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Blockchain-based Food Supply Chains: the role of Smart Contracts

Filiera agroalimentare, sostenibilità e blockchain: il ruolo degli Smart Contract

Emiliano Troisi
Ph.D. in Humanities and Technologies: an Integrated research pat
Suor Orsola Benincasa University of Naples

Abstract
Given blockchain's ability to record and maintain information in an accessible, verifiable, non-repudiable and tamper-proof manner, this technology appears to provide a secure environment to improve product traceability and provenance throughout the extended supply-chain, which would particularly benefit the agri-food industry. Indeed, the extension and the multi-participant/multi-phase nature of the production cycle that characterize modern agri-food supply chains has made them increasingly difficult to manage, while ensuring that stakeholders are properly informed, that counterfeiting is identified and prevented, that safety standards are met, and that the origin and quality of agri-food products are properly certified. It is a growing opinion, among scholars, that blockchain – as a resilient record-keeping and tracing system - could overcome some of these critical issues; accordingly, smart contracts would be a potentially innovative tool to automatically execute agreements between the various parties involved and, perhaps, help monitor, regulate, and verify each (processing, storage, transfer, etc.) stage that forms the workflow.
This paper – building upon the extant academic literature and taking into account Italian policies and legislation on the point – aims to explore the role of smart contracts in food-(block)chain traceability systems, evaluating suitability and critical issues. Finally, the possible contribution of smart contracts - when combined with IoT devices - for more effective (fully or partially automated) controls on food products will be analyzed.

Abstract

La blockchain, tecnologia in grado di registrare e gestire informazioni in modo accessibile, verificabile e resistente alle manomissioni, sembra offrire un ambiente sicuro per migliorare il controllo e la tracciabilità dei prodotti agroalimentari lungo l'intera filiera. L'estensione, spesso transnazionale, e la complessa ramificazione delle supply-chain agroalimentari rendono infatti sempre più difficile il monitoraggio dei prodotti e delle fasi di lavorazione, assicurando il rispetto degli standard di sicurezza, o che l'origine e la qualità dei prodotti agroalimentari non siano contraffatti, e al contempo che gli attori del mercato, in particolare i consumatori, abbiano adeguato accesso alle informazioni necessarie per scelte di consumo più salutari e sostenibili.

È opinione crescente tra gli studiosi che il ricorso alla blockchain potrebbe superare alcune di queste criticità, migliorare la gestione aziendale e contribuire allo sviluppo sostenibile di questo settore produttivo; di conseguenza, gli smart contract rappresenterebbero uno strumento potenzialmente innovativo in grado di gestire automaticamente e in modo trasparente i rapporti inter-filiera, contribuendo a monitorare, regolare e verificare quasi ogni fase (trasformazione, conservazione, distribuzione, ecc.) della catena di approvvigionamento.

Questo articolo, tenendo anche conto delle politiche e della legislazione eurounitaria e nazionale in materia, si propone di esplorare il possibile ruolo degli smart contract nei sistemi di tracciabilità alimentare basati su blockchain, valutandone benefici e criticità. Infine, verrà analizzato il possibile contributo della blockchain quale fattore chiave per politiche di sostenibilità e transizione verde dell'intero settore agroalimentare.

Keywords: Distributed Ledger Technology; Blockchain; smart contract; food; agri-food; supply chain; traceability; food safety; sustainability.

Introduction.

That complex regulatory apparatus, which may be defined as Food Law[1], imposes itself in the European context, with the Single Market, and here it evolves around, in particular, the concept of food safety, hence – above all – of

[1] Mainly, Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety, as last updated and amended, defining principles in food law and food safety, but also Regulation (EU) 2017/625 of the European Parliament and of the Council of 15 March 2017 on official controls and other official activities performed to ensure the application of food and feed law, rules on animal health and welfare, plant health and plant protection products; Commission Regulation (EC) No 2073/2005 of 15 November 2005 on microbiological criteria for foodstuffs and Regulation (EU) 2019/1381 of the European Parliament and of the Council of 20 June 2019 on the transparency and sustainability of the EU risk assessment in the food chain.

healthy food – in the sense of hygiene, toxicological safety, wholesomeness – with its primary aim being the right to life and health (cf. Article 32 of the Italian Constitution), comprehended also in a positive sense, as the right to well-being and a better quality of life.[2]

Around this pivot, it establishes a system of protections based on risk diagnosis for consumers of food products, stringent obligations of information and transparency, and end-to-end traceability in the entire production chain, from raw materials to the finished product, to consumption. This enables authorities and ultimately consumers to identify the place of origin, whether it be cultivation or breeding, of the food or the predominantly used ingredients.

The agri-food sector is an area where technology could, and indeed is, making a difference by offering new tools to ensure traceability and transparency in supply chains. In fact, in this field, Blockchain (or DLTs for Distributed Ledger Technologies) – a technology initially associated with Bitcoin but now independent from Fintech, due to its broad, 'general purpose' nature[3]; immediately holding a central position in European strategies for innovation[4]; of strategic interest also in the context of the Italian Agenda for Digital Transition[5], already attracting considerable investments under the Italian 2019 Budget Law[6] – is arousing specific attention, when it is not already providing answers.

Given Blockchain's ability to record and maintain information in an accessible, verifiable, non-repudiable and tamper-proof manner, this technology appears to provide a secure environment to improve product traceability and provenance throughout the extended supply-chain, which would particularly benefit the food industry and consumers.

1. Blockchain-based supply chain and benefits for SMEs and consumers.

In Italy, the Campania Region (among the first, but followed by many other Italian Regions), with Regional Law 2 March 2020, no. 3 – dedicated to the 'development and implementation of a system for traceability and tracking of the products of the agri-food and fishing supply chain in Campania through a

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[2] On the evolution of food law, from a hygienic-sanitary perspective to a more holistic approach, encompassing the protection not only of health but also of agricultural production, the ecosystem, consumers, and extending to food sustainability and food security, see, among others, M Ramajoli, 'Dalla «food safety» alla «food security» e ritorno', (2015) Amministrare, 2(3), 271-292, doi: 10.1442/80281

[3] The term "Blockchain 2.0" is used to denote the advancements and evolutions in the utilization of Blockchain technology. See, J Reed, *Blockchain: Blockchain. Smart Contracts. Investing in Ethereum. Fintech* (Createspace Independent Pub, 2016); P De Filippi, A Wright, *Blockchain and the Law* (Harvard University Press,2019), 27 ff.

[4] European Parliament Resolution of 3 October 2018 on distributed ledger technologies and blockchains: building trust with disintermediation (2017/2772(RSP)); European Parliament Resolution of 13 December 2018 on Blockchain: a forward-looking trade policy (2018/2085(INI)); European Parliament resolution of 20 October 2020 with recommendations to the Commission on a Digital Services Act: adapting commercial and civil law rules for commercial entities operating online (2020/2019(INL)). See also, EPRS, *Digital Services Act. European added value assessment* (October 2020) 84 ff.

[5] Cf. Decreto-legge 1° marzo 2021, n. 22 (GU Serie Generale n.51 del 01-03-2021).

[6] Many funding opportunities are covered precisely for projects on agri-food and fishing; cf. Legge 27 dicembre 2019, n. 160, Bilancio di previsione dello Stato per l'anno finanziario 2020 e bilancio pluriennale per il triennio 2020-2022 (GU Serie Generale n.304 del 30-12-2019 - Suppl. Ordinario n. 45).

blockchain data management system'[7] – has already equipped itself, precisely, with a normative tool prescribing the creation of such a system, in compliance with European obligations in terms of transparency of food supply-chains, and thus crowning the path started with the 'Circuito della filiera agricola trasparente', i.e., a series of measures that already aimed at the creation of an information system to protect the agri-food supply chain able to optimize the relationship between producer and end consumer and to ensure greater traceability and knowability of products[8].

The reason for this interest is that Blockchain, as – in broad terms – a secure and reliable system for the registration, sharing and management, in interoperable format, of non-repudiable information – by computer protocol – is well suited to serve as a potential unique register for information on the origin and processing and storage stages of food products (as well as other possibly connected information) and therefore lends itself to completely trace the origin and development of a product through the steps of highly complex supply chains, with many actors involved and often global ramifications.[9]

The benefits are evident. Blockchain, as a scalable and interoperable system, offers several advantages for the digitalization of the supply chain. It enables cost-effective digitalization with minimal hardware requirements, ensuring that it doesn't disrupt production or burden company management. Additionally, Blockchain has the potential to:

i) centralize and 'certify' product origin information, ensuring compliance with legal obligations;
ii) simplify controls by enhancing information security and accessibility (potentially replacing existing analytical control systems) resulting in a significant reduction in administrative costs;
iii) expose illegal or unethical market trading or activities;
iv) enhance transparency and consumer information, empowering consumers;
v) as a result, benefit the market and SMEs by fostering greater trust and competitiveness, particularly in sectors of excellence.

If the product is indeed traced in a reliable and transparent manner, it goes without saying that it is possible to favor and ensure access to information such as not only a certain and typified origin of food products, but also production techniques (perhaps more sustainable), production location, composition, specificity, and quality of the product. Therefore, bringing the consumer closer to the dynamics of production and guiding them towards more conscious and sustainable food choices.

It is indeed a primary objective under EU strategy for a fair, healthy, and environmentally friendly food system, to enable consumers to make informed,

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[7] The translation is ours.

[8] The 'Transparent Agricultural Supply Chain Circuit' (the translation is ours) is introduced by Campania Region under Reg. Law 20 November 2018, no. 40; cf. Legge Regionale 20 Novembre 2018, n. 40 (B.U.R.C. n. 86 del 21 novembre 2018)

[9] K Punnry and I P Nakorn, "A Framework of Blockchain Smart Contract for Sustainable Agri-Food Supply Chain, International Scientific Journal Of Engineering And Technology (2012) 5 (2),10-23; H Moudoud, S Cherkaoui and L Khoukhi, "An IoT Blockchain Architecture Using Oracles and Smart Contracts: the Use-Case of a Food Supply Chain", in 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), (Istanbul, Turkey, 2019) pp. 1-6, doi: 10.1109/PIMRC.2019.8904404.

healthy and sustainable food choices by providing clear, accessible and trustworthy information through digital means [10]. This pivotal approach highlights the EU's strong commitment to empowering consumers as proactive agents in the market and underpins its overarching goal of fostering a food-chain that has a neutral or positive environmental impact, driving a global transition towards competitive sustainability "from farm to fork".[11]

Furthermore, the significance of establishing a system that ensures the authenticity, accessibility, and interoperability of information from diverse sources is justified by its potential to effectively manage and capitalize on the vast and continually growing volume of data in the food industry, thereby bolstering risk assessments and safety measures. This data originates from various sources, encompassing surveillance, controls, and biomonitoring, with its volume expected to grow even more due to the increasing adoption of smart connected objects and automated services in food-chain governance [12]. Regrettably, a considerable portion of this valuable data remains underutilized primarily due to limited connectivity[13].

The ineffective exploitation of this data poses formidable challenges, particularly for institutions like the European Food Safety Authority (EFSA), which, as part of its strategy for 2027, aims to urgently explore and implement novel tools and methodologies for data management and analysis. [14] EFSA emphasizes the utmost importance of secure access to real-time data from monitoring systems within the food chain, as this would significantly augment their capacity to devise scenarios, refine risk assessments, and evaluate the impact of emerging risks or novel control approaches. The realization of these objectives can be further facilitated through the application of sophisticated artificial intelligence algorithms, encompassing predictive analysis. However, to accomplish these ambitions, the establishment of a robust infrastructure for the verified management of data is paramount; a role that Blockchain technology is well-suited to fulfill.[15]

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[10] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system, 20 May 2020, COM(2020)381 final, para 2.4., pag. 13

[11] The 'Farm to Fork Strategy' is at the heart of the European Green Deal and EU strategy to make Europe the first climate-neutral continent by 2050, recognizing the inextricable links between healthy people, healthy societies and a healthy planet. See, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, The European Green Deal, 11 December 2019, COM(2019) 640 final.

[12] According to EFSA strategy plan for 2027 the world is experiencing rapid growth in data production, with the volume expected to increase from 33 zettabytes in 2018 to approximately 175 zettabytes by 2025. There will also be significant changes in the storage and processing of data over the next five years. Currently, 80% of data processing and analysis occur in data centers and centralized computing facilities, while 20% takes place in smart connected objects. However, by 2025, these proportions are likely to be reversed. It is claimed that access to verified health data and real-time data from monitoring systems in the food chain would increase Agency's capacity to define scenarios, refine risk assessments or measure the impact of emerging risks or new control methods. See, European Food Safety Authority*, EFSA Strategy 2027* (June 2021) 9.

[13] Ibid.

[14] Ibid.

[15] Ibid.

2. The possible role for smart contracts and the integration of other technologies.

At the time of writing, in the aforementioned Campanian law, as well as in similar projects, it is evident that the primary focus is on blockchain as a reliable distributed ledger. There is little to no emphasis on smart contracts or other technologies, and the potential that could result from the combination of these tools is not explored.

To be precise, a programmatic reference to this combination can be found in one of the recitals of a Resolution of the Lombardy Regional Council dated 11 February 2020[16], which served as preparatory work for a regulatory solution similar to the one in Campania. This specific passage suggests the importance of considering "the combination and integration of Blockchain with other technologies, such as the Internet of Things and Artificial Intelligence" for improving "the reliability of the collected data[17]." Furthermore, it mentions the possibility of implementing smart contracts, particularly in the context of streamlining controls by utilizing these specific computer protocols to manage the movement of products along the supply chain and ensure the self-validation of relevant food information.

Blockchain, in fact, is not merely a public distributed ledger; it also offers the capability, through smart contracts, to automate various data collection and transfer operations, as well as functional data analysis, which can be entrusted to AI algorithms[18]. These applications are commonly referred to as precision agriculture systems. They serve the dual purpose of optimizing management, including cost reduction and yield improvement, while also analyzing and generating data that, when relevant, could be registered, shared, and securely validated on the blockchain[19]. As an illustrative example, consider systems responsible for overseeing mandatory hygienic-sanitary requirements, such as monitoring the cold chain of frozen products, potentially spanning the entire or a substantial part of the supply chain. The data generated in this context, which is frequently processed and stored within an IT environment, could be readily accessible at any stage of the supply chain in a blockchain-based system. They can be uniquely linked to individual products or batches through specially programmed smart contracts and securely recorded on the blockchain,

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[16] The Resolution was approved by Lombardy Regional Council with Delibera 11/02/2020, n. XI/995

[17] The translation is ours.

[18] T Schrepel, "Smart Contracts and the Digital Single Market Through the Lens of a 'Law + Technology' Approach," (European Commission, European Union, 2021) 27 ff., Available at: https://digital-strategy.ec.europa.eu/en/library/smart-contracts-and-digital-single-market-through-lens-law-plus-technology-approach; B Mo, et al., "A Solution for Internet of Things based on Blockchain Technology", in 2018 IEEE International Conference on Service Operations and Logistics, and Informatics - SOLI (2018) 112-117, Available at: https://ieeexplore.ieee.org/document/8476777; H Moudoud, S Cherkaoui and L Khoukhi, "An IoT Blockchain Architecture Using Oracles and Smart Contracts: the Use-Case of a Food Supply Chain", in 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), [Istanbul, Turkey, 2019] 1-6, doi: 10.1109/PIMRC.2019.8904404.

[19] Xiong Hang, Dalhaus Tobias, Wang Puqing, and Huang Jiajin, "Blockchain Technology for Agriculture: Applications and Rationale", (2020) 3 Frontiers in Blockchain, 2624-7852. Available at: https://www.frontiersin.org/articles/10.3389/fbloc.2020.00007 (Accessed 1 February 2023). DOI: 10.3389/fbloc.2020.00007; H Moudoud, S Cherkaoui and L Khoukhi, "An IoT Blockchain Architecture Using Oracles and Smart Contracts: the Use-Case of a Food Supply Chain," 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), (Istanbul, Turkey, 2019)1-6, doi: 10.1109/PIMRC.2019.8904404.

providing also the associated benefits of electronic timestamping[20].

Thanks to smart contracts programmed for this purpose, the process of tracking and recording this data could be fully automated. This would eliminate the need for intermediaries, reducing the risk of fraud and ensuring that the recorded information is accurate and up-to-date. Furthermore, the decentralized and tamper-proof nature of blockchains would ensure that the information cannot be altered, deleted, or manipulated, further increasing transparency and trust in the supply chain[21]. This would allow all parties involved to have a clear and verifiable record of the origin, quality, and safety of food products; and to controllers or consumers to have access to important product information. Smart contracts can in fact be programmed to provide on-demand real-time information and track food products during the various stages of production, storage, and transportation, up to final distribution.

The functionality of these smart contracts is ensured by the combination with AI systems, sensors and Internet of Things (IoT) technologies.[22] These tools can be integrated with smart contracts to automatically record and verify data such as the temperature and humidity of storage facilities, reducing the risk of food waste.[23]

Beyond its advantages for production, the reliability and certainty conferred by the immutable nature of blockchain records play a crucial role in strengthening and streamlining public control over food safety. Smart contracts would contribute significantly to reinforcing regulatory compliance within the food supply chain by automatically verifying and certifying that food products adhere to relevant standards and regulations. This not only enhances the safety of food products but also serves to prevents incidents of food fraud and contamination. Moreover, by aiding in the prevention of food loss and improving market transparency, as well as the reliability of information for consumers, this approach seamlessly aligns with the concept of an ethically sustainable food system[24]. This sectoral application of blockchain technology

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[20] The reference is to Italian Decree-Law No. 135 of 14 December 2018, Article 8ter, co 3 (cf. art. 8-ter, co3 decreto legge 135/2018) according to which (the English version is ours): "The storage of an electronic document through the use of technologies based on distributed registers shall produce the legal effects of electronic time stamping referred to in Article 41 of Regulation (EU) No 910/2014" In essence, the 'publication' in blockchain entails, thanks to a time-stamping server, the attribution to the data of certain and immutable date and time, with evidentiary value of legal presumption, even if not digitally signed.

[21] V Narayanan, et al., "Bitcoin and Cryptocurrency Technologies: A Comprehensive Introduction" (Princeton University Press, Princeton, NJ, 2016).

[22] T Schrepel, "Smart Contracts and the Digital Single Market Through the Lens of a 'Law + Technology' Approach" (European Commission, European Union, 2021) 27 ff., Available at: https://digital-strategy.ec.europa.eu/en/library/smart-contracts-and-digital-single-market-through-lens-law-plus-technology-approach. For an interesting use case related to product traceability, refer to: H Moudoud, S Cherkaoui and L Khoukhi., "An IoT Blockchain Architecture Using Oracles and Smart Contracts: the Use-Case of a Food Supply Chain," in 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications - PIMRC (2019) 1-6, doi: 10.1109/PIMRC.2019.8904404. Also available on Researchgate.net

[23] Besides being mere data carriers, oracles can also be programmed to evaluate, cross-reference, and analyze the data. In this case, decision-making algorithms, including Artificial Intelligence algorithms, are employed, integrated into customized software modules that process the information before transmitting it to the blockchain. B Mo et al., "A Solution for Internet of Things based on Blockchain Technology", in (proceedings) 2018 IEEE International Conference on Service Operations and Logistics, and Informatics - SOLI (2018) 112-117. Available at: https://ieeexplore.ieee.org/document/8476777

[24] Ensuring safety, reducing food loss and waste and empower consumers to facilitate the shift to sustainable and healthy food practices are indeed at the core of the EU 'farm to fork' strategy "to reconcile

so emerges as a pivotal method in achieving the sustainability goals outlined in the EU Green Deal, contributing to the broader evolution of food law in the pursuit of sustainability.

3. From food safety to food-chain sustainability.

Sustainability, understood as forming the foundation (and aim) for the agri-food supply-chain governance facilitated by blockchain, aligns with the evolving landscape of food law.

In the introduction, we highlighted that food law has been evolved around the concept of food safety (as in healthy for human individuals), while now tends to shift from that primary focus to a broader consideration of food (system) sustainability.

Environmental considerations have actually already been acknowledged, though somewhat secondary, in the general objectives of Regulation (EC) No. 178/2002. While its primary focus is ensuring a high level of protection for human health and consumers' interests in food[25], it also recognizes the need to consider the protection of animal health and welfare, plant health, and the environment, "where appropriate"[26]. The EU Green Deal, aligning with the Commission's agenda to achieve the UN's Sustainable Development Goals, now further recognizes as inextricable the links between healthy people, healthy societies and a healthy planet[27].

Sustainability, encompassing both food safety and the internationally recognized concept of food security[28], extends to ensuring access to adequate and high-quality food for citizens. This calls for robust and resilient food system that, in addition, prioritizes and promotes healthy, nutritious, and sustainably sourced food, bringing environmental, health, and social benefits[29]. It also embraces innovation in production, logistics optimization, and raw material

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our food system with the needs of the planet and to respond positively to Europeans' aspirations for healthy, equitable and environmentally-friendly food"; cf. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system, 20 May 2020, COM(2020)381 final.

[25] Cf. Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety.

[26] Cf. Article 5, Regulation (EC) No 178/2002

[27] Cf. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system, 20 May 2020, COM(2020)381 final, p. 2

[28] Food security is internationally derived from organizations such as FAO and WHO and refers to the fundamental human right of access to food in sufficient quantities and quality for a dignified existence. Among others, see E Clay, "Food security: concepts and measurement. trade reforms and food security: conceptualizing the linkages" (Rome, UN Food and Agriculture Organization, 2002) 25-34

[29] Cf. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system, 20 May 2020, COM(2020)381 final. Among the measures for promoting sustainable food consumption, incentives such as tax benefits and measures that enhance consumer information are being studied in Europe. For example, a revision of nutritional labeling rules is under consideration: see the EU steps for a Proposal for a revision of the Regulation on Food Information to Consumers (FIC), online at: https://food.ec.europa.eu/safety/labelling-and-nutrition/food-information-consumers-legislation/proposal-revision-regulation-fic_en

management, all geared towards waste reduction, both economically and environmentally[30].

This perspective embodies a "green" and ethically sustainable supply chain, intricately woven into the ongoing digitalization of agri-food supply chains. Notably, blockchain technology emerges as a preferred means of digitalization.

The Italy's National Recovery and Resilience Plan (PNRR) substantiates this commitment by allocating significant funding, indicating a strategic move towards sustainability, particularly within the agri-food sector.[31]

However, the link between blockchain and sustainability is not new and can be traced back to the Law Decree of May 19, 2020, No. 34. Formulated as an urgent response to economic challenges exacerbated by the Covid-19 pandemic, this decree introduced modifications to the 2019 Italian Budget law, allocating non-repayable grants to agricultural and fishing enterprises. The objective, as outlined in Article 222, centers on enhancing economic, social, and environmental sustainability within agri-food supply chains. It emphasizes leveraging innovative technologies, such as blockchain, to foster integration and equitable value distribution across the supply chain[32].

This substantiates the growing acknowledgment of blockchain and smart contracts as integral tools in advancing sustainability goals within the agri-food sector.

3.1. 'See-through' supply chains: a possible key driver for sustainability.

In the face of growing pressures from regulations, reputation concerns, investor expectations, and consumer demands,[33] businesses are increasingly

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[30] Special attention is devoted to promoting the use of renewable energy resources and fostering new green business models, both through funding measures and policies, such as carbon farming. To boost the land sector's role in achieving a climate-neutral economy, the European Commission introduced the Sustainable Carbon Cycles Communication in December 2021, aligning with the Farm to Fork Strategy (cf. p. 5).This initiative aims to incentivize climate-friendly practices, addressing challenges in carbon farming. Key actions include promoting practices in Common Agricultural Policy (CAP) and other EU programs, standardizing monitoring methodologies, and providing knowledge to land managers. Effective practices involve afforestation, agroforestry, conservation tillage, and peatland restoration. The Commission integrates carbon farming in CAP Strategic Plans and plans a legislative proposal in 2022 for a regulatory framework certifying carbon removals.

[31] The Italy's National Recovery and Resilience Plan (PNRR) – at the time of writing – indeed allocates 800 million euros for the development of logistics in the agri-food, fishing, and aquaculture sectors, foreseeing investments in the development of infrastructure adopting innovative solutions, including blockchain. Approximately 500 million euros, instead, for the development and adoption of precision agriculture systems; see the measures on the official portal of the Ministry of Agricultural Policies online at: https://www.politicheagricole.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/17910. For the continuous monitoring of the statistical impact of the PNRR measures on the Sustainable Development Goals of the UN 2030 Agenda by the Italian Institute of Statistics (ISTAT), online at: https://www.italiadomani.gov.it/content/sogei-ng/it/it/strumenti/il-contributo-del-pnrr-all-attuazione-dell-agenda-2030.html

[32] The Article 222 of the Law Decree of May 19, 2020, No. 34 (titled "Provisions in support of agricultural, fishing, and aquaculture supply chains"), amending Article 1, clause 520 of the Law No. 145 of December 30, 2018 (i.e., Italian 2019 Budget Law), non-repayable grants to agricultural and fishing enterprises for funding initiatives focused, among other objectives, on developing innovative production processes and product traceability using blockchain technologies. The provision emphasizes that these initiatives aim to "enhance the level of economic, social, and environmental sustainability of agri-food supply chains, fostering increased integration and a more equitable distribution of value along the supply chain through the utilization of emerging technologies." (The translation is ours and is done literally).

[33] Examples are the EU Taxonomy framework (operating under Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020), that establishes standardized criteria for classifying an

focused on addressing risks within their supply chains. These risks encompass a variety of issues, all falling under a broad concept of sustainability concerns, spanning from unfair competition and human rights violations to environmental degradation and gender inequality[34]. Many companies have responded by making ambitious public commitments, including promises to use renewable energy, combat deforestation, ensure the use of minerals and raw materials without human rights violations, or prioritize the use of recycled materials.

However, the complexity and opacity of global supply chains make it challenging for companies to implement and showcase these commitments effectively.[35] Provenance, traceability, and transparency of data throughout supply chains are not only crucial for fulfilling these commitments but also for enhancing overall business management. This includes improving risk management, facilitating corporate disclosure and reporting[36], and more.

Blockchain-based solutions can provide a ground-breaking level of transparency and traceability in supply chains. These solutions have the potential to instil trust in legitimate operations, expose unethical activities, enhance monitoring and reporting, and thereby promote sustainability while addressing quality and safety concerns. As these solutions become more widely adopted, they are likely to compel companies to be more accountable for their actions and demonstrate responsible and ethical practices efficiently. Additionally, access to transparent, secure, and verified blockchain data will empower investors to implement responsible investment practices more effectively,[37] while allowing consumers to steer the food market toward a greener future through their choices.

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economic activity as environmentally sustainable within the EU's sustainable finance framework; the Non-Financial Reporting Directive -NFRD (Directive 2014/95/EU of the European Parliament and of the Council of 22 October 2014) and the following Corporate Sustainability Reporting Directive-CSRD (Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022), that mandates that large companies and listed SMEs, excluding micro-enterprises, must disclose, in a standardized form, data regarding their perceptions of social and environmental risks and opportunities, as well as the impact of their operations on people and the environment, with the objective to provide investors and stakeholders with essential information for assessing corporate impacts on society and the environment; Green Public Procurement (GPP) Criteria: either voluntary or, in specific sectors, legally mandatory requirements guiding public authorities in the procurement of goods, services, and works with reduced environmental impact throughout their life cycle; the EU eco-label framework and the 'Green claims' directive proposal (COM(2023) 166 final) that, if approved, will enforce the substantiation of green claims in consumer-oriented commercial practices by introducing various requirements, including life-cycle assessments, and set forth rules for communicating these claims and regulations for environmental labeling schemes.

[34] Resolution of the General Assembly of the United Nations of 25 September 2015, Transforming our world: the 2030 Agenda for Sustainable Development, United Nations, General Assembly, A/RES/70/1, online: https://sdgs.un.org/2030agenda

[35] World Economic Forum, "Building Block(chain)s for a Better Planet", Fourth Industrial Revolution for the Earth Series (September 2018). Available at: https://www3.weforum.org/docs/WEF_Building-Blockchains.pdf

[36] This could have significant implications for corporate social responsibility governance. For instance, the involvement of blockchain applications may aid in implementation, but it is essential to ensure coordination with the EU's transparency and reporting requirements under the Non-Financial Reporting Directive (NFRD, Directive 2014/95/EU) and the subsequent Corporate Sustainability Reporting Directive (CSRD, Directive (EU) 2022/2464), where applicable. Additionally, alignment with potential future measures related to green claims in consumer-oriented commercial communication, as proposed in the Green Claims Directive (cf. COM(2023) 166 final), is crucial.

[37] Consider, for instance, the 'Green Asset Wallet 'project, the world's first blockchain-based platform for easy validation and impact reporting of green bonds; see, https://thefintechtimes.com/green-assets-wallet-transforming-the-green-finance-with-blockchain/

In this context, blockchain-based solutions for supply-chain management could represent some of the most valuable applications in addressing environmental, and sustainability challenges as a whole. Their adoption could indeed lead also to additional benefits beyond transparency enhancement and reliable sustainability reporting and verification.

The traceability ensured by blockchain, in addition to encompassing the product, its ingredients or derivatives, as well as the origin of other production factors (e.g., energy from renewable sources), could also extend to production waste materials or packaging. This could facilitate comprehensive monitoring of the production impact throughout the entire product life cycle. However, the potential of all this extends beyond merely inducing positive behavior changes through informed market choices (i.e., transparency leverage). It can also implement direct incentive mechanisms for companies to design and produce products in ways that make it easier and, more importantly, convenient to manage the product life cycle sustainably. For example, blockchain platforms could provide financial rewards for certain sustainable business practices, disbursed in cryptocurrency, and automatically verified through specific smart contracts and the use of intelligent sensors. [38] Furthermore, these systems could be used by businesses themselves – in the agri-food sector and more broadly – to reward commendable consumer behavior. For instance, in exchange for the return of recyclable plastic containers or other packaging, customers could be granted cryptographic tokens for use in purchasing products from the same company. This would incentivize positive and circular practices, resulting in economic returns and improved reputation for the company, and ultimately benefiting the environment[39].

Therefore, in addition to enhancing waste disposal monitoring, blockchain can also facilitate more efficient waste management systems, thereby incentivizing the transition to a circular economy. Mechanisms governed by smart contracts and distributed ledgers could integrate and redesign the traditional systems that implement the Extended Producer Responsibility (EPR) principle to promote, for example, the recycling of used packaging[40].

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[38] Consider, for instance, the case of 'Plastic Bank', a blockchain-based app aiming at rewarding the collection of ocean-bound plastic; see, https://plasticbank.com/about.

[39] A project similar to the Recycle-to-Coin initiative, a decentralized blockchain-based mobile app aimed at incentivizing waste recycling; see https://positiveblockchain.io/database/recycle-to-coin.

[40] The principle of Extended Responsibility of the Producer to the end of life of its products (EPR), originally inspired by the concept developed by the Organisation of Economic Co-operation and Development – OECD, is defined as "an environmental policy approach in which a producer's responsibility, physical and/or financial, for a product is extended to the post-consumer stage of a product's life-cycle" [see, OECD (2001), Extended Producer Responsibility: A Guidance Manual for Governments, OECD Publishing, Paris, https://doi.org/10.1787/9789264189867-en., p. 18] and imply that a producer is deemed liable for such a final phase, so that an implicit signal is sent to the producer to alter the design of his products so as to reduce the environmental impact in question. It is an economic instrument aimed to incentivize circular economy.

In the European Union this principle has been enacted through various directives addressing packaging and packaging waste with the aim of promoting sustainable management. Directive No. 94/62/EC, issued on December 20, 1994, mandated a financial contribution from packaging producers, encouraging them to manage waste across the entire product life cycle. Subsequently, Directive No. 2004/12/EC, dated February 11, 2004, established new national recycling targets for packaging. In 2018, Directive No. 2018/852 introduced additional provisions for packaging, reinforcing the Extended Producer Responsibility (EPR) principle and promoting sustainable design. The application of these directives has exhibited variations

Indeed, smart contracts offer the potential to significantly enhance transparency, scalability, and operational efficiency within these processes[41]. For instance, if properly designed, they could help distribute the environmental costs of waste collection and recycling more equitably throughout the supply chain, thereby reducing the economic impact of EPR. Furthermore, they could encourage environmentally responsible practices, for example, by (automatically) imposing reduced fees for businesses adopting (blockchain-verified) reusable or recycled packaging materials[42].

The 'blockchainization' of the supply chain, hence, opens the door to numerous related applications. As a final example, the collected and verified data on production practices could serve as the basis for, or to corroborate potential cryptographic certification of carbon farming practices. Dedicated blockchain platforms can be utilized to exchange cryptographic tokens with tradable value, thus optimizing existing carbon credit management platforms and creating new opportunities for carbon credit transactions. [43] Managing carbon markets on the blockchain has the potential to enhance platform efficiency and eliminate constraints to broader adoption of this market-based instrument for fostering sustainable agriculture and production.[44]

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among European Union Member States. These differences encompass governance structures, the categories of regulated packaging, contributory methods, and associated fees. More recently, Extended Producer Responsibility (EPR) systems have expanded to cover sectors beyond packaging, including electronic products and other areas such as tires, batteries, vehicles, pharmaceuticals, and chemicals. For instance, Directive No. 2006/66/EC of the European Parliament and the Council on September 6, 2006, establishes that battery manufacturers are financially responsible for end-of-life battery management. Similarly, Directive No. 2000/53 of September 18, 2000, concerning end-of-life vehicles (also known as ELV Directive), places responsibility on manufacturers to prevent and reduce waste generation when vehicles are dismissed.

[41] About this, see World Economic Forum, “Building Block(chain)s for a Better Planet”, Fourth Industrial Revolution for the Earth Series (September 2018) 18.

[42] In November 2020, the European Commission presented a Proposal for a EU Regulation Proposal on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC (COM/2022/677 final) with the aim of increasing sustainable packaging production in Europe and reducing the environmental impact of waste, especially plastics. The proposal includes the establishment of binding targets for the collection, recycling, and recovery of packaging to achieve a recycling rate of 70% by 2030. Additionally, various measures are introduced to promote eco-design of packaging, such as minimum recyclability requirements, incentives for the use of recycled materials in production, and a shift towards more reusable packaging as opposed to single-use packaging.
The system proposed here, involving blockchain application, aligns with the guiding principles of the proposed Regulation and will naturally need to consider and coordinate with the new measures once they are adopted.

[43] Among others, see A Sipthorpe, S Brink, T Van Leeuwen, I Staffell, “Blockchain solutions for carbon markets are nearing maturity, (2022) 5 (7) One Earth, 779-791, ISSN 2590-3322, https://doi.org/10.1016/j.oneear.2022.06.004; see also, Y Pan, et al. “Application of Blockchain in Carbon Trading” (2019) 158, Energy Procedia, 4286-4291,ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2019.01.509.

[44] The Kyoto Protocol (under Article 17) introduced a groundbreaking approach to address greenhouse gas emissions, transforming them into a tradable commodity – emission reductions or removals – commonly referred to as carbon (considering carbon dioxide's predominant role) within the "carbon market. Cf. https://unfccc.int/process/the-kyoto-protocol/mechanisms/emissions-trading
Emissions trading schemes may be established as climate policy instruments at the national level and the regional level. Under such schemes, governments set emissions obligations to be reached by the participating entities. The European Union Emissions Trading System is the largest scheme in operation and a cornerstone of the EU's policy to combat climate change (see https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en). In alignment with the Farm to Fork Strategy (cf. p. 5), the European Commission launched the Sustainable Carbon Cycles Communication in December 2021 to enhance the land sector's role in achieving a climate-neutral economy. This initiative incentivizes climate-friendly practices, with a focus on carbon farming challenges. The approach includes promoting practices through the

4. Technology constraints. Legal and regulatory challenges.

Despite being an extremely promising technology and the rapid proliferation of blockchain-based supply chain use cases, which are gaining support in both academic literature and practical applications, several technical challenges and legal uncertainties are associated with blockchain. Successfully addressing these challenges on both fronts could significantly influence its adoption for supply chain governance in the coming years.

For instance, the decentralized architecture of the blockchain network requires transactions to be verified through a distributed consensus mechanism. In the case of the most common Proof of Work (PoW) blockchains, this necessitates each network participant to solve a computationally challenging problem, the difficulty of which increases with the number of active nodes on the network and, simplifying, its extension. This is justified in terms of securing the chain against possible tampering or alterations by malignant hacking.[45] However, this poses several issues: processing time increases exponentially with the growing number of transactions; while greater computational work means enhanced security, the inability to process blocks quickly could become problematic when envisioning large, if not global, blockchain-based supply chains, presenting scalability limitations.

Moreover, as transactions and blocks accumulate, the Blockchain's size expands, and as adoption spreads, the growth of blockchain size becomes exponential, making large blockchains increasingly impractical for everyday users. This necessitates the incorporation of technical and user-friendly solutions to ensure that the chain remains practical.

Lastly, but not least, there is the issue of high energy consumption. Since the Proof-of-Work consensus mechanism is designed to be resource-intensive, some of the larger PoW blockchains consume an excessive amount of power to maintain, raising concerns about the environmental impact of blockchain technology. The Proof-of-Work consensus mechanism, while contributing to cybersecurity, consumes a substantial amount of power, resulting in a significant carbon footprint. Consequently, addressing the environmental sustainability of blockchain technology is a critical concern that must be considered in its ongoing development and adoption.

In conjunction with this, the scalability issue must be addressed; otherwise, the use of the system will remain constrained. To enable scalability, blockchain protocols are likely to require the development of consensus mechanisms that limit the number of nodes and the time necessary to validate each transaction without compromising the network's trust and security.

In fact, in this context, Proof-of-Work (PoW) is not the sole consensus

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Common Agricultural Policy (CAP) and other EU programs, standardizing monitoring methodologies, and providing knowledge to land managers. Noteworthy practices encompass afforestation, agroforestry, conservation tillage, and peatland restoration. The Commission plans to integrate carbon farming into CAP Strategic Plans and intends to propose a legislative framework for certifying carbon removals (see https://climate.ec.europa.eu/eu-action/sustainable-carbon-cycles/carbon-farming_en).

[45] Among others, P De Filippi, A Wright, "Blockchain and the Law" (Harvard University Press, 2019); A Narayanan et al "Bitcoin and cryptocurrency technologies: a comprehensive introduction" (Princeton University Press, 2016); H Natarajan et al., "Distributed Ledger Technology and Blockchain", FinTech Note, (2017) http://hdl.handle.net/10986/29053.

mechanism capable of sustaining a blockchain. An alternative system is known as Proof-of-Stake (PoS). Instead of relying on computational power, PoS-based systems establish their security on the ‘self-interest’ (i.e., the stake) of their users. The participants do not compete to solve complex mathematical problems for a 'reward'; rather, the nodes responsible for validating transactions are selected based on the amount of native cryptocurrency they stake. These validators, referred to as 'forgers,' risk losing both their collateral deposits and their reputation if they are ‘caught’ attempting to create fraudulent blocks. A tarnished reputation reduces their chances of being selected to validate the next block, while a higher collateral deposit increases their odds and compensation for their work[46]. This system, relying on crypto-economic incentives, consumes less energy, reduces e-waste, and is more accessible, requiring less specialized hardware and fewer device replacements. For these reasons, it is a consensus mechanism that has been widely proposed and implemented to improve blockchain scalability while addressing energy efficiency and sustainability issues. Nevertheless, according to some scholars, PoS may not meet the same security standards as Proof-of-Work, as the risk of capital loss may not be as effective a deterrent as the high (understood as unbearable) costs associated with a 51% Attack in PoW-based systems[47].

Recently, however, growing environmental concerns have prompted the most widely used blockchain platform for smart contracts, Ethereum, to definitively transition to a PoS-based validation system following a hybrid transitional phase that concluded in 2022. The change has reportedly reduced the network's energy consumption by over 90%[48]. Moreover, the specific system adopted, though it is too early to draw conclusions, may effectively address the doubts raised so far regarding PoS security[49] and push toward an

[46] A variation of PoS, known as Delegated Proof of Stake (DPoS) - first implemented on Bitshares by developer Daniel Larimer - or more commonly referred to as Proof of Authority (PoA), involves the verification and validation of transactions being entrusted to a limited number of 'delegates' elected by network users through weighted voting based on their virtual currency holdings. Since there is a potential for earning block formation fees, the system relies on the assumption that the 'delegates' have a vested interest in acting with integrity and punctuality to secure re-election through the vote.

[47] See, Proof of Stake versus Proof of Work: White Paper, BitFury Group, online: https://bitfury.com/content/downloads/pos-vs-pow-1.0.2.pdf

[48] See A De Vries, “Cryptocurrencies on the road to sustainability: Ethereum paving the way for Bitcoin” (2023)4(1) Perspective, DOI: https://doi.org/10.1016/j.patter.2022.100633

[49] The peculiarity of this protocol lies in the fact that the aforementioned security concerns seem to have been circumvented through the provision of a pool of 'validators' tasked with verifying and validating transactions. These validators are freely nominated among users, but to assume this role (and be rewarded), they are required to deposit a certain amount of ether (32 ETH). This deposit is transferred to a dedicated smart contract, which serves as leverage to ensure the proper formation of blocks. Once activated, validators are randomly assigned new transaction blocks to 'create' (the validator responsible for 'creating' the block is referred to as the proposer) and then send to a committee composed of other validators, whose task is to verify and confirm them. The block is finally 'finalized' if it is confirmed by 2/3 of the validators. In the affirmative case, the first validator is rewarded with ether, effectively 'recovering' an increased capital; in the negative case, the validator loses their investment. In addition to this disincentive system, there are also penalties in case of validator inactivity. When the network functions optimally, there is always and only a new block at the 'head' of the chain, and all validators attest to it. However, it is possible that validators have a different view of the chain's head block due to network latency, or that the block proposer makes an error (or that a malicious attack attempts to 'mine' a false block). In these cases, the blockchain forks, and a specific algorithm (called LMD-GHOST) identifies the chain to 'prefer' (the other is abandoned) in the fork that has the greatest number of validated blocks. For further details, refer to: Proof of Stake, ethereum.org, https://ethereum.org/en/developers/docs/consensus-mechanisms/pos/#validators.

evolution of blockchain in terms of scalability and efficiency, including management expenses and environmental costs.[50]

The technological barriers do not end here. One of the key features of blockchain is its perceived resistance to breaches due to its encryption and the distributed nature of the ledger, which also makes the data stored in the blocks subsequently unalterable. However, like all computer systems, blockchain is susceptible to cybersecurity risks. The security of blockchain data is fundamentally robust as it requires the precise combination of public and private keys for access. While this generally ensures a high level of security, it can also be a vulnerability. If someone gains access to the private key, they can unlock the data, potentially leading to unauthorized access or disclosure. Consequently, individual users bear the responsibility for safeguarding these keys, which can be a challenging requirement for those unfamiliar with blockchain technology.

Moreover, blockchain ledgers, by design, generally share all data with all participants (i.e., each node maintains an exact and updated copy of the chain). This raises even more concerns regarding privacy and confidentiality of data: supply-chain companies may be unwilling or unable to disclose certain data, either due to legal constraints (e.g., data protection obligations, contractual restrictions) or competitive reasons (e.g., industrial/commercial secrecy). While encryption and appropriate blockchain protocol design can facilitate secure data management, limiting access to specific data (e.g., only in the case of a public authority audit), decentralization, a fundamental characteristic of blockchain, could be a limitation if not effectively addressed: blockchain could revolutionize products safety controls, but being forced to disclose their network of suppliers or significant manufacturing data may deter many companies from fully embracing blockchain-based supply chain solutions.

Furthermore, there are legal aspects to consider. Blockchain records are immutable, meaning once data is stored, it is generally unalterable or deletable. This has significant implications, especially concerning personal data. Public blockchain systems, in particular, pose substantial challenges in balancing individual data protection rights with the concept of an open network. The immutability of the distributed ledger inherently conflicts with the "right to be forgotten" and the right to rectification of personal data and can virtually make it impossible for businesses (i.e., data controllers) to control where data is transferred and who has access to it on public networks. This may conflict with data governance principles[51]. The use of private or consortium blockchains, which offer diversified governance rights among users, may provide a solution. Nevertheless, it remains a delicate task to strike a balance,

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The threat of a 51% attack still exists on Proof-of-Stake, as it does on Proof-of-Work, but it is even riskier for attackers. They would need 51% of the staked ETH to control the majority of validators and manipulate consensus (forking the chain and attempting to 'divert' the network). Therefore, a significant economic barrier remains against a 51% attack.

[50] As said, this system does not require nodes with powerful CPUs and frequent replacements, as is typically the case with PoW systems, reducing both financial and environmental burdens, particularly related to energy consumption and carbon footprint.

[51] Cf. especially Article 5 and article 25(2) Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation).

even in network infrastructure and protocol design, between the legitimate public interest in supply chain transparency and the limits imposed by the lawfulness and security parameters for personal data processing required by the GDPR (or other applicable regulations), as well as the framework for protection of trade secret and competition. GDPR compliance and adequate balance between transparency and protecting business interests needs to be ensured. These issues will need to be carefully considered also within the framework of the European data strategy, which aims to create a more data-driven European economy while ensuring the protection of individuals' data rights and fostering innovation.[52]

Finally, given the extensive reach of agri-food supply chains, there emerges a potential additional challenge of interoperability. Successful integration of various blockchains with each other and with other IT systems is crucial. Specific and universally accepted standards for blockchain in supply chain applications are yet to be established due to its early development stages. As standards are developed within individual chains or local systems, interoperability between platforms and other systems remains extremely limited. This could pose a significant operational challenge that may incur substantial costs. Stakeholders will be required to develop appropriate data models and business processes that can accommodate different authentication and communication protocols. Consequently, considering the intricate nature of global supply chains, the integration of blockchain-based traceability applications with existing management systems might become costly and intricate[53].

Initiatives aimed at encouraging standardization and certification policies could aid in addressing these issues[54], fostering trust in this sector-specific implementation of blockchain technology and facilitating its spread adoption.

In addition to addressing the technical limitations of blockchain, it is also necessary to establish a suitable and uniform legal and regulatory framework for blockchain operating at the European and global levels. In the current state of general uncertainty, legal frameworks are currently defined by each State, lacking real legislative uniformity. Despite significant scholarly advances, blockchain logs, timestamps and smart contracts still lack a clear legal qualification, leaving doubts about their validity, enforceability, or legal effects. For example, assigning responsibility for blockchain technology could be a complex matter. Identifying the accountable party can be challenging and is contingent on various factors, including the specific use case, the entity managing the blockchain, and its operational characteristics. Moreover, the available legal remedies can differ significantly across various jurisdictions, and achieving clarity regarding the court having jurisdiction for a particular

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[52] See the EU data strategy for the digital age, here: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-data-strategy_en. The first regulatory proposals implementing the strategy are the Proposal for a Regulation of the European Parliament and of the Council on European data governance, COM/2020/767 final (Data Governance Act), recently complemented by a Proposal for a Regulation of the European Parliament and of the Council on harmonised rules on fair access to and use of data, COM/2022/68 final (Data Act).

[53] Cf. World Economic Forum, "Building Block(chain)s for a Better Planet", Fourth Industrial Revolution for the Earth Series (September 2018) 24.

[54] E.g., for data protection, consider certification under Article 42 of the GDPR; which could serve as an example of a policy applicable to other relevant domains.

blockchain transaction or the applicable substantive law is especially problematic in the context of decentralized and distributed blockchain systems.[55] This ambiguity not only undermines trust but also introduces the potential for intricate and overlapping regulatory and compliance requirements, which can be burdensome for companies implementing blockchain solutions[56].

For an effective transition to blockchain technology in supply chain governance, these challenges demand resolution. Specifically, the existing legal framework concerning the validity and formation of contracts in digital environment must evolve, leaving no room for ambiguity regarding the circumstances under which a smart contract (i.e., an on-chain automated transaction) can be considered a legally valid and enforceable contract.

5. Smart contract and on-chain automated transactions: contract law knots (to untangle).

In a digitized supply chain already based on blockchain for traceability, smart contracts – computer protocols enabling the automatic execution of pre-programmed operations between parties – play a new and significant role. Specifically, they mechanize a series of commercial operations that are normally standardized among established partners in the supply chain, who frequently exchange goods and services.

Currently, large entities already implement software systems for managing their trade relationships. Within these business-to-business (B2B) relationships, for example, the use of a tool called Electronic Data Interchange (EDI) is widespread. EDI is a computer-to-computer communication system for standardized commercial transactions. It essentially allows the sharing of a series of commercial documents – such as purchase orders, invoices, and delivery notes – in a standard format through a dedicated and encrypted channel. The recipient's computer receives the order and automatically processes the operation as specified. This electronic format replaces the need for paper documents, simplifying and automating the related procedures, saving time and costs, and minimizing errors. Smart contracts could potentially automate these same operations with several advantages:

- Automatic registration, validation, and preservation of significant goods and services exchange operations in terms of traceability (e.g., supplies of animal feed for livestock) without any duplicate management, and ensuring transparent and reliable record on a blockchain;
- More efficiency and cost reduction. While EDI or similar systems are limited to transmitting messages with static content, merely reproducing traditional terms and trade operations, smart contracts offer more potential. They can

[55] Among others, see T Cutts, 'Smart contracts and Consumers' (2019) 122 (2), online in SSRN:https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3354272; B Cappiello, 'Dallo smart contract computer code allo smart (legal) contract. I nuovi strumenti (para) giuridici alla luce della normativa nazionale e del diritto internazionale privato europeo: prospettive de jure condendo' (2020) 2 Diritto del Commercio Internazionale, 477

[56] Cf. World Economic Forum, "Building Block(chain)s for a Better Planet", Fourth Industrial Revolution for the Earth Series (September 2018) 23.

accommodate more complex and efficient operations; ensure automated execution; potentially avoid or internalize litigation. Furthermore, they can integrate AI systems, sensors, and robotic actuators, enabling a much higher degree of automation, including decision-making levels.

For instance, the systems could involve automatic payment upon verification of the actual delivery of goods and their condition, warehouse management systems capable of automatic negotiation based on needs/costs to avoid excess inventory and food waste, and so on.

It is important to clarify that smart contracts are, broadly speaking, software; encoded instructions designed to automatically execute programmed operations between parties, without the need for human intervention. These operations are expressed in program code and are automatically executed on blockchain when predefined conditions occur (self-executing). For example, the transfer of a certain amount of cryptocurrency upon the delivery of a batch of goods.

Smart contracts can be configured to automate the execution of contract clauses – an on-chain transaction – by expressing the terms of the agreement in a programming language. In other words, reducing the clauses to a series of code instructions that follow the causal schema "if x, then y", so that the protocol (i.e., the smart contract) is programmed to produce the intended effect or perform the specific task required by the contract (y) – e.g. the payment – when the presupposed condition (x) occurs – e.g., the delivery, automatically verified through sensors –[57]. Not all programmed operations that a smart contract can perform constitute the execution of contractual clauses or any legally relevant acts under contract law. Consequently, it is not automatically guaranteed that these protocols correspond to enforceable contracts; they may well be programs executing practical operations within a computer network (e.g., recording the temperature of a batch) rather than holding legal (i.e., negotiating) significance, such as a purchase order, or serving a contract performative function (e.g., a payment) under contract law. In literature, it is common to distinguish between smart legal contracts and smart contract code[58].

[57]The code is deployed on a distributed ledger technology (i.e., a DLT), such as the blockchain, which ensures a 'record' of the 'terms' of the smart contract and its execution, in a (principally) immutable manner.

[58] Referring – the latter – more generally, to those computer programs operating on DLT, designed to automatically execute if-then programmed operations upon the occurrence of predefined trigger events, capable of reading and writing information on distributed and synchronized registers in the network; in contrast, smart legal contracts would be the (only) ones to exhibit the semblance of a potentially legally binding agreement.

This distinction is emphasized, albeit more clearly, for example, in J Stark *Making sense of blockchain smart contracts* (CoinDesk, 2016), online: https://www.coindesk.com/markets/2016/06/04/making-sense-of-blockchain-smart-contracts/; R H Casper et al., 'Smart supply chains using smart contracts' (2022) 18, National Law Review, online: https://www.natlawreview.com/article/smart-supply-chains-using-smart-contracts, where smart legal contracts are considered contracts in every respect. In Italy, S Orlando, 'Gli smart contracts come prodotti software', Gli smart contracts come prodotti software, in S Orlando, G Capaldo (eds) *Annuario 2021 Osservatorio Giuridico sulla Innovazione Digitale* (Sapienza University Press, 2021) 235 ss, part. 235-238, distinguishes two different legal concepts of smart contracts: as a "computer program used exclusively to legally implement, in whole or in part, a contract" and as a "computer program used also to express, in whole or in part, the content of the contract that is automatically executed." According to UK Law Com. No. 401, *Smart legal contracts. Advice to Government* (November 2021) online: https://www.gov.uk/search/all, p. 11, smart legal contracts are "legally binding contracts in which some or all of the contractual obligations are defined in and/or performed automatically by a computer program."

Despite extensive studies and advanced academic debates, the existing legal framework regarding the validity and formation of contracts in the digital environment remains unclear. While there is a consensus that, under certain conditions, 'smart' agreements qualify as contracts in every respect [59], ambiguity persists regarding the circumstances defining when a smart contract (and consequently, an on-chain automated transaction) can be deemed legally valid and enforceable under contract law [60].

This ambiguity risks limiting the adoption of blockchain-based supply chains. It is evident that only the clear legal recognition of automated transactions among supply chain actors allows the combination of the advantages of traceability – reliably and transparently ensured on the blockchain – without relying on human intermediaries but solely on computer design. This includes the certainty of exchanges, along with the additional benefits of smart contracting, which refers to the automated execution of contractual terms through computer programming. The automation (and certainty) of contract performance on a transparent distributed ledger, reducing reliance on parties' discretion and mitigating contractual risk, would ensure greater efficiency, lower the risk of non-execution or breach, reduce transaction costs, minimize litigation (even possibly facilitated by transparency), and favor by-design compliance with product traceability requirements without duplicating tasks.

The Italian legislator's decision to define the smart contract by law, in contrast to the 'wait-and-see' approach adopted at the European level[61] and

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These are defined by the simple element of having their execution automated by programs operating on DLT, even if the legally binding contract's content has been formed exclusively in natural language and outside the blockchain. It is specified (p.22) that a smart legal contract also includes "a natural language contract in which some or all of the contractual obligations are performed automatically by the code of a computer program. The code itself does not define any contractual obligations but is merely a tool employed by one or both of the parties to perform those obligations. This type of smart legal contract can also be referred to as an 'external' contract, as the code falls outside the scope of the parties' legally binding agreement."

[59] Among others, J Stark, *Making sense of blockchain smart contracts* (CoinDesk, 2016); K D Werbach, N Cornell, 'Contracts ex machina', (2017) 67 Duke Law Journal, 345; M Maugeri, *Smart Contracts e disciplina dei contratti. Smart Contracts and Contract Law* (Bologna, 2021); M Corrales, M.Fenwick, H Haapio (eds) *Legal Tech, Smart Contracts and Blockchain* (Singapore, 2019); C Bomprezzi, *Implications of Blochchain-based Smart Contracts on Contract law* (Nomos, 2022); in Italian language: S Orlando, 'Gli smart contracts come prodotti software', Gli smart contracts come prodotti software, in S Orlando, G Capaldo (eds) *Annuario 2021 Osservatorio Giuridico sulla Innovazione Digitale* (Sapienza University Press, 2021) 235 ss; P Cuccuru, 'Blockchain ed automazione contrattuale. Riflessioni sugli Smart Contract' (2017) 1 Nuova Giur. Civ.,107; also, in favor of a case-by-case approach R Pardolesi, A Davola, 'Smart contract: lusinghe ed equivoci dell'innovazione purchessia', 2019(59) Foro it.,195; E Tosi, *Diritto privato delle nuove tecnologie digitali. Riservatezza, contratti, responsabilità tra persona e mercato* (Milan, 2021).

[60] The legal classification of these operations ranges from data transfer computer protocols, devoid of immediate legal relevance at one extreme, to contracts at the other. See R Pardolesi, A Davola, 'Smart contract: lusinghe ed equivoci dell'innovazione purchessia', 2019(59) Foro it.,195: On the possible contractual nature, while firmly denying the possibility of a reductio ad unum of the complex and granular technological phenomenon analyzed, see, among others, E Tosi, Diritto privato delle nuove tecnologie digitali. Riservatezza, contratti, responsabilità tra persona e mercato (Milano, 2021) 231-238.

[61] However, the case of the Republic of Malta should be highlighted, as it intervenes by adopting a statutory definition of smart contracts, albeit limited to the scope of the legislation contained in the Virtual Financial Assets Act, Act No. XXX of 2018 (published in the Government Gazette of Malta, No. 20,028, 20th July 2018, and available online on the Maltese Parliament portal at the link: https://legislation.mt/eli/cap/590/eng/pdf). This act was introduced to regulate Initial Coin Offerings. In Part I – Preliminary, dedicated to definitions, the aforementioned act (which also includes a definition of Distributed Ledger Technology) provides a definition of smart contract explicitly attributing to it, alongside the broad notion of a computer program, the meaning of an 'agreement, concluded wholly or partly in electronic form, which is automatable, and enforceable by computer code (…).

following a regulatory model observed predominantly overseas, particularly in USA[62], has not clarified the regulatory framework. The Italian Law Decree of

At the EU level, attention to blockchain and distributed ledger technology (DLT) applications, in general, can be traced back to the European Parliament resolution of 3 October 2018 on distributed ledger technologies and blockchains: building trust with disintermediation (2017/2772(RSP)). This resolution, recognizing the driving force of development and the strategic importance associated with advancements in DLT, underscores, among significant applications, the role of smart contracts. It emphasizes the importance of addressing any technical or legal doubts that may limit their diffusion in the digital single market (especially issues related to jurisdiction and the validity of cryptographic signatures). These challenges can be overcome through the adoption of technical standards, monitoring use cases, and evolving the legal framework, promoting coordination among member states. Furthermore, in the European Parliament resolution of 13 December 2018 on Blockchain: a forward-looking trade policy (2018/2085(INI)), the potential contribution of blockchain to Union trade policies, particularly smart contracts (highlighted in points 29 and 30), is reiterated. Smart contracts are recognized as tools capable of ensuring transparency in transactions, secure payments, and reduced transaction costs in supply chain relationships through the automatic execution of performances. However, it is noted that, at the moment, smart contracts may not be mature enough to be considered legally binding under any sectoral regulation, and a further risk assessment is necessary.
The need to regulate blockchain and smart contracts begins to be acknowledged later. Several studies address this concern. One conducted by the European Parliamentary Research Service (EPRS) of the European Parliament, titled "Digital Services Act. European added value assessment" in 2020, identifies doubts about the contractual qualification and binding effectiveness of smart contracts, as well as risks to consumer protection, as the main limitations to the spread of the tool in the digital single market. Part of these concerns, especially regarding the need for clarity about the level of protection for the weaker party in smart contract relationships, is reflected in the European Parliament Resolution of October 20, 2020, on recommendations to the Commission on the Digital Services Act: adapting commercial and civil law rules for businesses operating online (2020/2019(INL)). This resolution emphasizes the need to clarify the applicability of consumer protection rules and remedies, including the right of withdrawal.
Another important study, commissioned in 2018 by the Directorate-General for Communications Networks, Content & Technology of the European Commission and published in 2020 (Vv. Aa., *Study on Blockchains Legal, governance and interoperability aspects*, 2020, (SMART 2018/0038)), focuses more analytically on the applicability of national law and legal principles of Member States to smart contracts. It reports the considerable doctrinal debate on the issue but effectively observes, albeit with different solutions, a widespread protection of legal positions involved in smart contract relationships under national contract law.

[62] Among the first U.S. states to regulate smart contracts is Arizona, which in 2017 (cf. Arizona Revised Statutes. Title 44. Trade and Commerce § 44-7061, titled 'Signatures and records secured through blockchain technology; smart contracts; ownership of information; definitions', most recently updated in 2021) legislated that 'Smart contracts may exist in commerce. A contract relating to a transaction may not be denied legal effect, validity, or enforceability solely because that contract contains a smart contract term' (cf. AZ Rev Stat § 44-7061, letter C), where a smart contract is defined as 'an event-driven program, with state, that runs on a distributed, decentralized, shared and replicated ledger and that can take custody over and instruct transfer of assets on that ledger' (cf. AZ Rev Stat § 44-7061, letter E, no.1). The text is available at https://www.justia.com.
While the definition of a smart contract is clear and, in some respects, more precise than that adopted by the Italian Legislature, the scope of the provision in letter C is not equally clear. It would seem reasonable to exclude automatic identification with the contract, considering the smart contract more as a program capable of reproducing individual contractual clauses or giving mere implementation to them (cf. smart contract 'term'). However, the further clarification that legal effects, validity, and enforceability cannot be denied to contracts containing 'smart' clauses—unnecessary, in the opinion of the writer, if such programs were imagined as mere executive tools of the relationship—should lean towards the interpretative hypothesis that the smart contract, or rather the code that composes it, may contain at least part of the contract or express some of the contractual clauses, if not the entire structure desired by the parties.
In addition to Arizona, similar legislation has been adopted by the states of Tennessee (cf. Tennessee Code. Title 47. Chapter 10. Part 2. § 47-10-202), with an almost identical formulation to that of Arizona, and Arkansas (Arkansas Code. Title 25. Chapter 32. § 25-32-122). Texts are available in updated versions at https://www.justia.com.
Other states include Vermont, Ohio, Wyoming, Nevada, and others (for references, see AA.VV., Study on Blockchains Legal, governance and interoperability aspects, 2020, (SMART 2018/0038), 57 ss, online: https://www.eciia.eu/2020/03/study-on-blockchains-legal-governance-and-interoperability-aspects/) and also, M Maugeri, Smart Contracts e disciplina dei contratti. Smart Contracts and Contract Law (Bologna, 2021), 41-42, notes from 4 to 10).

December 14, 2018, No. 135, converted with amendments by Law of February 11, 2019, no. 12, indeed introduces legally relevant definitions of distributed ledger technologies and smart contracts into the legal system, attaching specific legal effects to them.[63] Notably, it specifies that storing a digital document through distributed ledger technologies produces the legal effects of electronic time stamps under Article 41 of Regulation (EU) No. 910/2014[64].

However, the smart contract definition embraced by the provision[65], does not directly address whether the smart contract should be identified with a legal contract, even under specific circumstances, or if it should be intended solely as a computer program entrusted, at most, with the automated performance of pre-existing agreements, in whole or in part[66]. This leaves uncertainties regarding the precise legal qualification of the smart legal contract in the Italian contract law system[67]. While this approach may not necessarily be incorrect and could be intentional, allowing for a case-by-case

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The legislation introduced in Arkansas, partly different in the notion and for the effects related to the smart contract, deserves specific attention.
Indeed, AR Code § 25-32-122 (a)(3) provides that:
(3) "Smart contract" means:
(A) Business logic that runs on a blockchain; or
(B) A software program that stores rules on a shared and replicated ledger and uses the stored rules for:
(i) Negotiating the terms of a contract;
(ii) Automatically verifying the contract; and
(iii) Executing the terms of a contract.
The smart contract, or more precisely, the coded instructions launched on distributed ledgers (cf. stored rules)—according to the legislation in question—not only can execute contractual clauses but is involved in their 'negotiation,' perhaps referring to a role of smart contracts and distributed ledger information technology in the formation of contractual will or, in any case, the conclusion (in a digital environment) of the contract. Moreover, expressly according to AR Code § 25-32-122 (d)(1): 'A smart contract shall be considered a commercial contract.'

[63] In accordance with Article 8-ter of the decree (cf. decreto legge 14 dicembre 2018, n. 135), indeed:
"*1. Si definiscono 'tecnologie basate su registri distribuiti' le tecnologie e i protocolli informatici che usano un registro condiviso, distribuito, replicabile, accessibile simultaneamente, architetturalmente decentralizzato su basi crittografiche, tali da consentire la registrazione, la convalida, l'aggiornamento e l'archiviazione di dati sia in chiaro che ulteriormente protetti da crittografia verificabili da ciascun partecipante, non alterabili e non modificabili. 2. Si definisce 'smart contract' un programma per elaboratore che opera su tecnologie basate su registri distribuiti e la cui esecuzione vincola automaticamente due o più parti sulla base di effetti predefiniti dalle stesse. Gli smart contract soddisfano il requisito della forma scritta previa identificazione informatica delle parti interessate, attraverso un processo avente i requisiti fissati dall'Agenzia per l'Italia digitale con linee guida da adottare entro novanta giorni dalla data di entrata in vigore della legge di conversione del presente decreto. 3. La memorizzazione di un documento informatico attraverso l'uso di tecnologie basate su registri distribuiti produce gli effetti giuridici della validazione temporale elettronica di cui all'articolo 41 del regolamento (UE) n. 910/2014 del Parlamento europeo e del Consiglio, del 23 luglio 2014.* (…)"

[64] Article 8-ter, paragraph 3 of Law Decree of December 14, 2018, No. 135 (cf previous note n. 64), indeed refers to Article 41 of the Regulation (EU) no 910/2014 of the European Parliament and of the Council of 23 July 2014 on electronic identification and trust services for electronic transactions in the internal market and repealing Directive 1999/93/EC.

[65] Which, at the time of writing, remains without the necessary technical implementing measures. See note n.63.

[66] Among others, see F Faini, 'Blockchain e diritto: la «catena del valore» tra documenti informatici, smart contracts e data protection', (2020) 1 Responsabilità Civile e Previdenza, 297.

[67] C Bomprezzi, 'Commento in materia di Blockchain e Smart contract alla luce del nuovo Decreto Semplificazioni', 2019 Diritto Mercato e Tecnologia, online: https://www.dimt.it/news/breve-commento-alla-legge-11-febbraio-2019-n-12-di-conversione-del-decreto-legge-14-dicembre-2018-n-135-recante-disposizioni-urgenti-in-materia-di-sostegno-e-semplificazione-per-le-imprese-e-per-la-pu/; see also M Manente, 'L.12/2019. Smart contract e tecnologie basate su registri distribuiti. Prime note', Studio 1/2019 DI, Consiglio nazionale del Notariato – Area Informatica, online: https://notariato.it/it/ufficio_studi/studio-12019-di-legge-122019-smart-contract-e-tecnologie-basate-su-registri-distribuiti/

qualification suitable for specific situations[68], it does little to mitigate the legal uncertainty surrounding smart contracting and raises questions about its exact legal reconstruction, given the widely varying academic opinions on the nature of the smart contract[69] and, consequently, the actionable private law remedies in case of disputes.

It is crucial to note that the widespread adoption of blockchain and smart contracts necessitates a legal and regulatory framework as uniform as possible, ideally at the European if not global level. Currently, legal frameworks, as mentioned in the paragraph above, are defined by each State, lacking real uniformity. The legal qualification and effects of smart contracts, especially the circumstances under which automated exchanges through on-chain computer code-driven transactions between different actors in a supply chain can be considered equivalent to genetically digital contracts, may differ from jurisdiction to jurisdiction, impacting the technical and legal interoperability of digitized agri-food supply chains.

Additionally, the inability to 'localize' on-chain transactions, due to the widespread distribution of the blockchain and decentralized execution[70], poses significant challenges in determining the jurisdiction and applicable law for specific disputed transactions[71]. Since the formulation of contract clauses in computer code and its self-execution do not exclude the possibility of a breach of contract[72] or litigation, the establishment of shared rules for resolving disputes arising in the context of cross-national supply chains will be decisive for the diffusion of blockchain solutions for food supply chain management. On the contrary, the risk is the overlapping and confusion of very different regulatory registers, decisions, and judicial remedies, which can be burdensome for companies implementing blockchain solutions.

One potential solution that public or private policy initiatives, whether led by stakeholders or trade associations, could consider is, for example, internalizing on-chain alternative dispute resolution tools.

It is indeed worth mentioning the recent proliferation of blockchain-specific

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[68] Faini concurs with this perspective, asserting that the categorization of a smart contract into either scenario is intricately tied to the specific circumstances. It depends on which of the two hypotheses the smart contract concretely embodies and the relationship between the agreement and the computer code. See F Faini, 'Blockchain e diritto: la «catena del valore» tra documenti informatici, smart contracts e data protection', (2020) 1 Responsabilità Civile e Previdenza, 297.

[69] Among others, see R Pardolesi, A Davola, 'Smart contract: lusinghe ed equivoci dell'innovazione purchessia', 2019(59) Foro it.,195; E Tosi, *Diritto privato delle nuove tecnologie digitali. Riservatezza, contratti, responsabilità tra persona e mercato* (Milan, 2021).

[70] Although the construction of a 'national' blockchain, with all nodes located within the same state, is certainly conceivable, the same issues arise when it comes to identifying counterparties and determining judicial jurisdiction in national disputes.

[71] On the challenges of applying Regulation Brussels I-bis to the contractual relationship arising from the smart contract, among other issues, see B Cappiello, 'Dallo smart contract computer code allo smart (legal) contract. I nuovi strumenti (para) giuridici alla luce della normativa nazionale e del diritto internazionale privato europeo: prospettive de jure condendo' (2020) 2 Diritto del Commercio Internazionale, 477; about these issues see also C Bomprezzi, *Implications of Blochchain-based Smart Contracts on Contract law* (Nomos, 2022).

[72] On the impossibility of blockchain producing 'breach-less' contracts, see also C Bomprezzi, who identifies possibilities of non-compliance are identified in the following scenarios: 'a) the code content does not match with the will of the parties, thus determining that the execution of the contract does not satisfy the creditor; b) technological problems that impact on the performance of the contract; c) other problems due to the closed nature of the blockchain, when there is the need to link the smart contract with the off-chain world to perform the contract' (cf. ibid.,217).

alternative dispute resolution systems, which align with the successful path of Online Dispute Resolution (ODR). These systems distinguish themselves by being based on or integrated into smart contracts deployed on the blockchain; hence are commonly referred to as ‘On-chain’ Dispute Resolution tools.[73]

With two distinct approaches, these systems contemplate the possibility, encoded in the protocol of the smart contract itself (or in another linked to the first one), to suspend or interrupt its execution when a dispute arises between the parties. This introduces an additional condition, preceding the execution of the main reciprocal obligations (if-then): a potential (activatable by each party) – but necessary at that point – confirmation/decision by a third intermediary – an arbitrator[74] – summoned to ‘judge’ the dispute and resolve issues – such as programming errors in the agreement – or, in any case, terminate the contract, redressing any resulting effects. Technically, it is indeed possible to code within the smart contract the power to interfere with the execution of the contractual code itself, agreeing to entrust this power to a third party. This third party can either be a human part of the same smart contract[75] or a stand-alone automatic agent: a different smart protocol, albeit related to the main contract, also summoned to 'judge' the dispute based on strictly – predefined – algorithmic parameters (in one approach). Another approach may involve a human (or a panel of human) arbitrators, whose determination – external, of course, to the blockchain – is then 'fed' – through an oracle – to the disputed smart contract, programmed to automatically influence its execution accordingly[76].

Regarding the effectiveness of these solutions, definitive conclusions can only be drawn when more data on the matter becomes available. Nevertheless, these systems de facto internalize to the blockchain not only the executive phase of the contract but also the resolution of its (potential) pathological phase. They promise, at least in some cases, a more effective and immediate enforcement in a Distributed Ledger Technology (DLT) environment, while still allowing the possibility for the party that disagrees with a particular resolution to seek recourse in court. The adoption of standardized systems of this kind would address numerous operational constraints, facilitating the development

[73] For a detailed description of various examples and their operational mechanisms, see A Kaal and C Calcaterra, ‘Crypto Transaction Dispute Resolution’ (2017) 73 Business Lawyer, 109-153.

[74] The function in code "Pause And Send To Arbitrator" in question appears to function as a veritable arbitration clause, directing disputes arising from the contract to an ad hoc arbitration.

[75] It is the simplest case, which configures so-called multi-signature (or multi-sig) transactions, a dispute resolution mechanism that allows users to settle a conflict without resorting to the judicial authority or an arbitral figure external to the system; on this point, see K D Werbach, N Cornell, ‘Contracts ex machina’, (2017) 67 Duke Law Journal, 345. Multi-sig transactions generally operate akin to a third-party escrow, as they allow "freezing" the cryptocurrencies involved in the transaction within an account not attributable to any of the parties individually but jointly managed by them and a third user who serves as an arbitrator in case of disputes. The transfer to and from one of the parties is thus subject to the authorization of a predetermined number of involved entities. In the simplest scenarios, involving the transfer of currency from A to B, supervised by C, the operation is unlocked with the consent of two out of three parties. In cases where no disputes arise between the main parties A and B, the funds can be autonomously unlocked by them; in contrast, if a conflict arises among the parties involved in the transfer, the third user-arbitrator C will decide the final cryptocurrency allocation along with the party deemed correct between the two. Thus, P Cuccuru, ‘Blockchain ed automazione contrattuale. Riflessioni sugli Smart Contract’ (2017) 1 Nuova Giur. Civ.,107.

[76] Furthermore, D Allen, A Lane, M Poblet, ‘The Governance of Blockchain Dispute Resolution’, (2019) 25 Harvard Negotiation Law Review,75-101, http://dx.doi.org/10.2139/ssrn.3334674. See also W A Kaal, And C Calcaterra, ‘Crypto Transaction Dispute Resolution’, (2017) 73 Business Lawyer, 109-153

of truly scalable and interoperable blockchain-based supply chains.

Concluding remarks.

In conclusion, the integration of Blockchain technology and smart contracts in the food supply chain hold substantial promise for enhancing transparency, safety, and overall efficiency. By providing a secure and verifiable record of information, eliminating intermediaries, and facilitating real-time traceability of food products, smart contracts can increase trust in the supply chain, ensuring the safety and quality of food products. Moreover, a blockchain-based supply chain can play a vital role in driving the transition towards a more sustainable and environmentally-conscious food system by empowering consumers with accessible and reliable information about the food they consume. Informed consumers are better equipped to make environmentally-friendly choices, support sustainable practices, and advocate for responsible production and sourcing methods, fostering a positive impact on the entire food ecosystem. By harnessing the potential of smart contracts and empowering consumers, the food industry can steer towards a more sustainable and 'green' future.

Additionally, the 'blockchainization' of the supply chain, particularly in the agri-food sector, has the potential, through integration with other technologies and functionalities, to serve as a technological infrastructure that enhances the overall sustainability of the production system. This integration streamlines management and enables reliable monitoring of social and environmental impacts, positioning it as a key driver for sustainability. [77]

However, technological constraints, along with legal and regulatory challenges, currently erode market trust and hinder scalability and interoperability of innovative solutions for the supply chain on a European or global scale. Addressing these challenges is crucial to achieving widespread adoption and realizing a tangible positive impact on the system. Governments, regulators, and stakeholders must confront these technological challenges and embrace the responsibility to ensure an ethical and environmentally responsible approach in navigating the transformative shift to the Fourth Industrial Revolution. This pivotal moment offers an unprecedented opportunity to guide our future towards a more sustainable existence.

[77] It is argued that the potential of blockchain to contribute to addressing environmental challenges can be exponentially amplified when combined with other emerging technologies such as Artificial Intelligence, the Internet of Things, drones, and biotechnologies. When applied in this manner, serving as a "cocktail mixer" for other emerging technologies, blockchain truly begins to emerge as a game-changing technology; cf. World Economic Forum, "Building Block(chain)s for a Better Planet", Fourth Industrial Revolution for the Earth Series (September 2018), 7 ff.