Food Chemistry 467 (2025) 142331

Contents lists available at ScienceDirect

Food Chemistry

journal homepage: www.elsevier.com/locate/foodchem

Review

Blockchain revolution in food supply chains: A positive impact on global food loss and waste

Carlos S.H. Shiraishi [a,b,c], Custódio Lobo Roriz [a,b], Márcio Carocho [a,b,*], Miguel A. Prieto [c], Rui M.V. Abreu [a,b], Lillian Barros [a,b], Sandrina A. Heleno [a,b]

[a] Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal

[b] Laboratório Associado Para a Sustentabilidade e Tecnologia em Regiões de Montanha (SusTEC), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal

[c] Universidade de Vigo, Nutrition and Bromatology Group, Department of Analytical Chemistry and Food Science, Instituto de Agroecoloxía e Alimentación (IAA) – CITEXVI, 36310 Vigo, Spain

ARTICLE INFO

Keywords
Blockchain
Internet of things
Food sustainability
Food quality and safety

ABSTRACT

The rising global population has created an urgent need for increased food production. Food loss and waste remain significant challenges throughout the food supply chain, from cultivation to consumption. Blockchain, a decentralized peer-to-peer network that stores information can help making food more traceable, from production to consumption. It can also help enhance food production sustainability, transparency, quality and safety. By tracking all aspects of food it plays a crucial role in reducing food loss and waste. Several organizations that have briefly introduced this technology, along with the Internet of Things, although the real benefit of blockchain is achieved when several players in the food chain adhere to this technology. This review emphasizes how blockchain was adapted to the food chain, its challenges, benefits and limitations, and how some food sectors have used this technology. A brief perspective on how the Internet of Things and Blockchain will evolve in the future.

1. Introduction

According to theUnited Nations the world's population is estimated to surpass 8.5 billion by 2030, 9.7 billion by 2050, and it is projected to reach 10.9 billion by 2100. It is well known that between 1960 and 2015, agricultural production more than tripled (de Vasconcelos et al., 2021); for instance, just fruit and vegetable production from 2000 to 2018 increased by 115 %, according to the Food and Agriculture Organization (FAO, 2020). Consumption and demand for fresh foods is expanding rapidly, but even with more innovation and technology, the food loss and waste (FLW) generated by the global food chain is not decreasing (Vilariño et al., 2017). Fruit and vegetables are the most impacting comodity, with 44 % (572 million tons) in loss and waste (Lipinski et al., 2013), due to a lack of adequate methods and infrastructure (Sagar et al., 2018). The human demand for natural resources is 1.7 times the resources available on Earth, evidencing the human-environment imbalance (Collins et al., 2020). In contrast to the increasing amount of food production, it is essential to remember that despite all the FLW associated with overproduction, malnutrition is still a reality for 663 million people worldwide (Ritchie, Rosado, & Roser, 2023).

It is necessary to adopt and disseminate new emerging technologies from several perpectives, namely logistical, preserving, environmental and digital innovations to help mitigate FLW. Among the digital technologies, blockchain can be an important tool for recording and sharing information securely and transparently, allowing traceability. This can translate into FLW reduction, efficient stock management, performance and sustainability increase among other improvements (Saurabh & Dey, 2021; van Hilten et al., 2020; Y. Zhang et al., 2022). This promising technology is based on the principle that information can be collected without an intermediary, allowing peer-to-peer sharing through blockchain cryptography, that stores information securely and reliably. This enables transparent food processes to be established, with monitoring from Farm-to-Fork, thus reducing FLW.

* Corresponding author at: Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal.

E-mail address: mcarocho@ipb.pt (M. Carocho).

https://doi.org/10.1016/j.foodchem.2024.142331
Received 3 September 2024; Received in revised form 27 November 2024; Accepted 1 December 2024
Available online 4 December 2024

2. Food supply chain

Fruits and vegetables are some of the most produced un processed comedies, and therefore tend to also be some of the most prone to loss and waste. Between the years 1960 and 2015, agricultural production more than tripled (de Vasconcelos et al., 2021) and is expected to reach an astounding 255 million tons (Mt) in 2028 (Food and Agriculture Organization of the United Nations, 2020). At this growth rate in 2050, it is estimated that fruit production will increase by at least another 70 %. It is predicted that the world population in 2100 will grow to approximately 11.2 billion people, given that the food sector is composed of an intricate network that promotes the supply of energy (calories) for a society that demands cheaper food with higher quality and transparency of information (location, sustainability, treatment of animals and evolution of the agri-food chain) (Saitone & Sexton, 2017) it will make this task increasingly challenging for this sector.

The food supply chain is responsible for the activities between the farming system to the final consumer. It handles the food supply management to consumers, promotion, maintenance, and progression of logistics across functions (e.g., new product development, marketing, distribution, finance, operations, and management). The food supply chain is optimized, considering expiration date, volume, time, place, price, and food condition. It also tries to use customer feedback to improve competitiveness in products, sales, delivery, and services or commodities with direct or indirect involvement in the various processes of the production and distribution chain (George & Al-Ansari, 2023; Gondal et al., 2023; Seyedghorban et al., 2019).

The challenging operations and decisions of the food supply chain, the transparency in health and food safety, and some other unique logistical challenges for preserving natural resources all contribute to the complexity of the production and distribution of perishable food assets (de Vasconcelos et al., 2021). There are undesirable losses along the different steps of this complex chain caused by various factors, including inadequate handling, lack of suitable transport facilities, and insufficient infrastructure logistics, among others. An example of inefficiency in the food chain is India, which produces enough food to meet the needs of its entire population, being ranked as the second largest fruit producer in the world, but still ranks 119th in the Global Hunger Index (GHI). This mismatch is due to an estimated food loss of around 25–30 % from inadequate transport logistics and a lack of controlled temperature and atmosphere facilities, which have high energetic costs.

Food is a sensitive biological matrix, particularly fresh produce, due to their short shelf life and higher demands when compared to non-perishable products. These fresh products require efficient hygiene and quality processes to meet the established safety standards. Fresh fruit handling along the process can cause minor physiological injuries and biochemical effects, resulting in a final product of inferior quality (sensory, microbiologically, and visually). Processed foods are more durable due to processes such as pasteurization, strengthening, preserving methods, among others (Davis et al., 2020). For fresh fruits, and as a particular example, Figs, present 75 % of relative humidity, making the optimum consumption interval between 1 and 2 days when removed from storage. Their main post-harvest losses are caused by yeasts, fungi, and bacteria, carried by vectors such as wasps and vinegar flies, which can initiate the fermentation reaction and alter the quality of the fruit (Paolucci et al., 2020). These factors require conservation measures, such as cold storage or exogenous ethylene exposure, for controlled ripening and to assure quality standards (Crisosto et al., 2011).

Besides the post-harvest practices, the transport factor and the material in which the fruits are carried are fundamental for the fruit to arrive at the final customer, fulfilling all necessary quality requirements. Fruits with sensitive epicarps are more susceptible to pressure and blow that can end up causing injuries, leaving an open "wound" for pathogens, possibly leading to fruit decomposition, as is the case of figs, which are susceptible fruits due to their physical characteristics. Therefore, it is essential to transport the fruit in a material that can ensure the preservation of the physical integrity and distinctive features so that the fruits can retain the essential standards of quality (Arvaniti et al., 2019; Ayuso et al., 2022).

2.1. Global disruptive challenges of the food supply chain: the 2020 covid pandemic and wars

Food logistics is a complex global interconnected network that struggles to deliver food to finals consumers even in "normal"conditions. Still, during the 2020 Covid pandemic and the Russo-Ukrainian war, the network was disrupted in several ways (Barman et al., 2021; Ben Hassen & El Bilali, 2022). These disruptions negatively impacted producers and consumers, leading to empty shelves, increased demand for bread (76 %) and vegetables (52 %), and higher food costs due to reduced workforce, transportation challenges, and delays in delivering of fresh products. In Hawaii, local farmers and ranchers experienced a 50 % decline in sales at the start of summer 2020. Substantial efforts were required to maintain the supply chain's functionality. To address these challenges, producers and distributors had to embrace new technologies and innovative production methods, including e-commerce, to ensure business continuity and meet the public's demand for safe, traceable, and transparent food (Barman et al., 2021; Berning et al., 2022; Mardones et al., 2020).

The influence of the Russian military invasion of Ukraine in 2022, it has caused severe impacts on global food security, affecting Ukraine's ability to export agricultural products and generating food shortages and price increases in conflict-affected countries. Thus, with a vast network that mostly ahndles short-lifespan goods, the food network is quite sensitive to conflicts (even if local) that can have a global reach, as nowadays most food requires ingredients from several geographical locations. Being able to digitally identify, trace, locate, inform and report on the status of food and ingredients is a quick and reliable manner to overcome the constraints posed by wars, pandemics and climatic disasters.

2.2. Management and sustainability in the food sector

Supply chain management is an essential component of business management at the intra-organizational level. It is responsible for coordinating departments and companies' integration and the supply chain transformation from supplier to customer (Ivanov, 2018).

With more complex food products (ethnic and organic), new quality criteria are emerging, with more significant challenges for insurance and affordability (Castro Campos & Qi, 2024; Vigar et al., 2020).

The United Nations (UN) designated 2021 as the "Year of Fruits and Vegetables" to raise awareness about their benefits, loss reduction policies, waste management, and food safety along the production chain. These aspects, which include social, economic, and environmental advantages, can be aligned with the Sustainable Development Goals (SDGs) related to fruits and vegetables, according to the Food and Agriculture Organization (FAO) in 2020 (Food and Agriculture Organization of the United Nations, 2020):

i. Health benefits of fruit and vegetables:

02: Zero Hunger:
03: Good Health and well-being

ii. Food Loss and Waste:

02: Zero hunger

In 2000, the Millennium Development Goals (MDGs) were established during the Millennium Summit of the United Nations to combat poverty and promote sustainable development by 2015, which were then replaced by the Sustainable Development Goals (SDGs).

According to FAO, 2020 (FAO, 2020) regarding population growth, by 2050, it will be necessary to produce 50 % more food, feed, and biofuels to meet population demand than in 2012. Currently, one-third (1.3 billion tons) of the world's food production is wasted at the various stages of the food chain, either in production, post-harvest, processing, distribution and consumption (Vilariño et al., 2017) or lost due to pests, diseases, limited harvesting techniques and price volatility. This FLW represents an overall monetary value of €800 billion with the corresponding social and environmental impacts (Ishangulyyev et al., 2019). Due to their high perishability, fruits and vegetables account for 40 to 50 % of global food loss (dos Santos et al., 2020).

FLW represents the non-consumed, edible parts harvested or produced from plants or animals, and it is related to processes present in the food chain and to the consumers' decision to discard food (waste) (Ruviaro et al., 2020). FLW can be used as a scale to assess the food chain from production to consumption, seeking to represent the waste of resources (soil, water, and energy) used at each production stage based on life cycle assessment (Vilariño et al., 2017). According to Ishangulyyev et al. (2019) who reviewed the different concepts of FLW according to different sources (FAO, Fusions EU, High-Level Panel of Experts, and the United States Department of Agriculture), Food Loss (FL) and Food Waste (FW) represent different parts of the food production chain, being FL a reduction in the weight of edible food along the first three stages of the production chain (production, handling & storage and processing), and FW responsible for the distribution & marketing and consumption stages (Nicastro et al., 2021). This reinforces the difficulty and unclarity of the concept in literature. For einstance, in the FAO concept FL occurs in the production, post-harvest and processing stages. FW is present in the actions of retail, food services and consumers. Another definition by Kim & Lee (2020) states that FL can be characterized as a "decrease in quality and quantity of food in the processing stages", while FW is described as food spoilage by retailers, food service providers and households.

Efficiency in managing FL issues tends to be less prominent in developed countries, where advanced production and distribution systems, stringent regulations, and adequate infrastructure minimize FL. In contrast, many developing countries exhibit seemingly lower rates of FW, primarily due to pre-consumption losses. Still, they face distinct challenges, such as significant losses in storage, transportation, and processing stages, underscoring the global complexity of the FL problem and the need for multifaceted approaches to addressing it.

Legislative strategy measures are fundamental in the different stages of the food chain to promote the reduction of FLW and improve the sustainability of the food production chain through public investments and by establishing protocols with private companies. Examples of these types of collaborations were seen in Italy after the implementation of the "Gadda Law", which occurred through the cooperation of the association "Io Potentino Onlus" with the Basilisca Brewery of Potenza, which reused unsold bread to produce the beer "LA166" to combat FW. Another example is the FUSIONS project (Food Use for Social Innovation by optimizing Waste Prevention Strategies), which aims at a more resource-efficient Europe, preventing FLW by stimulating innovation, funding guidelines, encouraging donations, and raising awareness, among other measures (Nicastro et al., 2021).

Fig. 1 shows the most important drivers in FLW in developed and underdeveloped countries, divided by the operational constrains (upper section) and the factors that promote the loss of food. Underdeveloped countries mainly have one operation problem, which is the lack of means to produce enough food to fit the needs of the population, be it through lack of equipment, resources, staring-materials and others. Developed countries have comparable lower losses (although they do generally produce higher amounts), which are distributed among the chain. The loss is also due to overconsumption or overbuying, but also due to management, transports, and other. In terms of the drivers of these losses, in developed countries, aggressive marketing, high discarding of good food and a higher threshold of what food is safeor secure to eat. In underdeveloped countries, climate has a very high impact due to lack of infrastructure to produce and store food, which also leads to faster and higher deterioration, but also ineffective production and transportation.

In developed countries provided with technologies (logistics, management, marketing, transportation) a total of 222 Mt. of FW per year is produced, a value almost identical to the total net production in Sub-Saharan African counties (230 Mt) (Ishangulyyev et al., 2019). In the European Union, for example, most FW comes from households (47 Mt) and the processing sector (17 Mt), resulting in 72 % of total FW. According to Amicarelli and Bux (2020), the Sub-Saharan African waste is less than 9 % kg/capita of North America and Oceania.

In Europe, it is estimated that about 30 % of FW comes from production and processing steps and 70 % from households, food services and retailers (Nicastro et al., 2021) in China alone, US$32 billion worth of waste was thrown away in 2013 (Lipinski et al., 2013) and Asia 278 Mt. are wasted (Joshi & Visvanathan, 2019). Fig. 2 shows some measures that can be used to reduce FLW along the productive,

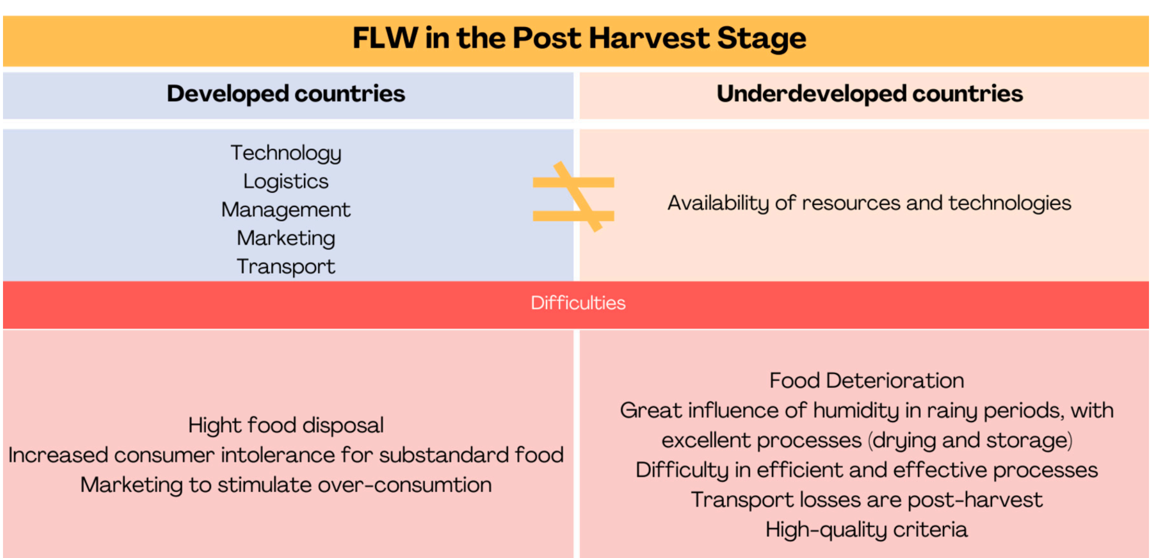

Fig. 1. Influence of FLW in developed and underdeveloped countries.

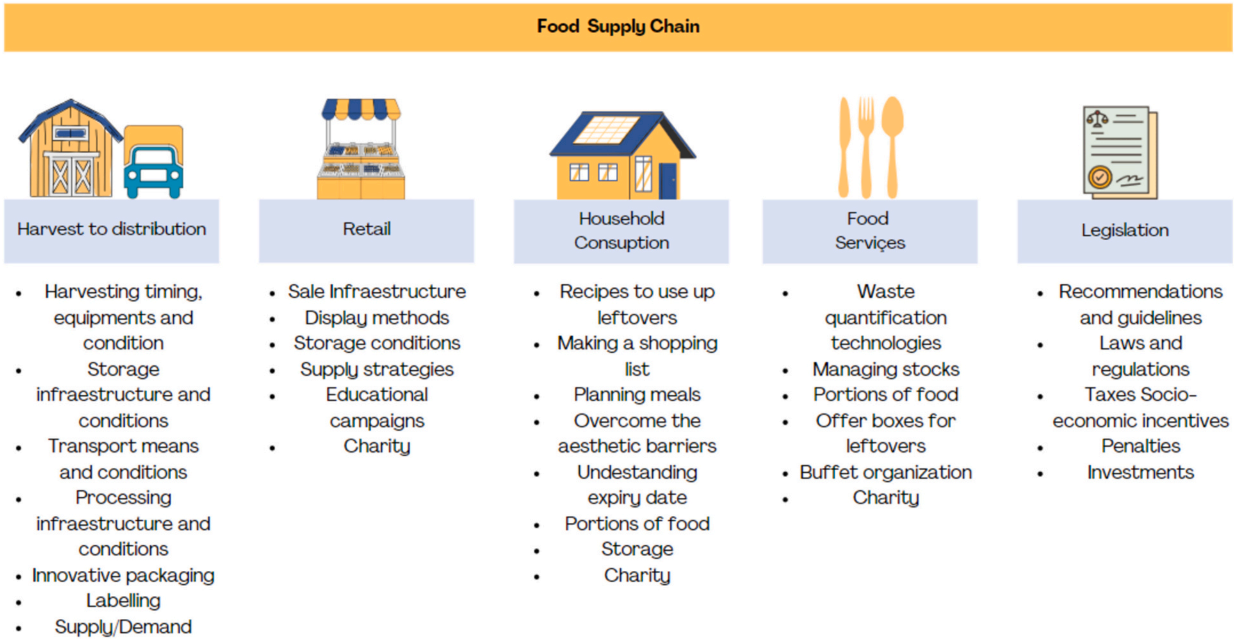

Fig. 2. Prevention and reduction measures at the various stages of the food production chain to reduce and prevent FLW.

transportation and retail chains.

2.3. *Sustainable solutions and technological advancements in the food supply chain*

For a better understanding of how *sustainability* correlates with the

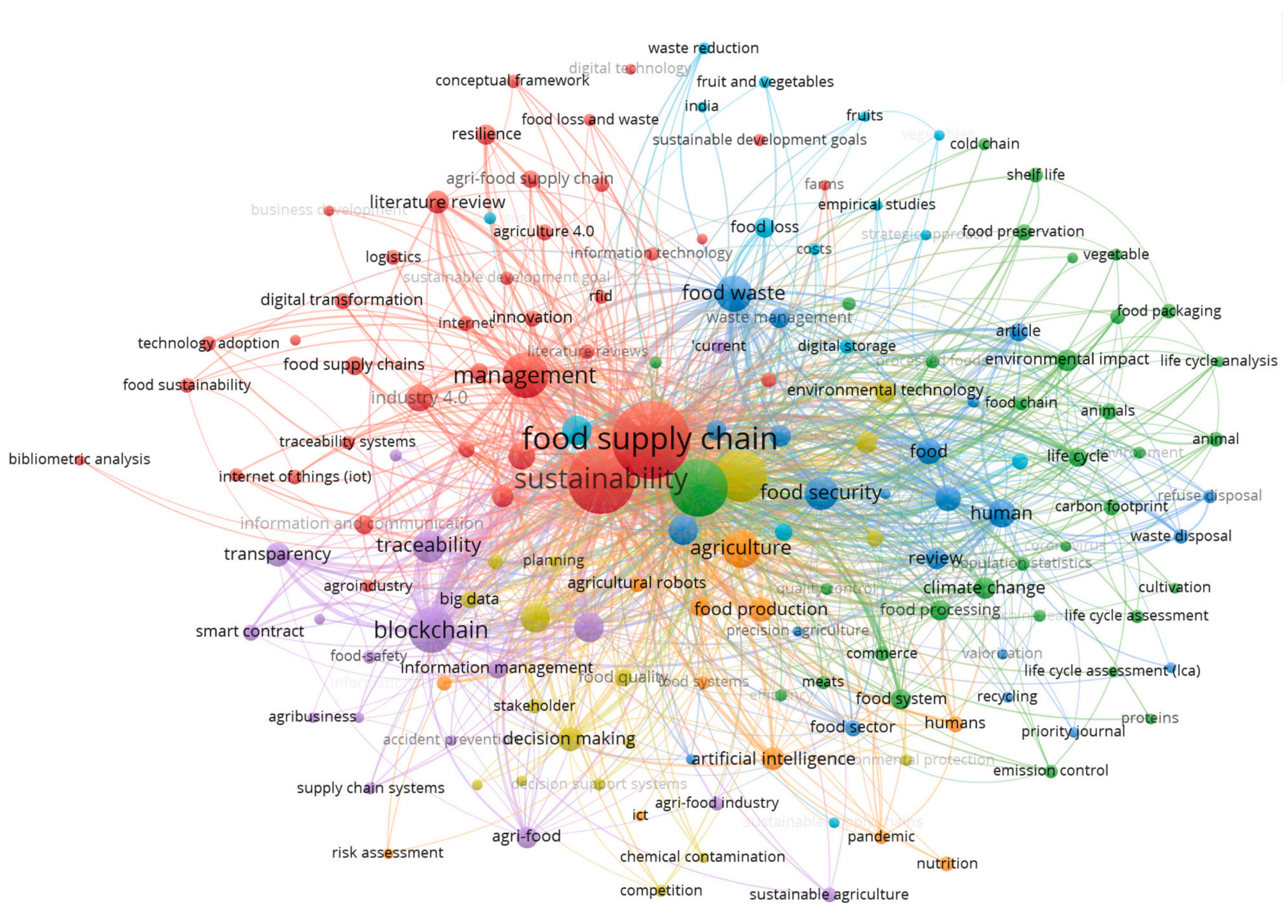

Fig. 3. VOSviewer software plots of the bibliographic data obtained from the SCOPUS database showing the result of 451 documents and their relationship with the keywords “sustainability”, “technology” and “food supply chain” between 2009 and 2024.

food supply chain and *technology*, using the VOS viewer software, a search was made for those keywords on SCOPUS, among articles published between 2009 and 2024. The search engine showed four hundred and fifty-one documents as well as other keywords related to these terms, and is shown in Fig. 3.

Fig. 3 represents a list of keywords, determined based on the number of documents that occur together, considering a minimum of 5 occurrences of the selected keywords. Lines represent the connection between the keywords, while the circles represent the weight of the keyword, although there are circles with a greater distance, which implies a lower correlation. Examples of the most vital connections with the keywords are *supply chain*, *sustainable development*, *blockchain*, *management*, *agriculture*, *food waste*, *food security*, *traceability*, *food safety*, *industry 4.0*, and *internet of things*. Among the keywords shown in Fig. 3 there are two digital technologies, namely blockchain and internet of things, which are highly correlated with the original keywords, meaning that these two technologies can have influence in optimizing the food chain, which could be achieved through reducing food loss and waste.

These innovations are also aligned with the pillars of sustainability (environmental, economic and social) are increasingly influenced by the digitization, integration and transparency of information (Food and Agriculture Organization of the United Nations, 2020), taking advantage of the internet of things (IoTwa) (Taj et al., 2023) and mathematical methods, such as artificial intelligence, machine learning, communication technology, radio frequency identification (RFID) and cloud computing (Saurabh & Dey, 2021; Toorajipour et al., 2021). Several current techniques were developed to solve potential problems in supply chain management in the areas of marketing, logistics, and production; among them, the main ones are:

RNAs: A method that stands out for its versatility, using mathematical regression, it finds complex patterns in extensive amounts of data and can be applied in several categories (pattern classification, process control, optimization, vendor selection, sales and consumption forecast, marketing decision framework, among others).

FL (Fuzzy Logic): A method dealing with “partial truth” used for hybrid intelligent systems with applications in manufacturing, marketing, production, and supply chain.

ABS (Agent-based Systems)/MAS (Multi-agent Systems): Used to solve specific problems, such as supply chain planning, design and simulation of supply chain systems, analysis of complex supply chain behavior, and collaborative negotiation-based modeling.

Other techniques are tree-based models, k-means, heuristics, bayesian networks, decision trees, and gaussian models, but they are less present in supply chain management applications.

These tools are crucial to improve food supply chain management, generating and interpreting a large amount of data that needs to be shared securely and transparently. Given this reality, blockchain can play a crucial role in the food production chain, allowing the data generated to be shared securely and transparently (Y. Zhang et al., 2022).

3. Blockchain in the food sector

One of the Sustainable Development Goals is “End hunger and achieve food security for all people by 2030”, promoting and highlighting the importance and need for safety regulations, food quality, traceability and transparency in food supply chains. The main goal is to prevent food loss but also fraud, mainly involving animal disease problems, such as “Mad Cow Disease”, “Nipah Virus” and “Avian Influenza”. These examples have highlighted the importance of traceability, stimulating technological advances to decrease food safety risks, promote health, and control diseases and their management. Targas & Manolakos (2010) defined this process as “the ability to identify and trace a product or component back to its “point of origin”. According to Westerlund et al. 2021, there are six key elements of traceability:

Product: location of the product along the production chain.

Process: geographical, physicochemical, biological, and regulatory activities affecting the product.

Genetic: specific characteristics.

Input: additives and chemical products.

Disease and pest: epidemiology and pathogens.

Measurement: quality control.

Current scenarios, such as the pandemic, promoted reflections on food losses, food waste (Cattaneo, Sánchez, et al., 2021; Mardones et al., 2020) and food insecurity, as demonstrated by Adjognon et al. (2021) in their study in Mali (West Africa). According to FAO (2020) (FAO, 2020) traceability systems to collect, record and share data are still lacking and are essential for the food sector. However, measures such as understanding, developing and implementing protocols and ensuring the integration of low-income farmers to benefit from these technologies due to the complexity involved in screening procedures make the process slow and inefficient. Technology such as “5G in agriculture” or terms like “smart farming” (Tang et al., 2021), “precision farming” (Cisternas et al., 2020), and “agricultural internet of things (AioT)” (Terence & Purushothaman, 2020) are present in a technological reality for more efficient productions that allow the sharing of product information, but the use of this technology is not the reality and is not a reality for all.

Given this scenario, technologies ranging from the simplest, such as bar codes limited to one product at a time, to more complex for the identification of individual species, such as molecular biology tools like DNA Barcoding (Gorini et al., 2023) or DNA metabarcoding (DNA barcoding with next-generation sequencing) in ultra-processed food applications (Gense et al., 2021), are essential to improve food safety and prevent food loss. Other technologies include Radio Frequency Identification (RIFD), used to capture data in real-time, for example, for animal tracking, and Wireless sensor networks (WSN) that allow the integration of wireless devices for decision-making to communicate with intelligent devices with wide use in agriculture (Awan et al., 2021; Gondal et al., 2023; Taj et al., 2023). Of all the technologies that are being adopted in food supply chains, blockchain technology stands out as one of the six “megatrends” in computing, enabling open information and security with the construction of smart contracts (van Hilten et al., 2020), transparency, reliability and high levels of traceability reducing the cost of financial transactions in agri-food supply chains (Wahyuni et al., 2024) as seen in the areas of meat and organic food (van Hilten et al., 2020), being an essential technology for assessing FLW (Cattaneo, Federighi, & Vaz, 2021).

Blockchain is a database of digital transactions that allows the description of food products from the origin to the production process, providing the product’s identity. This technology is maintained by a decentralized or centralized machine network that allows data to be transmitted, processed, stored, and represented without intermediaries, with information exchange through peer-to-peer communication containing date and time stamps, transaction data, and information on the previous block. Its structure is made up of blocks that contain a hash, a “label” that determines the specificity of the block required for the subsequent block and transmission of information, resulting in a highly secure process with several blocks united that contain information from the previous block to the subsequent one, forming a chain in chronological order with permanent and unchangeable records. In this way, the transaction information is validated by each participant in the food supply chain, and the processes involved at different stages of the chain are recorded and validated (provider, producer, processing, distribution, retailer, and consumer), as illustrated in Fig. 4.

The security of the cryptographic system is intended to make it difficult to manipulate the information due to the connection between the blocks and the incompatibility in the hashes of all successive blocks, adding confidence to all the stakeholders along the food chain, but specifically the consumer that buys the food. This allows for a logical story to be told on the origin of the products, cultivation, certification of organic products and awareness of the production process (Cocco &

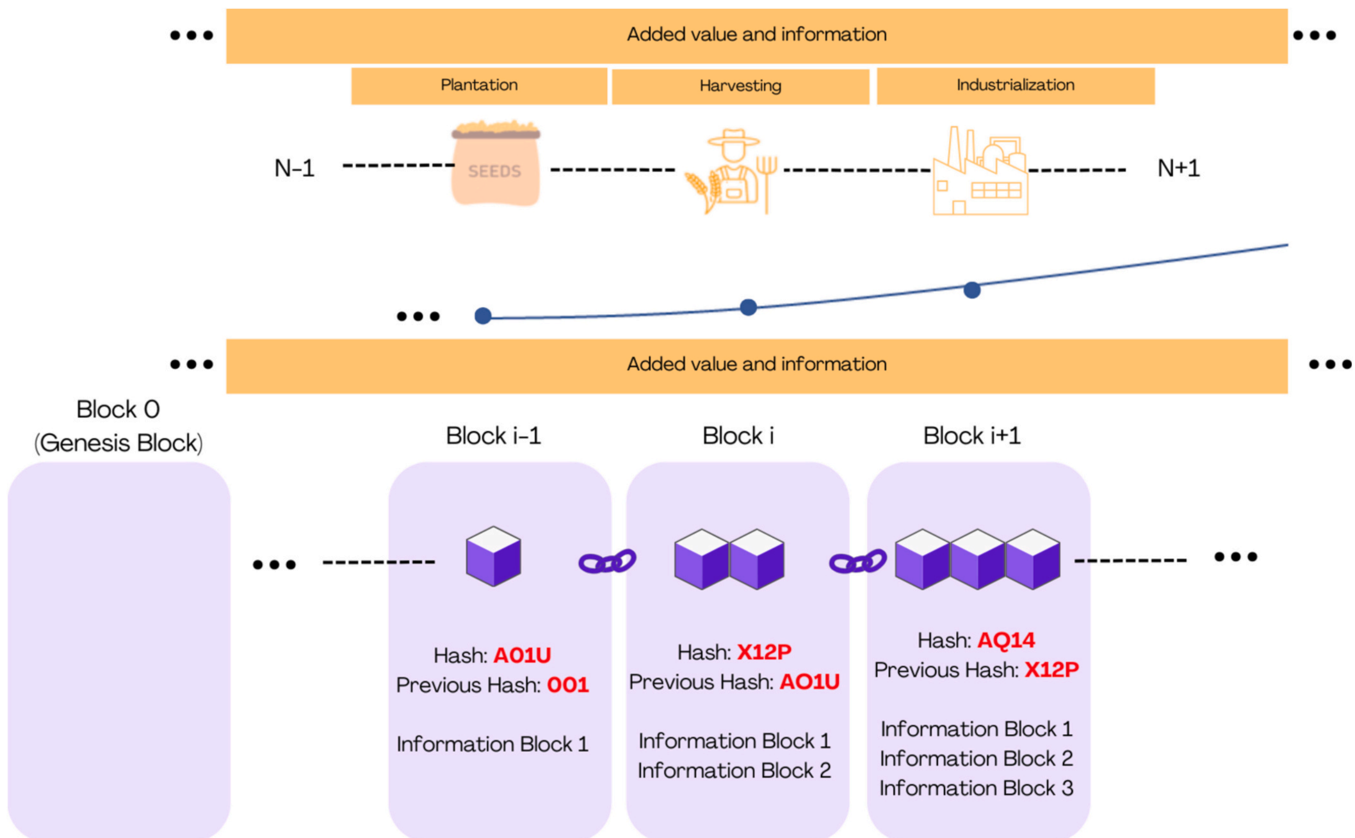

Fig. 4. Representation of the blockchain structure from farm-to-fork, each block contains a header and its respective transaction parts. Within the blocks there is information pertaining to the food, from its origin to its actual location on the food chain, including geographical locations, timestamps, temperature, among many other information that will inform on the security, inviolability and safety of the food. The blocks are connected using hash links, which are all interconnected.

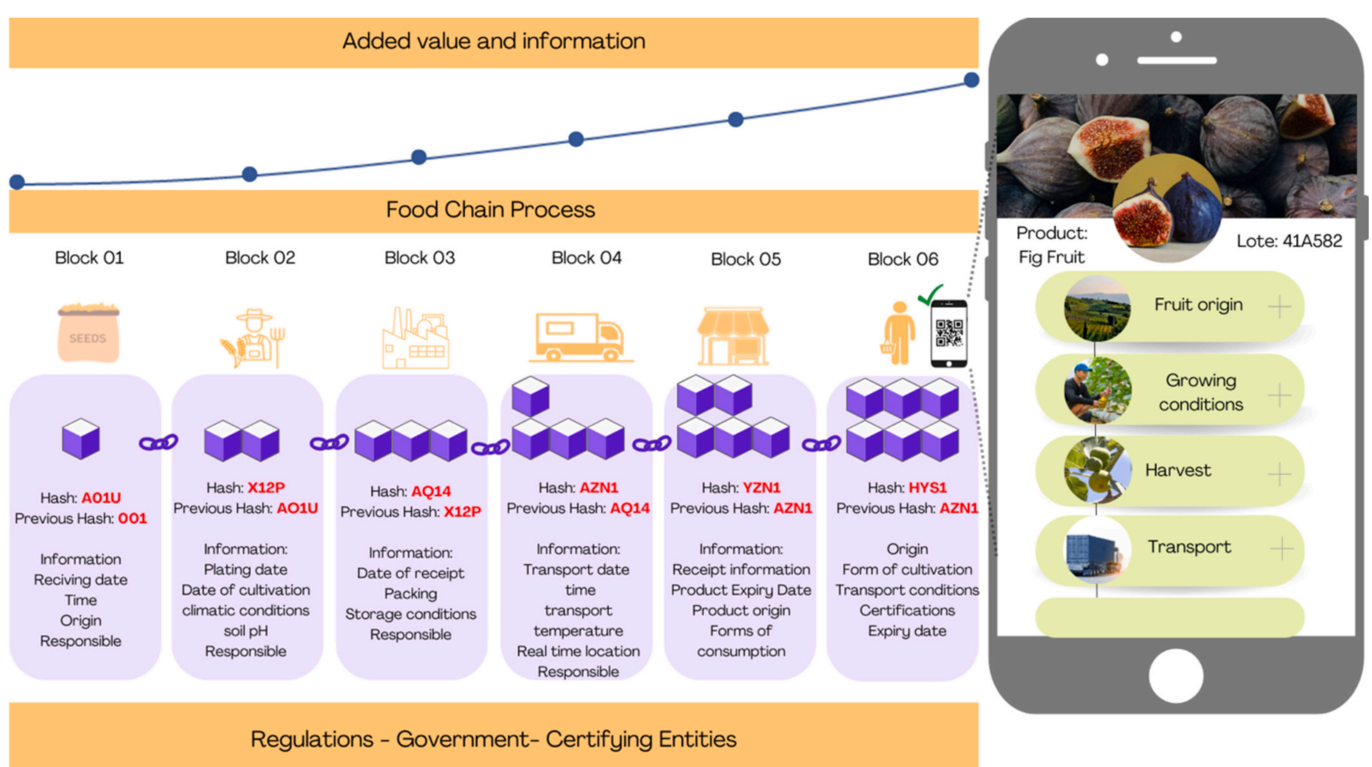

Fig. 5. Representation of the blockchain blocks with increasing information and linkage, and connection to smartphone for displaying all relevant information.

Mannaro, 2021; Tang et al., 2021). Fig. 5 presents an example of a blockchain Farm-to-Fork application using the fig fruit chain as example. One great advantage of blockchain is the fact that all information can be accessed real-time with smart devices like smartphones, showing all relevant information since the product was first planted or collected from the field or farm. This is an empowering tool for consumers, which can be clarified on the origin of meats or vegetables, used processes for animal sacrifice, food additives used, timespan since shipping to shelves, storage conditions, among many other important information, in seconds.

The need for an efficient, safe, and high-quality fruit system may be possible by using blockchain as a "ledger" that connects information transactions in an inviolable, transparent, fast, and secure way with smart contracts that allow communication and trust. The origin of this technology first appeared in 2008, when Satoshi Nakamotusing a pseudonym, published "Bitcoin: A Peer-to-Peer Electronic Cash System." This peer-to-peer electronic cash system allows for reliable transactions without intermediaries and was the basis for developing the first cryptocurrency, Bitcoin (Nakamoto, 2008.). Blockchain technology, also known as Distributed Ledger Technology (DLT), enables transparent and tamper-proof record-keeping of transactions, contracts, and other data without the need for intermediaries such as banks, governments, or other central authorities, with the potential to transform various industries and sectors by increasing efficiency, reducing costs, increasing transparency and facilitating secure transactions. The financial industry is one of the most significant applications of DLT, as it is used for safe and efficient cross-border payment and settlement systems or for issuing and tracking digital assets such as cryptocurrencies (Ko et al., 2018). There are several types of blockchain technologies, namely public blockchain, a distributed and unrestricted operating system where anyone can join the network anonymously and access available information, although with limited volume and speed, validate blocks, and send transactions. Private blockchain, which is a closed and restricted operating system used by invitation for internal and personal company usage, with high speed of shared information transmission. Consortium blockchain, a closed, privately owned, open operating system with companies or individuals who need to collaborate with data from different sources, and finally hybrid blockchain, a network with public and private blockchain characteristics, with information available publicly and restricted, allowing participate to view only specific information.

3.1. Opportunities and challenges

Blockchain is revolutionizing the food manufacturing industry with its potential for secure and decentralized information sharing between producers, farmers, and markets. A great example of the use of blockchain in the industry is the IBM Food Trust, a collaborative network involving several players in the food industry, aiming at enhancing the visibility and the accountability across the food chain. By sharing Farm-to-Fork information with security, transparency and traceability based on the blockchain technology, the platform is an outstanding example of how blockchain can create an innovative, efficient, and sustainable ecosystem for sharing food-related data, as is represented in Fig. 6. By automating processes and ensuring information security, this technology is enabling a more secure and transparent future for the food industry (Rejeb et al., 2020).

Table 1 presents problems related to FW and FL in different food chain processes and respective blockchain solutions either through enterprises that have implemented them or research that points to a resolution through blockchain methods.

Technology in the food industry can significantly impact financial transparency and supply chain management by reducing verification and surveillance costs, and help establish trusting relationships between trading partners, lowering the overall cost. Real-time transparency through blockchain further enables manufacturers to save on management surveillance expenses, decreasing the need for intensive and costly surveillance (Ko et al., 2018). In addition, it can reduce network costs between companies and suppliers by eliminating intermediaries (Xiong et al., 2020). Modern companies and their stakeholders have diverse objectives, including maximizing total revenue rather than just profit (Ko et al., 2018).

The contributions of digital technology to the food market are undeniable; however, regarding blockchain, there are still several

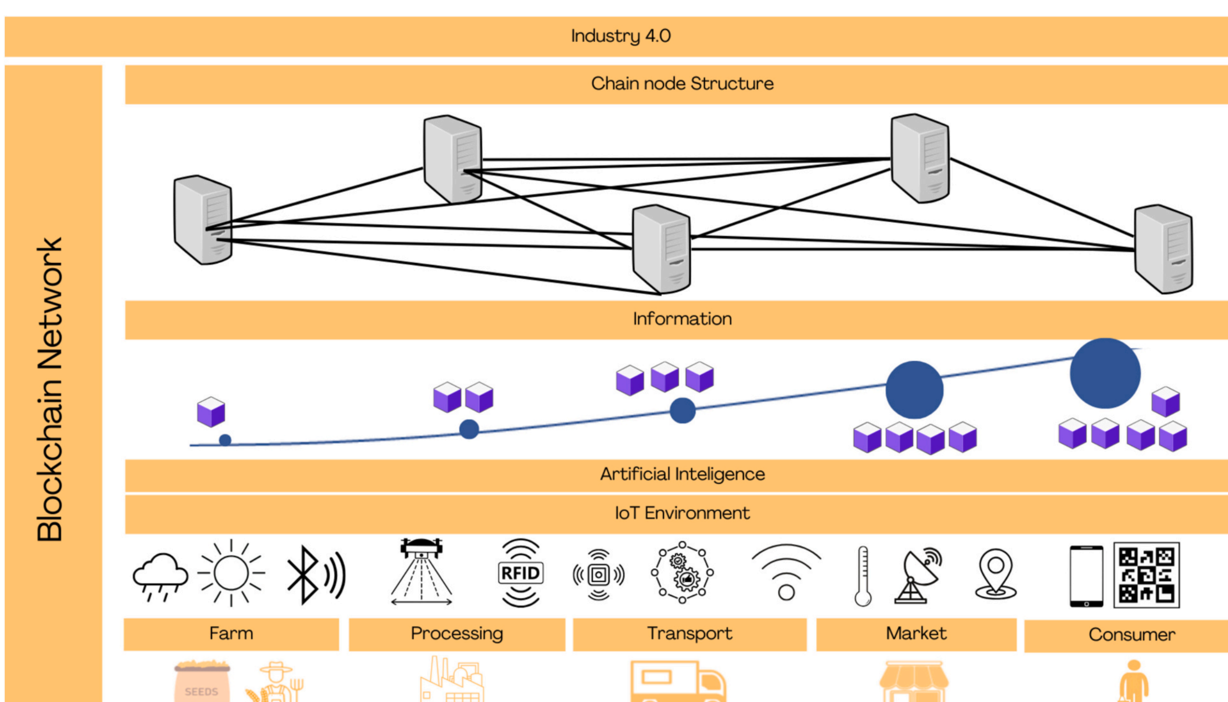

Fig. 6. Representation of the functioning of IoT, AI, and blockchain technologies in the production chain: farm-to-fork.

Table 1
Solutions involving blockchain in the food production chain.

Problems	Process involved	Cause	Blockchain solution
Loss	Cold storage	Maturation control (Crisosto et al., 2011)	Transport environment control (Y. Zhang et al., 2022)
Loss	Post-harvest	Granulation in citrus fruit associated with pre-harvest factors, including fruit size, fruit picking time, tree age and irrigation (Yao et al., 2018)	Sensors in real-time for controlling the production process and harvesting (Benyam et al., 2021)
Loss	Supply chain	Management and security problems	Mojix company (https://www.mojix.com/) has traceability to provide operational insights
Waste	Management	Food waste management in the hospitality industry	Increased performance and customer loyalty (Kopanaki et al., 2021)
Waste	Farm	Rural waste	Efficient use of agricultural waste (D. Zhang, 2019)
Waste	Distribution and Logistics	Inefficiency in transport	A real-time tracking system with machine learning tools (Saurabh & Dey, 2021)

challenges that have to be overcome. The large amounts of generated data (Pandey et al., 2022) in food production require quick processing capacity for transactions, data storage, and personal or commercial information privacy, which is not always easy, and places pressure on facilities that store this data. Programs with flaws in the source code can generate security threats that put companies at risk of losing data and revenues, giving rise to privacy and security problems. Interoperability between different platforms is also challenging, due to several programming languages having to be used to communicate among the platforms (Rejeb et al., 2020; Tanwar et al., 2022).

van Hilten et al. (2020) pointed out the main constraints of adopting blockchain technologies by most food sector enterprises, until it could be a practical and efficient solution. Adopting blockchain could be difficult due to a lack of familiarity, high initial costs, and uncertainty about the long-term benefits. Furthermore, some sectors require data with different levels of detail, and blockchain can face difficulties meeting this need, especially in complex environments. Confidentiality and privacy is also quite paramount, as some information might be confidential for specific stakeholds, constitute trade secrets of intellectual property. A lack of transparent governance in blockchain can lead to difficulties in defining who has the authority to make decisions and manage system updates. Some blockchain implementation and maintenance processes may require a high level of labor, especially in initial phases. Deciding which data is included in the blockchain is challenging, as too much data can be irrelevant or overwhelm the system. A high level of computerization is required to support this level of technology integration, which may exclude some partners from blockchain-based solutions.

3.2. Case studies

Some stakeholds of the wine industry have put it among the few that have adopted blockchain in their network, promoting greater efficiency, traceability, transparency, and sustainability in various processes, such as cultivation, production, packaging, distribution, increasing consumer confidence and promoting authenticity (Malisic et al., 2023). As reported in the study by Adamashvili et al., 2024 in which IoT was used to monitor every stage of the process, from the cultivation of the vines to the packaging of the bottles. Wineries such as De Maison Selections and Ste. Michelle Wine Estates, the third largest producer of premium wines in the United States, are at the forefront of adopting blockchain technologies to offer consumers and business partners a complete and transparent view of the production chain. Using this technology, both brands allow access to detailed information about each stage of the process, including the preservation of the wine, strict temperature control during storage and transportation. The traceability offered by the blockchain ensures that the wine maintains its quality from its origin until it reaches the end consumer. De Maison Selections, for example, uses blockchain to immutably document and monitor every stage of the production and logistics process, ensuring that essential temperature control is maintained to preserve the characteristics of fine wines. With this technology, consumers can verify the origin of each bottle and have full confidence in the authenticity of the product they are buying. At the same time, the winery's commercial partners have the guarantee that quality standards are strictly adhered to. The technology makes it possible to record every detail of agricultural and manufacturing practices, so that both retailers and consumers know the complete journey of each bottle of wine adopted blockchain and other technologies developed in collaboration with the IBM Cloud. VinAssure™ connects all links in the wine supply chain, increasing traceability and efficiency through secure data exchange, highlighting the benefits of transparency in communication with consumers. Ernst and Young also collaborates with wineries to create blockchain solutions that guarantee the authenticity of wine, allowing consumers to trace its journey to the bottle. Wineries like Rucci Curbastro and Ruffino use the *My Story* platform to offer verified product information via QR codes, increasing brand visibility. In addition, renowned brands such as Robert Mondavi and Trefethen Family Vineyards are experimenting with selling limited edition wines via cryptocurrencies, exploring new forms of marketing and traceability (Adamashvili et al., 2024).

In the food sector, other supply chains are pondering the application of these technologies, namely for fresh produce, including tracking systems that monitor products from Farm-to-Fork, namely the HerB-Chain cryptographic algorithm, together with blockchain technology to maintain data integrity and require a mobile app to decode QR codes, allowing fast and scalable access to data, optimizing storage and security. Other examples used in grains and cereals is the Rice Coin, which combines IoT and blockchain technologies for real-time monitoring and use sensors to ensure the safety and traceability of rice. Artificial intelligence (AI) technology assists in quality grading and monitoring rice throughout the supply chain, facilitating real-time data tracking and analysis. The NUTRIA and Algorand projects use blockchain and AI to monitor quality and consumption data, automating data collection and enabling predictive analysis to prevent waste. AI-based smart contracts optimize the storage and distribution of dairy data and simplify chain management. AI analyzes demand and storage conditions, helping reduce costs and ensure supply meets demand.

Meat, Poultry, and Seafood: Blockchain solutions integrated with IoT offer traceability for halal beef and seafood.

The global blockchain market in agricultural and food supply chains was valued at $133 million in 2020 and is expected to reach $948 million by 2025, growing at an annual rate of 48.1 %. Major retailers such as Walmart and Carrefour, as well others such as Nestlé and Conde de Benalúa, have adopted blockchain technology to improve product traceability for consumers. For example, the Spanish olive oil cooperative Conde de Benalúa, with more than 2000 farmers, uses blockchain to monitor product life cycles, ensuring traceability, authenticity, and quality. Similarly, Dole uses blockchain to track salads and fresh vegetables, while Carrefour monitors the journey of chickens, eggs, and tomatoes from the farm to the store. Nestlé applies blockchain to its luxury coffee brand Zoégas, securely recording production and transaction data (Cao et al., 2022; Sri Vigna Hema & Manickavasagan, 2024).

Platforms like IBM Food Trust, TE-FOOD, FairChain, Open SC, and Water Ledger use blockchain to increase transparency and traceability in food production and supply. Here, blockchain technology helps trace food products' origin, quality, and sustainability, ensuring that data about their origins and production processes is reliable and transparent. In terms of food delivery, platforms such as DoorDash, Uber Eats, Eat, Deliveroo, Domino's, and Pizza Hut incorporate blockchain to improve the reliability and transparency of food delivery services. The blockchain ensures that data on the origin, preparation, and delivery of food items is accurate and secure, offering customers greater confidence in the quality and safety of their food.

4. Challenges of implementing blockchain technology from "farm-to-fork"

Although blockchain offers several advantages, such as trust, responsibility, and information sharing, significant barriers exist to its effective implementation. Adoption and governance are critical aspects of blockchain reaching its full potential, especially in complex sectors such as the food supply chain.

5. Conclusion and perspectives

In a scenario of continuous population growth, the demand for massive volumes of food becomes an undeniable reality; the food industry faces significant challenges in meeting growing global demand while minimizing food loss and waste. These issues span developed and developing regions, driven by inefficient processes, outdated technologies, and low consumer awareness. This problem is particularly pressing in perishable supply chains, like those for fruits, where spoilage rates are high. Emerging technologies, especially blockchain, offer transformative potential by enhancing transparency, traceability, and food safety. Blockchain's secure data management and increased accountability can help mitigate FLW, align with global sustainability efforts, and foster a more resilient and efficient future.

With the emergence of these technologies, integrating blockchain on a large scale is challenging. Key challenges, including scalability, interoperability, data accuracy, security, and ethical concerns, particularly around AI and IoT integration. Addressing these will demand collaboration among governments, regulatory bodies, and supply chain stakeholders to establish interoperability standards, provide clear policy recommendations, and drive broader blockchain adoption. Additionally, future research must encompass cost-benefit analyses to evaluate blockchain's economic viability, comparative studies of different platforms, and an expanded focus on diverse food products, regions, and supply chain actors.

Achieving a sustainable food system also requires a shift from traditional linear supply chains to circular models emphasizing co-product reuse, reducing FLW across all stages of production. This transition is essential for advancing the United Nations Sustainable Development Goals. Public policies, consumer awareness, and coordinated action among technology providers, supply chain participants, and policymakers are pivotal to this transformation.

Future challenges involve leveraging blockchain alongside AI, IoT, and Industry 4.0 innovations to make the food supply chain more efficient, reliable, and sustainable. This holistic approach will help meet the demands of a growing global population while minimizing environmental impacts, ultimately creating a secure and sustainable food system that aligns with the SDGs and secures resources for future generations. While new disruptive technologies might appear in the food chain, it is expected that with higher connectivity of society to the digital world the food chain will become more digital, and with it, blockchain is a means of using that digitalization to improve safety and security but mainly to reduce FLW. Access to internet will increase, as the cost of acces will decrease, sustainable and discardable tracking devices and microprocessors will reduce in price, allowing an easier integration of blockchain in underdeveloped countries, which will help the implementation of blockchain. Overall, while this technology is used by big players in the foodchain (with resources to monitor their logistical environment and reduce waste and costs) or in niche sectors (wine), with lowering costs and higher demand of transparency from consumers, blockchain will inevitably become more prevalent in the industry in the coming years, probably a widespread technology in a not so distant future.

CRediT authorship contribution statement

Carlos S.H. Shiraishi: Writing – original draft, Conceptualization. **Custódio Lobo Roriz:** Writing – review & editing, Writing – original draft. **Márcio Carocho:** Writing – review & editing, Funding acquisition, Conceptualization. **Miguel A. Prieto:** Writing – review & editing, Supervision. **Rui M.V. Abreu:** Writing – review & editing. **Lillian Barros:** Writing – review & editing, Supervision, Funding acquisition. **Sandrina A. Heleno:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they do not know competing financial interests.

Acknowledgments

This work was supported by national funds through FCT/MCTES (PIDDAC): CIMO, UIDB/00690/2020 (DOI: 10.54499/UIDB/00690/2020) and UIDP/00690/2020 (DOI: 10.54499/UIDP/00690/2020); and SusTEC, LA/P/0007/2020 (DOI: 10.54499/LA/P/0007/2020); national funding by FCT, P.I., through the institutional scientific employment program-contract for L. Barros and S. Heleno, and the contract of M. Carocho (CEEC-IND/00831/2018) through the individual scientific employment program-contract; and C.S.H·S thanks the Fundação para a Ciência e Tecnologia (FCT), Portugal for the Ph.D. Grant 2023.04950.BD.

Data availability

No data was used for the research described in the article.

References

Adamashvili, N., Zhizhilashvili, N., & Tricase, C. (2024). The integration of the internet of things, artificial intelligence, and blockchain technology for advancing the wine supply chain. *Computers, 13*(3), 72. https://doi.org/10.3390/COMPUTERS13030072, 2024, Vol. 13, page 72.

Adjognon, G. S., Bloem, J. R., & Sanoh, A. (2021). The coronavirus pandemic and food security: Evidence from mali. *Food Policy, 101*, Article 102050. https://doi.org/10.1016/J.FOODPOL.2021.102050

Amicarelli, V., & Bux, C. (2020). Food waste measurement toward a fair, healthy and environmental-friendly food system: A critical review. *British Food Journal, 123*(8), 2907–2935. https://doi.org/10.1108/BFJ-07-2020-0658/FULL/PDF

Arvaniti, O. S., Samaras, Y., Gatidou, G., Thomaidis, N. S., & Stasinakis, A. S. (2019). Review on fresh and dried figs: Chemical analysis and occurrence of phytochemical compounds, antioxidant capacity and health effects. *Food Research International, 119*, 244–267. https://doi.org/10.1016/J.FOODRES.2019.01.055

Awan, S., Ahmed, S., Ullah, F., Nawaz, A., Khan, A., Uddin, M. I., … Alyami, H. (2021). IoT with blockchain: A futuristic approach in agriculture and food supply chain. *Wireless Communications and Mobile Computing, 2021*(1), Article 5580179. https://doi.org/10.1155/2021/5580179

Ayuso, M., Carpena, M., Taofiq, O., Albuquerque, T. G., Simal-Gandara, J., Oliveira, M. B. P. P., … Barros, L. (2022). Fig "*Ficus carica* L." and its by-products: A decade evidence of their health-promoting benefits towards the development of novel food formulations. *Trends in Food Science & Technology, 127*, 1–13. https://doi.org/10.1016/J.TIFS.2022.06.010

Barman, A., Das, R., & De, P. K. (2021). Impact of COVID-19 in food supply chain: Disruptions and recovery strategy. *Current Research in Behavioral Sciences, 2*, Article 100017. https://doi.org/10.1016/J.CRBEHA.2021.100017

Ben Hassen, T., & el Bilali, H. (2022). Impacts of the Russia-Ukraine war on global food security: Towards more sustainable and resilient food systems? *Foods, 11*(15). https://doi.org/10.3390/foods11152301

Benyam, A., Soma, T., & Fraser, E. (2021). Digital agricultural technologies for food loss and waste prevention and reduction: Global trends, adoption opportunities and barriers. *Journal of Cleaner Production, 323*, Article 129099. https://doi.org/10.1016/j.jclepro.2021.129099

Berning, E. H., Andersen, C. V. H., Mertz, O., Dickinson, N., Opgenorth, M., Lincoln, N. K., … Rønsted, N. (2022). Resilience of breadfruit agro-ecosystems in Hawai'i during the COVID-19 pandemic. *CABI Agriculture and Bioscience, 3*(1). https://doi.org/10.1186/s43170-022-00125-3

Cao, Y., Yi, C., Wan, G., Hu, H., Li, Q., & Wang, S. (2022). An analysis on the role of blockchain-based platforms in agricultural supply chains. *Transportation Research Part E: Logistics and Transportation Review, 163*, Article 102731. https://doi.org/10.1016/J.TRE.2022.102731

Castro Campos, B., & Qi, X. (2024). A literature review on the drivers and barriers of organic food consumption in China. *Agricultural and Food Economics, 12*(1). https://doi.org/10.1186/s40100-024-00312-y

Cattaneo, A., Federighi, G., & Vaz, S. (2021). The environmental impact of reducing food loss and waste: A critical assessment. *Food Policy, 98*. https://doi.org/10.1016/j.foodpol.2020.101890

Cattaneo, A., Sánchez, M. V., Torero, M., & Vos, R. (2021). Reducing food loss and waste: Five challenges for policy and research. *Food Policy, 98*, Article 101974. https://doi.org/10.1016/J.FOODPOL.2020.101974

Cisternas, I., Velásquez, I., Caro, A., & Rodríguez, A. (2020). Systematic literature review of implementations of precision agriculture. *Computers and Electronics in Agriculture, 176*, Article 105626. https://doi.org/10.1016/J.COMPAG.2020.105626

Cocco, L., & Mannaro, K. (2021). Blockchain in agri-food traceability systems: A model proposal for a typical Italian food product. In *2021 IEEE international conference on software analysis, evolution and reengineering (SANER)*. https://doi.org/10.1109/SANER50967.2021.00085. March).

Collins, A., Galli, A., Hipwood, T., & Murthy, A. (2020). Living within a one planet reality: The contribution of personal footprint calculators. *Environmental Research Letters, 15*(2), Article 025008. https://doi.org/10.1088/1748-9326/AB5F96

Crisosto, H., Ferguson, L., Bremer, V., Stover, E., & Colelli, G. (2011). Fig (Ficus carica L.). *Postharvest Biology and Technology of Tropical and Subtropical Fruits: Cocona to Mango*, 134–158. https://doi.org/10.1533/9780857092885.134

Davis, K. F., Downs, S., & Gephart, J. A. (2020). Towards food supply chain resilience to environmental shocks. *Nature Food, 2*(1), 54–65. https://doi.org/10.1038/s43016-020-00196-3, 2020 2:1.

FAO. (2020). The role of digital technologies in livestock traceability and trade. *FAO*. https://www.fao.org/publications/card/en/c/CA9939EN/.

Food and Agriculture Organization of the United Nations. (2020). *Fruit and vegetables- your dietary essentials*. https://doi.org/10.4060/cb2395en

Gense, K., Peterseil, V., Licina, A., Wagner, M., Cichna-markl, M., Dobrovolny, S., & Hochegger, R. (2021). Development of a DNA Metabarcoding method for the identification of bivalve species in seafood products. *Foods, 10*(11), 2618. https://doi.org/10.3390/FOODS10112618, 2021, Vol. 10, page 2618.

George, W., & Al-Ansari, T. (2023). Review of blockchain applications in food supply chains. *Blockchains, 1*(1), 34–57. https://doi.org/10.3390/BLOCKCHAINS1010004. *2023, Vol. 1,* Pages 34–57.

Gondal, M. U. A., Khan, M. A., Haseeb, A., Albarakati, H. M., & Shabaz, M. (2023). A secure food supply chain solution: Blockchain and IoT-enabled container to enhance the efficiency of shipment for strawberry supply chain. *Frontiers in Sustainable Food Systems, 7*, Article 1294829. https://doi.org/10.3389/FSUFS.2023.1294829/BIBTEX

Gorini, T., Mezzasalma, V., Deligia, M., de Mattia, F., Campone, L., Labra, M., & Frigerio, J. (2023). Check your shopping cart: DNA barcoding and mini-barcoding for food authentication. *Foods, 12*(12). https://doi.org/10.3390/foods12122392

van Hilten, M., Ongena, G., & Ravesteijn, P. (2020). Blockchain for organic food traceability: Case studies on drivers and challenges. *Frontiers in Blockchain, 0*, 43. https://doi.org/10.3389/FBLOC.2020.567175

Ishangulyyev, R., Kim, S., & Lee, S. H. (2019). Understanding food loss and waste—why are we losing and wasting food? *Foods, 8*(8), 297. https://doi.org/10.3390/FOODS8080297, 2019, Vol. 8, page 297.

Ivanov, D. (2018). *Structural dynamics and resilience in supply chain risk management* (p. 265). https://doi.org/10.1007/978-3-319-69305-7

Joshi, P., & Visvanathan, C. (2019). Sustainable management practices of food waste in Asia: Technological and policy drivers. *Journal of Environmental Management, 247*, 538–550. https://doi.org/10.1016/J.JENVMAN.2019.06.079

Kim, S., & Lee, S. H. (2020). Examining household food waste behaviours and the determinants on Korea using new questions in a national household survey. *Sustainability, 12*, 8484. https://doi.org/10.3390/su12208484

Ko, T., Lee, J., & Ryu, D. (2018). Blockchain technology and manufacturing industry: Real-time transparency and cost savings. *Sustainability, 10*(11), 4274. https://doi.org/10.3390/SU10114274, 2018, Vol. 10, page 4274.

Kopanaki, E., Stroumpoulis, A., & Oikonomou, M. (2021). The impact of blockchain technology on food waste management in the hospitality industry. *Entrenova - Enterprise Research Innovation, 7*(1), 428–437. https://doi.org/10.54820/cqrj6465

Lipinski, B., Hanson, C., Waite, R., Searchinger, T., & Lomax, J. (2013). *Installment 2 of "creating a sustainable food future" reducing food loss and waste*. http://pdf.wri.org/reducing_food_loss_and_waste.pdf.

Malisic, B., Misic, N., Krco, S., Martinovic, A., Tinaj, S., & Popovic, T. (2023). Blockchain adoption in the wine supply chain: A systematic literature review. *Sustainability (Switzerland), 15*(19), Article 14408. https://doi.org/10.3390/SU151914408/S1

Mardones, F. O., Rich, K. M., Boden, L. A., Moreno-Switt, A. I., Caipo, M. L., Zimin-Veselkoff, N., … Baltenweck, I. (2020). The COVID-19 pandemic and global food security. *Frontiers in Veterinary Science, 7*. https://doi.org/10.3389/FVETS.2020.578508

Nakamoto, S. (2008). *Bitcoin: A Peer-to-Peer Electronic Cash System*. www.bitcoin.org.

Nicastro, R., Carillo, P., Lange, S., & Schmidt, T. (2021). Food loss and waste prevention strategies from farm to fork. *Sustainability, 13*(10), 5443. https://doi.org/10.3390/SU13105443, 2021, Vol. 13, page 5443.

Pandey, V., Pant, M., & Snasel, V. (2022). Blockchain technology in food supply chains: Review and bibliometric analysis. *Technology in Society, 69*, Article 101954. https://doi.org/10.1016/J.TECHSOC.2022.101954

Paolucci, M., di Stasio, M., Sorrentino, A., la Cara, F., & Volpe, M. G. (2020). Active edible polysaccharide-based coating for preservation of fresh figs (Ficus carica L.). *Foods, 9*(12). https://doi.org/10.3390/FOODS9121793

Rejeb, A., Keogh, J. G., Zailani, S., Treiblmaier, H., & Rejeb, K. (2020). Blockchain technology in the food industry: A review of potentials, challenges and future research directions. *Logistics, 4*(4), 27. https://doi.org/10.3390/LOGISTICS4040027, 2020, Vol. 4, page 27.

Ritchie, Hannah, Rosado, Pablo, & Roser, Max (2023). *Hunger and Undernourishment*. Published online at OurWorldinData.org. Retrieved from https://ourworldindata.org/hunger-and-undernourishment [Online Resource].

Ruviaro, C. F., Borges, A., Farinha, M., Bernardo, L. M., Morais, H. B., Leis, C. M., & Domingues, C. F. (2020). Food losses and wastes in Brazil: A systematic review. *Desenvolvimento Socioeconômico Em Debate, 6*(1), 78–90. https://doi.org/10.18616/RDSD.V6I1.5878

Sagar, N. A., Pareek, S., Sharma, S., Yahia, E. M., & Lobo, M. G. (2018). Fruit and vegetable waste: Bioactive compounds, their extraction, and possible utilization. *Comprehensive Reviews in Food Science and Food Safety, 17*(3), 512–531. https://doi.org/10.1111/1541-4337.12330

Saitone, T. L., & Sexton, R. J. (2017). Agri-food supply chain: Evolution and performance with conflicting consumer and societal demands. *European Review of Agricultural Economics, 44*(4), 634–657. https://doi.org/10.1093/ERAE/JBX003

dos Santos, S. F., de Cardoso, R. C. V., Borges, Í. M. P., Almeida, A. C. E., Andrade, E. S., Ferreira, I. O., & do Ramos, L. C. (2020). Post-harvest losses of fruits and vegetables in supply centers in Salvador, Brazil: Analysis of determinants, volumes and reduction strategies. *Waste Management, 101*, 161–170. https://doi.org/10.1016/J.WASMAN.2019.10.007

Saurabh, S., & Dey, K. (2021). Blockchain technology adoption, architecture, and sustainable agri-food supply chains. *Journal of Cleaner Production, 284*. https://doi.org/10.1016/j.jclepro.2020.124731

Seyedghorban, Z., Tahernejad, H., Meriton, R., & Graham, G. (2019). *Supply chain digitalization: Past, present and future*. Doi:10.1080/09537287.2019.1631461. *31 (2–3)* pp. 96–114). https://doi.org/10.1080/09537287.2019.1631461.

Sri Vigna Hema, V., & Manickavasagan, A. (2024). Blockchain implementation for food safety in supply chain: A review. *Comprehensive Reviews in Food Science and Food Safety, 23*(5), Article e70002. https://doi.org/10.1111/1541-4337.70002

Taj, S., Imran, A. S., Kastrati, Z., Daudpota, S. M., Memon, R. A., & Ahmed, J. (2023). IoT-based supply chain management: A systematic literature review. In *, Vol. 24. Internet of things (Netherlands)*. Elsevier B.V. https://doi.org/10.1016/j.iot.2023.100982. Vol.

Tang, Y., Dananjayan, S., Hou, C., Guo, Q., Luo, S., & He, Y. (2021). A survey on the 5G network and its impact on agriculture: Challenges and opportunities. *Computers and Electronics in Agriculture, 180*, Article 105895. https://doi.org/10.1016/J.COMPAG.2020.105895

Targas, P., & Manolakos, E. S. (2010). Traceability from "farm to fork" using RFID technology. *17th IEEE International Conference on Electronics, Circuits and Systems, Athens Greece* (pp. 958–961). https://doi.org/10.1109/ICECS.2010.5724672

Tanwar, S., Parmar, A., Kumari, A., Jadav, N. K., Hong, W. C., & Sharma, R. (2022). Blockchain adoption to secure the food industry: Opportunities and challenges. *Sustainability, 14*(12), 7036. https://doi.org/10.3390/SU14127036, 2022, Vol. 14, page 7036.

Terence, S., & Purushothaman, G. (2020). Systematic review of internet of things in smart farming. *Transactions on Emerging Telecommunications Technologies, 31*(6), Article e3958. https://doi.org/10.1002/ETT.3958

Toorajipour, R., Sohrabpour, V., Nazarpour, A., Oghazi, P., & Fischl, M. (2021). Artificial intelligence in supply chain management: A systematic literature review. *Journal of Business Research, 122*, 502–517. https://doi.org/10.1016/J.JBUSRES.2020.09.009

de Vasconcelos, D. C., Viana, F. L. E., & de Souza, A. L. (2021). *Circular economy and sustainability in the fresh fruit supply chain: A study across brazil and the UK*. Doi: 10.1080/10978526.2021.1941070. *22(4)* pp. 393–421). https://doi.org/10.1080/10978526.2021.1941070.

Vigar, V., Myers, S., Oliver, C., Arellano, J., Robinson, S., & Leifert, C. (2020). A systematic review of organic versus conventional food consumption: Is there a measurable benefit on human health?. In *Nutrients*. MDPI AG. https://doi.org/10.3390/nu12010007. Vol. Vol. 12, Issue 1.

Vilariño, M. V., Franco, C., & Quarrington, C. (2017). Food loss and waste reduction as an integral part of a circular economy. *Frontiers in Environmental Science, 5*, 21. https://doi.org/10.3389/FENVS.2017.00021/BIBTEX. MAY.

Wahyuni, H. C., Rosid, M. A., Azara, R., & Voak, A. (2024). Blockchain technology design based on food safety and halal risk analysis in the beef supply chain with FMEA-FTA. *Journal of Engineering Research (Kuwait)*. https://doi.org/10.1016/j.jer.2024.02.002

Xiong, H., Dalhaus, T., Wang, P., & Huang, J. (2020). Blockchain technology for agriculture: Applications and rationale. *Frontiers in Blockchain, 3*. https://doi.org/10.3389/fbloc.2020.00007

Yao, S., Cao, Q., Xie, J., Deng, L., & Zeng, K. (2018). Alteration of sugar and organic acid metabolism in postharvest granulation of Ponkan fruit revealed by transcriptome profiling. *Postharvest Biology and Technology, 139*, 2–11. https://doi.org/10.1016/j.postharvbio.2018.01.003

Zhang, D. (2019). Application of blockchain technology in incentivizing efficient use of rural wastes: A case study on Yitong system. *Energy Procedia, 158*, 6707–6714. https://doi.org/10.1016/J.EGYPRO.2019.01.018

Zhang, Y., Chen, L., Battino, M., Farag, M. A., Xiao, J., Simal-Gandara, J., … Jiang, W. (2022). Blockchain: An emerging novel technology to upgrade the current fresh fruit supply chain. *Trends in Food Science and Technology, 124*, 1–12. https://doi.org/10.1016/J.TIFS.2022.03.030