-FSMA-204-Food-Traceability-Rule.pdf> accessed 20 June 2025; Michael Roberts, *Food Safety Modernization Act: A guide for the Food Industry* (CRC Press 2020).

[33] Souza-Monteiro, Hooker (n 27) 253.

[34] See paragraph 7.

In both legal systems under analysis, the quality of agri-food products is safeguarded through distinct regulatory frameworks. Consequently, data related to logistics management, transportation, and product compliance verification are managed by multiple entities—differing from one jurisdiction to another—and are stored using paper-based records, centralised databases, or other non-automated systems.

Nonetheless, in the absence of interoperable systems among businesses operating within a given commodity sector, no unified framework currently exists for the digital management of such information.

Fragmentation, incompleteness, and internal inconsistencies in available data hinder the ability to ensure product reliability and obstruct timely responses in cases of malfunction, contamination, or administrative non-compliance.

As a result, the primary concern among stakeholders in the agri-food supply chain has shifted toward the issue of integrity—understood as the "accuracy and authenticity of food within food value chains"[35].

It is important to emphasise, as we have already said, that under the current sector-specific regulatory framework, blockchain technology cannot serve as a substitute for state-certified authorities. Rather, it is more appropriate to assert that this technology may improve the management of data generated throughout the production chain and subsequently subjected to regulatory audits.

Its adoption could offer substantial benefits, including cost reductions through the elimination of paper-based data exchanges and documentation. Moreover, it has the potential to mitigate inefficiencies, vulnerabilities, inconsistencies, and other structural limitations associated with analogue systems[36].

Indeed, blockchain enables the creation of sequentially linked, validated, and time-stamped data sets that are legally enforceable and technically immutable. This architecture allows for the decentralised management of all product-related information, encompassing not only transformations and processing stages but also certification procedures.

The tracing process—currently constrained by the registration and storage of off-chain data—could be substantially optimised. Owing to its intrinsic characteristics, blockchain guarantees that all legally mandated information is recorded in a secure, transparent, and tamper-proof manner. Each block in the chain contains a complete, time-stamped record of all transactions executed up to that point. This structure effectively functions as a digital "blackboard," enabling the reading of every transaction, its temporal reference, the identity of the asset holders, and the traceability of each transfer. In light of the need

[35] Eloisa Marchesoni, 'La blockchain per la tracciabilità del made in Italy: Origine, Qualità, Sostenibilità. Caso di studio applicato al settore tessile' (Ministero dello sviluppo economico & Ibm. 2019) <https://www.agendadigitale.eu/documenti/blockchain-per-lagrifood-rivoluzione-smart-contract-ecco-vantaggi-e-limiti/> accessed 20 June 2025.

[36] Bharat Bhushan, Abhishek Kumar, Latyar Katiyar, *Security Magnification in Supply Chain Management Using Blockchain Technology, Blockchain Technologies for Sustainability* (Springer 2022) 47.

to adopt an integrated supply chain perspective, blockchain technology may also serve to ensure that all stakeholders operate on the basis of a uniform level of information concerning the validity and provenance of certifications. Moreover, such data would be rendered tamper-proof and resistant to manipulation.

Although current applications of blockchain in supply chain management primarily focus on the agri-food sector—highlighting the technology's capacity to process and secure large volumes of data—the true paradigm shift lies in the convergence of blockchain with the Internet of Things (IoT) and smart contracts[37].

One of the most concrete examples in this regard is the IBM Food Trust[38], which provides all network participants with a safe, intelligent and sustainable food ecosystem that considers food provenance, transaction data, and processing details, thus making the origin of the purchased product, certifications, and quality data available to the customer-consumer within seconds.

Traceability obliges operators to think in terms of an 'integrated chain' approach by implementing a standardised and uniform coding system[39].

However, the integration of blockchain into the agri-food supply chain is not cost-neutral.

On the contrary, the development and deployment of such a system require substantial financial investment on the part of businesses. These expenditures are primarily associated with the technical infrastructure necessary for the creation, validation, and maintenance of a secure and decentralised ledger—ranging from computational power and energy consumption to personnel training and compliance with applicable regulatory frameworks. Unsurprisingly, these operational expenditures are ultimately passed on to the end consumer in the form of higher product prices. Nevertheless, empirical studies[40] suggest that consumers may be willing to absorb such additional costs, provided that they are accompanied by tangible improvements in the perceived quality, safety, and traceability of the product.

That said, when measured against the current level of technological maturity, limited standardisation, and lack of full interoperability of blockchain-based agri-food systems,

[37] Maria Teresa Della Mura 'IoT, AI Blockchain per le Supply Chain: nuova efficienza e nuovi modelli di business' *Il Post* (29 May 2020) <https://www.industry4business.it/industria-4-0/iot-ai-blockchain-per-le-supply-chain-nuova-efficienza-e-nuovi-modelli-di-business/> accessed 15 July 2024.
[38] IBM site <https://www.ibm.com/it-it/products/supply-chain-intelligence-suite/food-trust> accessed 20 June 2025.
[39] Stefano Masini, *Corso di diritto alimentare* (5th edn, Giuffrè Francis Lefebvre 2022) 173. And what does the blockchain look like, if not as a product obtained from the processing of computer code, ontologically uniform and homogeneous, valid for all users who participate in it.
[40] Lorenzo Compagnucci, Dominique Lepore, Francesca Spigarella, Emanuele Frontoni, Marco Baldi, Lorenzo Di Berardino, 'Uncovering the Potential of Blockchain in the Agri-food Supply Chain: An Interdisciplinary Case Study (2022) 65 Journal of Engineering and Technology Management 5.

these added costs may still appear not proportionate to the concrete benefits currently achievable throughout the supply chain[41].

Furthermore, although the regulation prescribes which information[42] must be disclosed to the public authority, eg, in the event of contamination, it leaves it up to individual operators to decide how to collect and store this data.

In the United States as well, the principle of traceability is established by the same legislative act, the Food Safety Modernization Act (FSMA), where it is referred to as traceback. This concept embodies the one step back, one step forward principle, requiring operators to identify not only the entities to which they have distributed the product but also those from whom they have received it. Unlike the European framework, however, the U.S. system is less stringent and is not governed by a dedicated set of regulations.

The *tracing* process, today slowed down by the costly off-chain data recording and storage, would indeed be facilitated using blockchain technology[43].

The intrinsic nature of the 'blockchain' would make it possible to manage all the information that the law prescribes in a certain, transparent and immutable manner: each block of the chain, in fact, keeps a copy of the totality of the transactions executed up to that moment, thanks to which it is possible to read all the transactions, the time at which they were finalised, the owners of the values exchanged and the traces of the passage of these assets[44].

The integration of blockchain technology into the agri-food supply chain cannot, in itself, be regarded as a solution for all systemic inefficiencies or compliance challenges. One of the most critical limitations lies in the fact that the accuracy and reliability of the data entered into the blockchain remain largely dependent on the discretion of individual operators at various stages of the supply chain.

Although the immutability of blockchain ensures that, once recorded, data cannot be altered without detection, it does not guarantee the accuracy or authenticity of the data at the point of entry. This limitation gives rise to what is commonly referred to as the "garbage in, garbage out" problem, whereby inaccurate or fraudulent information, once entered, is perpetuated across the system as if it were valid[45].

Nonetheless, the insertion of erroneous or misleading data does not absolve the responsible operator of legal liability. On the contrary, blockchain's inherent traceability mechanisms may serve to enhance accountability, as every transaction—together with the

[41] Luigi Costato, 'La rintracciabilità degli alimenti' in Luigi Costato, Alberto Germanò, Eva Rook Basile (eds), *Trattato di diritto agrario* (Utet Giuridica 2011) 539; Noila Mohd Nawi, 'Consumers' preferences and willingness-to-pay for traceability systems in purchasing meat and meat products' (2023) 7 Food Research 3.

[42] These are: nature and quantity of raw materials, name and address of suppliers, date of receipt, nature and quantity of products marketed and date of delivery of products.

[43] Pierluigi Gallo, Giovanni Capizzi, Maria Timoshina, 'SeedsBit: Blockchain per la tracciabilità agroalimentare multifiliera' (2021) 2 Federalismi 92.

[44] Maugeri (n 7) 21.

[45] Warwick Powell, Marcus Foth, Shoufeng Cao, Valeri Naraelov, 'Garbage in garbage out: The precarious link between IoT and blockchain in food supply chains' (2022) 25 Journal of Industrial Information Integration 1, 4.

identity (or pseudonym) of the party responsible for generating it—is permanently recorded and subject to audit.

Accordingly, while blockchain can significantly improve transparency, traceability, and auditability within agri-food supply chains, it cannot substitute the need for robust regulatory oversight and human due diligence in the verification and certification of input data[46].

With respect to the need to think in terms of an integrated supply chain, blockchain could also be used to ensure that different *players* share the same level of information on the validity and provenance of certificates and that they are tamper-proof.

However, while in the field of *supply management* the main use cases of blockchain relate to the food supply chain, with specific reference to the blockchain's features concerning the ability to manage large amounts of data, the real key must be read in the light of the combination of blockchain, IoT and smart contracts[47].

According to some studies, the possibility of eliminating the insertion of false data into the blockchain by human agents could be achieved through the use of the Internet of Things, particularly by means of computerised sensors responsible for automatically recording the parameters to be entered into the chain[48].

It is worth pointing out that, indeed, we are faced with two mechanisms that, although useful together, are different from each other: while ensuring greater transparency and capillary traceability in the supply chain is an objective that can be achieved through L.T.D., ensuring real-time data collection, on the other hand, is an operation that must necessarily be performed through the use of the Internet of Thing and Machine Learning.

4 Balancing blockchain governance: public vs private models

A key issue to address is the choice of *governance* model for blockchain to be applied to the business opportunities previously examined. According to its creator, *Satoshi Nakamoto*, the only possible form of *governance* for this technology is a 'public' model-one in which all network participants have free access to the chain, can validate transactions and be custodians of the sequence of the entire chain[49].

However, such a system is ill-suited to the objective of integrity that one would like to achieve, due to the dense regulatory system of public controls that inevitably clashes with the circumstance that, with this type of *governance*, any individual with a computer and an Internet connection could well enter false information into the so-called *permissionless* chain, thus defeating the usefulness of the entire system thus designed.

[46] For further insight into the relationship between external controls and supply chain integrity Cfr infra, par 5.
[47] Della Mura (n 37) accessed 15 July 2025.
[48] Powell and others (n 45) 3.
[49] Satoshi Nakamoto, 'Bitcoin: A Peer-to-Peer Electronic Cash System' <https://bitcoin.org/bitcoin.pdf> accessed 20 June 2025.

On the other hand, a completely privatised (so-called *permissioned*) system, whose information is not freely accessible, would not be able to guarantee the adequate transparency required and which would instead constitute the main element of the implementation of consumer confidence.

Therefore, the right compromise could be reached using *consortium* platforms, where only a few authorised nodes can execute and approve transactions, but whose information is accessible to all interested parties[50].

A concrete example of the application of this solution is the DIH Agrifood project[51], which utilises a consortium-type blockchain based on Ethereum[52]. In this context, any participant can access the blockchain and verify information related to the products of the food supply chain, such as their origin and journey, simply by scanning the QR codes placed on the products. Each transaction on the blockchain handles basic blockchain-related information, such as the timestamp, digital identity, and signature, as well as specific product-related information, such as the type, harvest region, harvest date and time, and logistics-related information, such as the batch number and product type. The solution also allows for the storage of digital proofs, such as photos of the harvest or delivery, on a related IPFS or Swarm network, along with other rich data, such as certificates, nutritional data, farmer/producer information, agricultural practices data, and environmental footprint data. In this model, however, users do not have the necessary powers to approve transactions but only the ability to observe and verify the information.

5 Smart contracts, the point of contact between real and virtual

It is interesting to explore how the 'off-chain' dimension interacts with the blockchain and the methods through which this connection occurs.

This possibility can be provided by *smart contracts* technology, which consists of code sequences that self-execute according on the predefined patterns they are programmed to follow[53]. Without delving too deeply into an attempt to provide a universally agreed-upon legal definition of smart contract[54], what is truly relevant are its characteristics once it begins operating on the blockchain.

It is important to clarify that, although they function effectively in synergy, smart contracts and blockchain are distinct technologies. While blockchain is a decentralised

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[50] Stazi (n 6) 100.

[51] For more information: DIH Agrifood project <https://itc-cluster.com/dih-agrifood/> accessed 20 June 2025.

[52] Ethereum is an open-source, decentralised platform based on blockchain that enables the development and management of smart contracts.

[53] Stazi (n 6) 109.

[54] Florian Möslein, 'Legal Boundaries of Blockchain Technologies: Smart Contracts as Self-Help?' in Alberto De Franceschi, Robert Schulze (eds), *Digital Revolution - New challenges for Law* (Nomos 2019); Maria José Schmidt-Kessen, 'Creating Markets in No-Trust Environments: The Law and Economics of Smart Contract' (2019) 35 (1) Computer Law and Security Review 69, 77; Pierluigi Gallo, 'Dlt, blockchain e smart contract' in Marco Cian, Claudia Sandei (eds), *Diritto del Fintech* (CEDAM 2020) 137; Sara Rigazio, 'Smart contracts e tecnologie basate su registri distribuiti nella L. 12/2019' (2021) 2 Diritto dell'informazione e dell'informatica 369, 374.

ledger, smart contracts are software programs designed to automatically execute transactions.

The idea of integrating smart contracts with blockchain technology was proposed by Nick Szabo, who authored two seminal papers: Formalising and Securing Relationships on Public Networks and The Idea of Smart Contracts. In these works, Szabo compares the operational mechanism of this combined technology to the process of purchasing goods from a vending machine, where the execution of the contract via the insertion of money is, in essence, the transfer of a right through the execution of computer algorithms, contingent upon the fulfilment of a specific condition[55]. Thus, with smart contracts, the aim is to minimise, or even eliminate, human involvement in the creation of contractual conditions and their subsequent execution, using binary language as the fundamental tool[56].

The code used for the drafting of a smart contract, the Boolean language, is capable to meet both the requirements of (im)modifiability, certainty and transparency requirements of the supply chain, as well as flexibility of the agri-food sector's *managing*. It eliminates any ambiguity regarding the origin of goods and ensures that each step in the process is subject to controls that can only be passed if certain predefined conditions are met in advance.

These conditions could concern both the origin of the product, the transformations it has undergone, and the characteristics required for a product to be defined as 'quality', as well as indications concerning sustainability such as soil consumption, use of plant protection products, carbon dioxide production and water impact.

Therefore, *stakeholders* whose goal is to produce a specific type of product, with specific labelling and capable of attracting a significant number of consumers, could equip themselves with as many *smart* contracts as there are critical points in the supply chain, so that the contract code is set up so that each step in the supply chain, starting with the production of raw materials, is subject to a system of conditions designed to arrive at a specific finished product, with characteristics that, acquired throughout the supply chain, are controlled and monitored.

Only that particular product, coming from that territory and having undergone that specific processing, will fulfil the conditions identified from time to time by the Boolean language '*If this/then that*', thus perfecting the different smart contracts, executing them and thus initiating the process of storing data in the blockchain: when the network nodes approve the transaction, it will be added to the last block of data existing up to that point.

[55] Nick Szabo, 'Formalizing and Securing Relationships on Public Networks' (1997) 2(9) First Monday <https://doi.org/10.5210/fm.v2i9.548> accessed 20 June 2025; Nick Szabo, 'The Idea of Smart Contract' (1997) 6 199 <https://www.fon.hum.uva.nl/rob/Courses/InformationInSpeech/CDROM/Literature/LOTwinterschool2006/szabo.best.vwh.net/idea.html> accessed 20 June 2025.

[56] Max Raskin, 'The Law and Legality of Smart Contracts' (2017) 1(2) Georgetown Law Technological Review 305, 315.

This ensures strict adherence to the clauses identified within each contract regulating the supply chain relationship, which, once verified and executed, tends not to be altered[57], and then proceeds to the next stage of the supply chain, where a subsequent smart contract will identify further conditions and so on, until it reaches the final consumer.

The integration of smart contracts within the agri-food supply chain can significantly enhance the traceability and transparency of product data. By automating the execution of predefined contractual conditions through blockchain technology, smart contracts ensure that each transaction or step in the production process is recorded and verified without the need for intermediaries. This automated, immutable data recording guarantees the integrity of the entire supply chain, providing a clear and verifiable audit trail from raw materials to final product.

As a direct consequence of this enhanced transparency and traceability, businesses within the supply chain are better positioned to obtain voluntary product certifications. These certifications, such as those related to sustainability, organic farming, or product origin, often require rigorous documentation and verification to ensure compliance with specific standards. Blockchain, using smart contracts, simplifies and streamlines this process by providing an immutable record of compliance at every step of the supply chain.

Thus, the use of smart contracts not only strengthens the integrity of the agri-food supply chain but also facilitates the acquisition of voluntary certifications by reducing the complexity and cost of verifying compliance. This opens the door for businesses to access premium markets where certification plays a crucial role in consumer decision-making, all while maintaining the credibility and authenticity of the product claims[58].

Such system would not have the strength to replace the system of controls necessary to provide voluntary quality labels, but it would facilitate their acquisition, allowing the supply chain to transmit certain, unchangeable data and reducing the number of intermediaries present, with considerable savings in terms of transaction costs and error recovery, generating greater confidence in the end consumer.

The importance that voluntary product certifications assume in terms of transparency towards the consumer and greater profit for the company is such that mere compulsory product certification is not sufficient for the company to be competitive on the market. BIO, DOP, IGP and STP) that certifies the peculiarities of a product and that - although voluntary - is in any case subject to compliance with specific technical rules, incorporated within legal regulations and therefore binding[59].

[57] Chiara Campagna, 'Intelligenza artificiale e blockchain nel settore agroalimentare: il made in Italy che diventa smart' in Filippo Romeo (ed), *La difesa del made in Italy nel settore agroalimentare fra spinte protezionistiche e crisi pandemica* (Giappichelli Editore 2021) 151.

[58] Emiliano Troisi, 'Blockchain-based Food Supply Chains: the Role of Smart Contract' (2023) Special Issue EJPLT 138, 144.

[59] Giorgia Chiaramonte, 'Crisi Pandemica, certificazioni non obbligatorie dei prodotti agroalimentari e pratiche commerciali sleali alla luce della normativa emergenziale' in Filippo Romeo (ed), *La difesa del made in Italy nel settore agroalimentare fra spinte protezionistiche e crisi pandemica* (Giappichelli Editore 2021) 171.

In this regard, the European Commission, in its Communication No. 2010/C 341/04 'EU Best Practice Guidelines for voluntary certification schemes for agricultural products and foodstuffs' has well specified that' private certification is not necessary to demonstrate compliance with legal requirements. Any private certification scheme in the agri-food sector must remain voluntary. If operators use certification of compliance with minimum requirements to facilitate transactions with other actors in the food chain, it must be clear that this practice cannot be used to differentiate products on the market."

Thanks to the system of signs of quality and origin, an attempt is being made to shift competition from price to quality, thus enabling the market to pursue objectives other than mere corporate profit, such as the inescapable one of sustainability[60], now the *fil rouge* of European and global innovation. In a fully implemented situation, therefore, each contractual relationship within the supply chain could be viewed, verified and executed by several *smart contracts*, while managing to keep corporate confidentiality inviolate[61].

As mentioned, the blockchain/smart contracts system should, however, include, in order to achieve satisfactory result, the implementation of further technologies such as, for example, IoT and QR-code technology, which guarantee greater security and transparency for all players in the food supply chain.

Think of an IoT sensor with which it is possible to measure and certify the agricultural area that the producer has decided to allocate to the P.D.O. or P.G.I. product, to precisely identify cultivated plant varieties, to measure the density of production activity as well as to constantly monitor the processes adopted for the processing and treatment of raw materials.

The QR code, on the other hand, would make it easier to understand the stages of the manufacturing process, the history of each food product, from its genesis to its distribution, i.e. from the origin of the raw materials to their processing, through to transport, storage and warehousing at the point of sale, simply by scanning the code with a smartphone.

6 Liability for blockchain in supply chain networks

It is necessary to ask what happens if, in a system in which the information entered is so secure that it cannot be changed or removed and on which everyone places extreme trust, nodes in the chain were to enter untrue information.

The problem shifts to the responsibility of the nodes[62] and, in particular, to the form of responsibility existing in the person – be it a natural person or a legal entity – who enters the data into the decentralised system and who should guarantee its veracity.

[60] Michail Bitzios, Lisa Jack, Sally-Ann Krzyzaniak, Marl Xu, 'Country-of-Origin Labelling, Food Traceability Drivers and Food Fraud: Lessons from Consumers' Preferences and Perceptions' (2017) 8(3) European Journal of Risk Regulation 541.
[61] Gururaj, Kumar and Goundar (n 19) 247.
[62] Nodes which, at the stage of implementation we are discussing, would be none other than the players in the supply chain.

This issue is not new, as the same question was posed, before the emergence of this new technology, when - with the introduction of the HACCP system - a regulatory burden was placed on the producer/processor/distributor to track a given good, with the aim of causing them to take responsibility[63].

The issue of the fragmentation of responsibilities along the supply chain is a significant one, and it has engaged States in the search for a complex balance between rules concerning the allocation of liability of supply-chain players and the need to manage the risks inherent in production activities that follow different regulatory paths[64].

In general, two distinct approaches can be identified within continental European legal systems. On the one hand, some have decided to impose a series of obligations on producers related to food safety, requiring a high degree of diligence in their compliance. On the other hand, since the adoption of the Directive on defective products, some others have considered extending these rules to operators within the agri-food supply chain.

In Italy, case law[65] has established the principle that an operator in the supply chain must take measures proportional to the characteristics of the product, and in doing so, they are required, under Article 1227, paragraph 2, of the Civil Code, to adopt measures linked to the level of diligence demanded, which is higher than that of a reasonable man[66]. Some authors have attempted to frame this operation within the framework of the strict liability for dangerous activity under Article 2050 of the Civil Code[67] with the assumption that the activities falling within this paradigm are not only those indicated by the Consolidated Law on Public Safety, but also those that could have a significantly greater impact, in terms of public protection, than ordinary situations[68].

In Germany, through the same reasoning, the theory of *Stufenverantwortlichkeit*[69] has developed, according to which the fragmentation of the supply chain translates into adherence to Article 17 of the Regulation 178/2002, whereby each operator is held accountable for any product discrepancies arising from their actions, without a general liability for any potential event. This approach aligns perfectly with the adoption of a technological traceability system, which precisely identifies the steps and interventions of each player involved.

France explicitly affirmed that the liability of food producers could be linked to that outlined in the Directive on defective products. This created an objective standard of protection regarding the identification of unsafe food products, particularly considering

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[63] Lessio (n 15) 519.
[64] Giuseppe Toscano, 'Suggestioni del *lebensmittelstraftecht* in vista di una riforma degli illeciti agroalimentari' (2020) 63 (4) Rivista Italiana di diritto e procedura penale 1843.
[65] Cass. n. 5824/2014.
[66] Maria Pia Genesin, 'La responsabilità primaria dell'operatore del settore alimentare in relazione alla food safety' (2018) 3 Responsabilità Civile e Previdenza 809.
[67] Marianna Giuffrida, 'Innovazione tecnologica e responsabilità dell'operatore nel settore alimentare' (2018) 4 Rivista di diritto alimentare 4.
[68] Alessandro Ghiani, *Blockchain: linee guida. Dai casi pratici alla regolamentazione* (Giappichelli Editore 2021) 77.
[69] Gerhard Dannecker, 'Stufenverantwortung - wer haftet wofür?' [2002] ZLR 20.

the direct connection between defective products and the safety expectations of consumers, as defined in the 1985 Directive and continuing to evolve. The adoption of Regulation 178/2002 did not alter this regime, except by highlighting the need to strengthen the system through the establishment of a public agency, the General Service for Consumer Protection, Competition, and the Fight Against Fraud[70].

Therefore, with the advent of the Industrial Revolution 4.0. the problem would not be so much to identify the form of liability, but to establish the criteria for imputing this liability when using blockchain technology.

It is possible to identify two forms of liability attributable to the individual nodes of the network: that based on the failure of the operator who decided to enter incorrect data, or that resulting from the malfunctioning of the computer code underlying the blockchain and smart contracts.

While the regulatory regime applicable to the first form of liability is easy to grasp, as it can follow *sic et simpliciter* the traditional civil law rules[71], for the second the issue is different.

The nature of civil liability for damage caused by an algorithm depends, first and foremost, on its degree of autonomy and, in the case at hand, we are dealing with 'ordinary' algorithms for which, after receiving data, a model established by the programmer is applied in order to obtain a result; in this case, the assumption of liability for damage generated by the malfunctioning algorithm should fall on all those who took part in the chain of its production, with the discipline of defective product damage being applied extensively. This would therefore be, according to part of the doctrine[72], strict liability.

This being the case, programmers are held objectively liable for any defects in the code that has been used to make the system operational, forcing them to bear - in the event of damage being done - such a cost that innovation would be financially unsustainable, with the consequence that the development of Blockchain and Smart Contracts would be discouraged.

Indeed, if the Product Liability Directive were to be applied to the case at hand, in the light of the European defect in the matter, an excessively broad interpretation would be made: Directive 1985/374/EC provides that goods that are movable and tangible fall within the definition of a product, but it is quite clear that a tangible code string is not[73].

To remedy this problem, in some European jurisdictions, tangible software is considered to be tangible at the moment it is incorporated into the movable asset that

[70] Elodie Rouviere, Julie Caswell, 'From punishment to prevention: A French case study of the introduction of co-regulation in enforcing food safety' (2012) 3 Food Policy 246, 254.
[71] Think, from a purely civil law point of view, of the regulation of product liability.
[72] Remo Trezza, *Diritto e Intelligenza Artificiale* (Pacini Giuridica 2022) 54.
[73] Duncan Fairgrieve, Eleonora Rajneri, 'Is Software a Product under the Product Liability Directive?' (2019) 1 IWRZ 24.

will contain it[74], producing the knock-on effect - in terms of liability allocation - of having to involve, in terms of solidarity, not only the creator of the code but also, if different, the manufacturer of the asset[75].

An approach that limits the liability of developers by establishing appropriate standards of conduct could help safeguard and promote technological development; one might expect the software industry to do its best to ensure that algorithms are secure against computer intrusion, but one can never demand certainty[76]. Therefore, the European legislator could develop a liability standard that focuses on reasonable care and best efforts to avoid malfunctions as far as possible[77]. Indeed, it is precisely in this direction that the European institutions are moving, through the proposal for a directive put in place by the European Parliament in September 2022[78] and adopted in November 2024[79].

Notwithstanding possible regulatory developments to meet these regulatory shortcomings, however, the question of qualifying the applicable liability regime remains while relying, in fact, on increasingly automated technologies[80], there is a discrepancy between the attribution of liability to the parties programming these machines and the way in which control over these technologies could take place[81]. Particularly sensitive to the subject has been the German doctrine, which considers that product liability law is an appropriate instrument to regulate the phenomenon, only if the producer continues to be able to exert a certain influence on the damage that the product causes[82].

In the light of all these considerations, it is interesting to observe that, albeit through different interpretations and very different starting points, the conclusion has been reached that, at least with respect to the current state of the art, the discipline around which liability would revolve - both of the planners and of the protagonists of the supply chain - is the one, in some respects now outdated, of product liability, which moreover represents the pivot of the discipline of the liability of the operators of the supply chain.

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[74] Giovanni Commandè, 'Intelligenza artificiale e responsabilità tra liability ed accountability' (2019) 1 Analisi Giuridica dell'Economia 169, 177.

[75] The main European jurisdictions that favour this hypothesis are Germany and United Kingdom; see, respectively: Ulrich Magnus, 'Product Liability in Germany' in Piotr Machnikowski (ed), *European Product Liability: An analysis of the State of the Art in the Era of New Technologies* (De Gruyter 2018) 245; Eden Miller, Richard Goldberg, *Product Liability* (OUP 2004) par 9.100. However, there is no lack of reflections to the contrary, for example, in Italy: Lavinia Vizzoni, *Domotica e diritto. La smart house tra regole e responsabilità* (Giuffrè Francis Lefebvre 2021) 185.

[76] Predrag Cvetkovic, 'Liability in the Context of Blockchain-Smart Contract Nexus: Introductory Considerations' (2020) 89 Зборник радова Правног факултета у Нишу 83, 85.

[77] Gitta Veldt, 'The New Product Liability Proposal - Fit for the Digital Age or in Need of Shaping Up? An Analysis of the Draft Product Liability Directive' (2023) 12(2) EuCML 24.

[78] The report accompanying the proposal for a directive is available at the following link: <https://eur-lex.europa.eu/resource.html?uri=cellar:b9a6a6fe-3ff4-11ed-92ed-01aa75ed71a1.0013.02/DOC_1&format=PDF> accessed 20 June 2025.

[79] Full text of Directive <*https://data.consilium.europa.eu/doc/document/PE-7-2024-INIT/it/pdf.*> accessed 20 June 2025.

[80] *Smart contracts* operating on blockchain are in fact *self-executing* contracts and once activated there is no way back, unless special chain *fork* or self-destruct functions are provided within the source code.

[81] Cvetkovic (n 76) 93.

[82] Gerhard Wagner, 'Robot Liability' [2018] SSRN <://papers.ssrn.com/sol3/papers.cfm?abstract_id=3198764> accessed 20 June 2025.

The reform deserves credit for attempting to adapt existing regulations to the growing complexity of new digital goods covered by the Directive. This is especially relevant given that these products are not always tangible—consider, for example, software—or, if they are, some of their components may not be, as highlighted in Recital 13 of the Directive.

Article 4, paragraph 1 defines products as any movable goods, even if integrated into or interconnected with other movable or immovable goods. This resolves a practical issue by eliminating the distinction, for proof purposes, between physical goods incorporating or interconnected with software and the software itself[83]. This clarification ensures that stakeholders in the supply chain are subject to the liability regime established by the Directive, even in cases where liability arises due to data manipulation or falsification.

Regarding the definition of "product," the 1985 Directive's concept of "movable goods" remains in place, with digital manufacturing files and software specifically added. However, some scholars[84] argue that separate definitions should be introduced for "digital manufacturing files" and "software" to align them with Directives 770 and 771 of 2019, thereby harmonising the rules on contractual liability for defects in services and extracontractual liability[85].

On the other hand, the European legislator has excluded open-source software acquired for free from the scope of the new Directive, a decision that has raised concerns, especially considering that the previous Directive did not exclude free products from liability coverage[86].

Article 8 of the new Directive is particularly relevant for the food chain, as it establishes the principle of joint liability for all economic operators involved in the production of a defective product, which is especially useful for analysing liability in long, multi-stage supply chains.

Questions may arise when the software causing damage is open source, as seen in public governance blockchains. Recital 14 and Article 2 of the new Directive use the need to protect innovation as a pretext to exclude open-source code, provided it is not part of a commercial activity—defined here as instances where the software is sold, or personal data is exchanged. However, it remains unclear why open-source software should be excluded, given that the previous Directive did not impose such exclusions for free products.

Despite these concerns, an interesting aspect of the reform is the shift in the reference moment for determining liability—from the time of market placement to when the

[83] Tommaso De Mari Casareto dal Verme, *Intelligenza artificiale e responsabilità. Uno studio sui criteri di imputazione* (Editoriale Scientifica 2024) 343.
[84] Izquerdo Grau, 'An Appraisal of the Proposal for a Directive on Liability' (2023) 2(5) EuCML 198; Christiane Wendehorst, 'Product Liability or Operator Liability for Ai – What is the best Way Forward' in S Lohsse, R Schulze, D Staudenmayer (eds), *Liability for AI* (Hart 2023) 99.
[85] Karni Chagal-Feferkorn, 'Am I an Algorithm or a Product? When Products Liability Should Apply to Algorithmic Decision-Makers' (2019) 30 Stanford Law & Policy Review 61.
[86] Andrea Cioni, 'Nuovi pregi e vecchi difetti della proposta di direttiva sulla responsabilità da prodotto difettoso, con particolare riferimento all'onere della prova' (2023) 88(2) Responsabilità civile e previdenza 656, 667.

manufacturer's control over the product ends[87]. While this change was likely aimed at software, it could also apply to any movable goods subject to stringent post-market monitoring, as in the case of food products. However, some argue that post-market controls should apply only to the software component, not the hardware[88].

The recent European reform, despite some limitations, represents a significant attempt to adapt the regulatory framework to the specificities of digital products, ensuring consumer protection while also fostering innovation. However, it will be crucial to monitor the evolution of these regulations to ensure that software developers, especially those working with open-source code, are not penalised, thereby maintaining the balance between accountability and incentives for innovation, but the way is clear: the development of the liability framework must provide a regulatory structure capable of harnessing the full potential of these new technologies, while mitigating their risks. It should outline responsibility not only along the supply chain but also throughout the blockchain[89].

7 Digital food liability law in United States

In the United States, the study of the functioning of digital-supply chain liability necessarily passes through a not insignificant systematic premise.

The rules concerning food safety on the 'new continent' are decidedly more confusing than those on the European scene, also in light of the fact that, on the one hand, the matter is entrusted to state competence and, on the other, that the tasks entrusted to the agencies dealing with food safety - unlike in Europe - include not only the preliminary scientific assessment of the risk, but also its management[90]. Furthermore, there is a further division of state competence concerning the type of foodstuff, with the added difficulty of having to manage different agencies not only in different states, but also according to the different product in question.

This fragmented nature has significant implications for the applicable regulations: even product liability laws, which apply to damages caused by food products, are limited by the jurisdiction of individual states. As a result, this creates considerable inconsistencies, not only in the sanctions imposed but also in the burden of proof the producer must meet to be exempt from liability. In some states, contributory negligence cannot be used as a defence by the manufacturer, while in others, such as Mississippi, it can. Additionally,

[87] Gerhard Wagner, 'Liability Rules for the Digital Age – Aiming for the Brussel Effect' (2022) 13 (3) Journal of European Tort Law 191, 206.
[88] ibid 210.
[89] Callegari (n 2) 1219.
[90] Carolina Magli, *Il danno da alimenti tra responsabilità del produttore e stile di vita del consumatore* (Cedam 2018) 173.

some states have statutes of limitation—time limits within which claims must be made—while others do not, further adding to the complexity[91].

To be able to resolve this composite situation, various solutions have been put forward that aim to achieve the same degree of harmony as the solutions adopted in European systems. First came the *Restatment (Third) of the Tort*, which, however, has no binding force for the Courts of the individual American States; subsequently, various proposals were launched for a *federal product liability*, which, however, Congress never followed up on, also in view of the difficulty in choosing the legislation to be raised to federal discipline[92].

A further solution envisaged by a part of the doctrine aims to avoid the - increasingly constant - phenomenon of the so-called *choice of law* and concerns the enactment of a rule that identifies, depending on the case, which law is applicable[93], creating, where necessary, a *federal pre-emption* of state law, assigning the agencies the task of achieving the much-desired regulatory harmony.

It is essential to establish a form of liability that is independent of the complex and often ambiguous regulatory framework. In the United States, when examining the liability regime for blockchain users, greater emphasis is placed on understanding the operational mechanisms of the technology itself, with a clear distinction made between public and private blockchains.

In permissionless one, liability is thought to be allocable under the theory of 'joint control', which is understood as the outcome of specific decisions made within the context of shared network governance. Instead, in permissioned blockchains, liability would be assigned to the individual node based on its specific level of involvement in the transaction that resulted in harm to a user, following a 'contractual theory'.

According to the theory of joint control[94], the civil liability of blockchain nodes is argued to be based on an analogy with the rules governing joint venture partnerships, equating the relationships between nodes to those between participants in a shared enterprise[95]. The central assumption is that liability is tied to the control exercised by certain actors over the network's organisational structure. Consequently, an inquiry into liability would focus on identifying who controls the structure and who bears its operational risks (and benefits)[96]. However, while the complete decentralisation of decision-making could, in theory, grant all nodes significant influence over one another's

[91] As an illustration, consider that the law of most states imposes disclosure requirements even after the sale, while in some, such as Mississippi, this obligation is not required by law.

[92] Carolina Magli, *La sicurezza alimentare tra norme preventive, obblighi risarcitori ed 'autoresponsabilità' del consumatore. Sistema italiano e statunitense a confront* (D.U. Press 2021) 72.

[93] Russell J Weintraub, 'Methods for Resolving Conflict-of-Law Problems in Mass Tort Litigation' [1989] U Ill Law Review 129, 141.

[94] Dirk Zetzsche, Ross Buckley, Douglas Arner, 'The Distributed Liability of Distributed Ledgers: Legal Risks of Blockchain' (2018) 4 U Il L Rev 1361.

[95] Hugh Collins, 'Introduction to Networks as Connected Contracts', Gunther Teubner (ed), *Networks As Connected Contracts* (Hart 2011).

[96] Rainer Kulmsal, 'Blockchains: Private Law Matters' [2020] Sing J Legal Stud 63, 86.

positions, it has already been demonstrated that some users possess the ability to direct the behaviour of others by embedding specific commands in the source code, which in the context of a supply chain could be more easily traced.

In this regard, the theory of joint control faces significant limitations in relation to the principles of causal liability, as it risks extending responsibility to parties that have no direct involvement in the actions leading to the harm[97]. Although this approach attempts to align blockchain dynamics with existing legal frameworks, it fails to adequately account for the fundamental principle that liability—whether joint or several—should be rooted in a clear and direct causal connection between an actor's conduct and the resulting damage. This gap leads to potential uncertainty and inequities in the allocation of risk.

The contractual theory of liability, by contrast, finds fertile ground in blockchains with private governance, which are particularly common in the agrifood sector. This theory shifts the focus to how access to the platform is granted and emphasises the precise identification of the roles of those involved. In this context, a relationship is presumed between the "user-nodes" participating in a transaction and the entity managing the underlying infrastructure, with liability framed within a form of contractual responsibility. The network operator, in accordance with the contractual theory, would be liable for damages resulting from any defect in the infrastructure's operation, while the nodes involved in the transaction would be responsible for damages caused in other ways.

This theory gains further support from the fact that, in the United States, some States[98] have begun to recognise that a digital asset can be considered an object of property rights under two alternative conditions: the existence of specific regulations on the matter or the successful passing of the so-called *Wilberforce test*, the principle born in *National Provincial Bank v Ainsworth*[99]. According to this test, an asset can be subject to property law if it is determinable or identifiable, distinguishable by third parties, permanent, and stable criteria that seem to be met by tokens recorded on the blockchain.

However, attributing contractual liability to the software distributor that provides access to the network could serve as a disincentive to innovation, potentially rendering the model financially unsustainable. A preferable approach would be to limit such liability by setting clear standards of expected diligence, while also providing explicit guidelines for the cybersecurity measures required to safeguard the network[100].

Despite ongoing discussions about how to address these shortcomings, the question of the most suitable liability regime remains unresolved. As automation advances, a clear gap emerges between the assignment of responsibility to those who design such technologies and the practical mechanisms available for exercising control over them[101].

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[97] Mireille Hildebrandt, *Smart Technologies and the End(s) of Law* (Elgar 2016).
[98] Arizona, Nevada, Wyoming, Illinois e Delaware.
[99] *National Provincial Bank Ltd v Ainsworth* [1965] AC 1175 (House of Lords).
[100] Cvetkovic (n 76) 100.
[101] ibid 93.

German legal scholarship has been particularly engaged with this issue, maintaining that product liability law offers an effective framework for regulation—provided that manufacturers retain a degree of influence over the harm their products might cause[102].

In Conclusion, it is particularly striking that, despite divergent interpretations and starting points, scholars broadly agree that product liability law remains the central legal framework governing liability for both software developers and supply chain actors. At least given the current state of technological development, this body of law serves as the primary regulatory mechanism for assigning liability across the industry—even beyond Europe.

8 Enhancing supply chain sustainability through blockchain technology

Thanks to the increased protection in the collection of data to facilitate the awarding of quality certifications, the capillarity of product traceability, and the increase in consumer confidence in the product, the supply chain may increase its competitiveness thus being able to pursue other objectives, not strictly related to immediate profit, such as environmental sustainability. This outcome is achieved through the assessment of corporate sustainability measurement via ESG (Environmental, Social, and Governance) ratings, the Sustainable Development Goals (SDGs), and the positive implications that a strong ESG performance can have on a company in terms of external investments[103]; specifically, it has been observed that value chains utilizing blockchain are rated more favourably compared to those that do not, precisely because of the data certification guarantees provided by this technology, which it implements in the aforementioned ways[104]. It can thus be concluded that the integration of ESG metrics has an increasingly significant impact on the economic and financial valuation of companies, linked to enhanced market reputation[105].

In fact, the practical application in which blockchain has been shown to be most conducive to sustainability has been supply chain traceability[106].

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[102] Gherard Wagner, 'Robot Liability' in V Mak, T F E Tjong Tjin Tai, A Berlee (eds), *Research Handbook Data Science and Law* (Elgar 2018) 61.

[103] Tai Ming Wut, 'Intangible Assets and Sustainable Development' in Leal Filnho (ed), *Encyclopedia of Sustainability in Higher Education* (Springer 2019).

[104] Roberto Moro-Visconti, 'Fake news and (mis)information asymmetries' [2024] <https://www.researchgate.net/publication/380890830_Fake_news_and_misinformation_asymmetries.> accessed 20 June 2025.

[105] Kalpana Tyagi, 'A Global Blockchain-Based agro-food value chain facilitate trade and sustainable blocks of healthy lives and food for all' (2023) 10(1996) Humanities & Social Sciences Communications 1, 4; Roberto Moro Visconti, 'Rating ESG ed impatto sulla valutazione di marchi, brevetti, intelligenza artificiale e altri intangibili' (2024) 4 Il diritto industriale 386, 397. However, some scholars argue that the intersection between sustainability and profit may distort competition. Ex multis: Andrea Pezzoli, 'Come era verde il mio cartello' (2022) 1 Analisi Giuridica dell'economia 327.

[106] Francisco Luis Benítez-Martínez, Pedro Nuñez-Cacho, Valentin Molina-Moreno, Esteban Romero-Frías, 'Blockchain as a Service: A Holistic Approach to Traceability in the Circular Economy' in S Muthu (ed), *Blockchain Technologies for Sustainability* (Springer 2022) 119.

As companies' sustainability strategies evolve and sustainability reports require a high volume of data, the reliable and secure management of indicators such as water and energy consumption, chemical usage or the CO_2 impact of cultivation is an imperative that only blockchain can address.

Indeed, this technology guarantees the possibility of following a model of economy that is no longer linear, typical of the current supply chain (raw materials, production, distribution, consumption, waste), but circular[107]. This is undoubtedly a matter of primary importance, as the circularity of materials would be reliably and securely tracked, thanks to the peculiarities analysed so far.

Recording this information, however, is important not only in terms of environmental friendliness, but also in terms of corporate profitability: more and more consumers are orienting their purchases according to the sustainability of their choice[108].

Blockchain technology can play a crucial role in advancing a circular economy by enhancing the treatment, reuse, and disposal of waste. Through the transparent and immutable records provided by blockchain, it becomes possible to track the exact nature of waste materials, understand how best to recover them, and determine the most efficient methods for their reintegration into the supply chain. This includes processes such as recycling and reuse, where all previous steps and treatments the materials underwent are fully traceable and verifiable[109].

In addition to improving waste management monitoring, blockchain technology can facilitate more streamlined and efficient systems for managing waste, further supporting the shift towards a circular economy. By enabling the integration of various stakeholders and processes within the supply chain, blockchain systems can promote more sustainable practices such as the recycling of packaging materials and the reduction of waste.

The use of smart contracts and distributed ledgers within this context provides an added layer of efficiency and accountability. Smart contracts, which automate transactions based on pre-set conditions, could be utilised to optimise waste management processes, ensuring timely and accurate actions at each step. These mechanisms significantly enhance transparency, scalability, and operational efficiency across the waste treatment process, making it easier to implement and track circular economy initiatives. Ultimately, blockchain has the potential to create a more sustainable and closed-loop system, reducing waste and maximising resource recovery throughout the entire supply chain[110].

Finally, one of the most interesting aspects to be analysed is the challenge of constantly monitoring sustainability through tokenisation of assets; through this procedure, in fact,

[107] Circular economy in the context of the supply chain can be understood as that system whereby, once the end of the production cycle is reached, resources remain within the economic system so that they can be reused again in the production cycle and realise new value.
[108] On 28 November 2020, the Alliance of Agri-Food Cooperatives and Vodafone signed a cooperation agreement in the field of *smart agriculture* via apps for smartphones and tablets, sensors for monitoring agro-climatic parameters.
[109] Gallo, Capizzi, Timoshina (n 43) 94.
[110] Troisi (n 58) 150.

different stakeholders increase their cooperation and competition in building circular economy environments[111].

In this context, of great interest is the use of the so-called digital twin, ie, the virtual representation of an object, asset or process, which is updated in real time through IoT sensors placed on the actual product that transmit data to its 'digital' version, allowing measurements and simulations to be made in the areas of - among others - environmental impact and maintenance, with a huge reduction in costs[112].

In Spain, with reference to this possibility, a platform has been developed by the start-up Nutrasign2, allowing users to create a unique, secure and immutable digital token of each product, offering traceability from the origin of the raw material to the table.

However, the main problem encountered in this area concerns the absence of a definition of sustainability, which, to date, can only be found in a few *soft-law* texts[113] , the application of which is left to the free choice of the parties, even though it has, as mentioned above, a considerable impact on consumer choices[114].

9 Conclusions

Despite the incredible numbers of benefits that the use of blockchain would bring to the agri-food sector, there is a considerable level of mistrust among stakeholders about the technology, due to its still not optimal reputation, as well as several technical-legal problems that need to be questioned.

The first point concerns the reliability of the data that are stored by the blockchain. In addition to the system of node accountability above, the blockchain can never be sufficient to definitively eliminate fraud in the food chain, although, as more and more data becomes available and is linked to it, it will be easier to detect and trace it, significantly reducing the likelihood of fraudulent information corrupting the system.

It is also important to note that, from a business asset protection perspective, total transparency is not sustainable, because part of the industry's activity has an interest in not being known to the rest of the market[115]. To partially solve this problem, some data could be made available or visible only to certain node-participants, to guarantee corporate confidentiality, without the possibility of tampering. However, the conditions

[111] Benítez-Martínez, Nuñez-Cacho, Molina, Romero-Frías (n 106) 123.
[112] Laura Cappello, *L'evoluzione del consumatore negli ecosistemi decentralizzati. L'impatto della digitalizzazione e della blockchain* (G Giappichelli 2022) 115.
[113] An example is Article 12 of the Italian Code of Self-Regulation for Commercial Communications: "commercial communication claiming or evoking environmental or ecological benefits must be based on truthful, relevant and scientifically verifiable data. Such communication must make it clear to which aspect of the advertised product or activity the claimed benefits relate."
[114] Beatrice La Porta, 'L'etichettatura di sostenibilità nel settore vitivinicolo' in Giuseppina Pisciotta Tosini (ed), *Atti del convegno di comunicazione di sostenibilità e blockchain* (Palermo University Press 2022) 53.
[115] One thinks of the secrecy of information concerning the composition of certain products such as Coca-Cola.

for data access should be planned from the outset, making it complex for a new player to enter the supply chain.

However, the conditions of access to data would have to be planned before the starting of the system, making access to the supply chain complex for a new actor[116].

Before implementing the blockchain in the supply chain, it would be necessary to review the procedures that manage it, undertaking a thorough evaluation of the systemic effects it would have on operational procedures and trying to simplify them as much as possible. The solution, as doctrine has argued[117] , is not to integrate all possible data and documents on the blockchain, but only those considered most important.

Another long-standing issue concerns the environmental energetic impact of *mining*, the operation through which one node of the network, before all others, approves the transaction to be added to the ledger: the node with the highest computational power will be the first to solve the mathematical question necessary to approve the transaction, obtaining a reward for its work, which is usually a crypto-currency.

The problem concerns the increasing of one's computing power, because to do it, it is necessary to use very powerful computers, which consume considerable amounts of electricity, generating a nonsense whereby one tries to promote environmental sustainability through a technology that wastes huge amounts of energy. The solution to this question lies in the possibility of using other transaction approval mechanisms, which already exist, but are little used, such as *proof of stake*, which does not use the computational energy as the preferred criterion, but that of the resources that the individual node has available.

Finally, although the consumer has the computer certainty that a *smart contract* performs certain transactions and verifies certain conditions without being able to be tampered with in any way, he does not understand what these conditions are specifically: the smart contract, in fact, is not only written in a computer language[118] that the consumer does not know, but he does not even have the possibility of reading what conditions have determined its execution.

The lack of intelligibility of smart contracts, which results in a decrease in the trust users place in them, could be stemmed by the use of hybrid language - computer/linguistic idioms - that balances both the requirements of food security and the need for easy-to-read information that food security itself brings; it is no coincidence that the creation of

[116] Eloisa Marchesoni 'La blockchain per la tracciabilità del made in Italy: Origine, Qualità, Sostenibilità. Caso di studio applicato al settore tessile' (Ministero dello sviluppo economico & Ibm. 2019) <https://www.agendadigitale.eu/documenti/blockchain-per-lagrifood-rivoluzione-smart-contract-ecco-vantaggi-e-limiti/> accessed 12 June 2024.

[117] Hernandez (n 25) 567.

[118] Gallo, Capizzi, Timoshina (n 43) 100.

a copy of the smart contract written in natural language is becoming increasingly common in practice[119].

It was thus realised that blockchain technology enables the keeping of an infallible record of information, smart contracts allow, by analysing their content, an understanding of the history of the stored data, while machine learning technologies[120], such as IoT, guarantee real-time monitoring of the supply chain.

In conclusion, the integrity of the agri-food chain could certainly be achieved through these new technologies.

It is equally true, however, that talking about food integrity and food security necessarily leads the discourse towards the problem of subjectivity. Blockchain, in whatever form it takes, would not enjoy the legal subjectivity recognised by the law as a certifying body and, therefore, it would be appropriate to make a distinction between the use of blockchain as a technology capable of 'certifying the product' from a technology capable of 'certifying the supply chain', raising its safety standards, and in this latter concept, the sense of blockchain in the agri-food supply chain.

[119] Damiano Di Maio, Gioacchino Rinaldi, 'Blockchain and the legal revolution of smart contracts' (*Diritto bancario*, 11 July 2016) <https://www.dirittobancario.it/art/blockchain-e-la-rivoluzione-legale-degli-smart-contracts/> accessed 20 July 2025.

[120] With particular reference to artificial intelligence systems, they can play a crucial role in achieving sustainability goals: their computational power enables more precise interoperability and interconnection with the various technologies used within the supply chain. Cfr. Ricardo Vineusa, 'The Role of Artificial Intelligence in Achieving the Sustainable Development Goals' (2020) 233 Nature Communications 11. These studies have also been taken into consideration in the recent AI Act, as evidenced by Recital 4, which suggests that "it can provide key competitive advantages to businesses and lead to favourable social and environmental outcomes" in the agricultural sector. Upon careful reading of these regulations, it emerges, among other things, that these are the exact same indicators used in ESG assessments.