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Agri-food traceability today: Advancing innovation towards efficiency, sustainability, ethical sourcing, and safety in food supply chains

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A R T I C L E I N F O

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A B S T R A C T

Background: The increasing globalization and complexity of agri-food supply chains have heightened the demand for transparency, safety, and traceability in food systems. The integrity, authenticity, and safety of food products are critical, and the implementation of specific and reliable protocols for tracing and tracking is becoming the priority in food industry. Food supply chains often lack efficiency and consumers are becoming more conscious of the origin and quality of the foods they purchase, demanding more accurate systems for data delivery. In this light a straightforward understanding of agri-food supply chain traceability has become necessary.

Scope and approach: This review provides a roadmap for food traceability systems from legal requirements, to technological and analytical perspectives. The review explores key concepts such as tracking and tracing, outlines international regulatory frameworks, and introduces a novel taxonomy that classifies traceability systems by technological maturity and data granularity. Particular focus is given to innovative analytical technologies, such as proteomics, metabolomics/volatilomics, genomics, stable isotope and elemental profiling, as well as emerging digital technologies including AI and AsI, blockchain, IoT and FCM. Case studies for wine, garlic, and coffee traceability, demonstrate the application of these tools in real-world industrial and local scenarios.

Key findings and conclusion: By integrating regulatory insights with innovative technologies, the review highlights best practices and strategic directions for boosting efficiency for end-to-end traceability. The review addresses innovative technologies for advanced food supply chains and underscores the role of traceability systems in building consumer trust, supporting public health, and advancing sustainable food production.

1. Introduction

The evolution of food systems into globally interconnected and highly complex networks has redefined consumer expectations and heightened demands for transparency and traceability, reshaping consumer evaluation and purchasing decisions. Effective control of product flow and assurance of food safety are based on robust traceability systems capable of identifying each unit from production to consumption (Anastasiadis et al., 2022). Nonetheless, the integrity of agri-food supply chains is often compromised by food safety incidents resulting from adulteration, dilution, tampering, or counterfeiting. Notable food safety incidents (Chammem et al., 2018), such as bovine spongiform encephalopathy (Smith & Bradley, 2003), the Chinese milk scandal (Parry, 2008), and the European horse meat incident (Stanciu, 2015), have contributed to decline in consumer trust, underscoring the necessity for technologies that enable automatic and reliable monitoring of product throughout the agri-food supply chain (Anastasiadis et al., 2022). While not all incidents posed direct health risks, the opacity of supply chains has compromised consumer confidence in the integrity of food system. Safety of food and matrices is of critical importance and tracing food and feed throughout the food chain is crucial for the protection of consumers, particularly when food and feed are found to be faulty. A scalable, sustainable, and inclusive traceability system may play a critical role in mitigating consumer uncertainty, preventing food

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safety crises, and safeguarding public health, thereby protecting economic interests and business reputations. As supply chains become more globalized, understanding the cues and information on which consumers rely becomes essential (Wu et al., 2021). Taking inspiration from these necessities, **traceability/authentication** of food is implemented to ascertain several factors: i) whether the food descriptions align with the legal requirements for its designation; ii) whether the ingredients have been substituted with lower-cost alternatives to boost profits; iii) if the manufacturing process is appropriate; iv) whether the claims regarding origin, geographical or species-specific are accurate (Molyneux, 2017) and v) whether targeted and accurate information on specific products is delivered to the consumer thus facilitating the rapid identification of batches to be recalled in the event of non-compliance or risks to public health. However, full traceability remains challenging due to the inherent complexity of agri-food supply chains which limits farm-to-table traceability. Consequently, the aim of this review is to offer a comprehensive and accessible overview of food traceability by addressing its conceptual, legal, and technological dimensions, taking into account the rapid evolution of technologies such as blockchain, AI, IoT and their potential in advancing the Sustainable Development Goals (FAO, 2025) related to the agri-food sector.

The first section is dedicated to the definition of traceability from both the producer's and the consumer's perspectives, highlighting their role in ensuring safety, transparency, and accountability across the food supply chain. The review then positions traceability within the current legal and regulatory frameworks, clarifying the documentation, standards, and compliance obligations that underpin traceability practices. The second section presents a new level stratification of the main systems, technologies, and analytical strategies employed in traceability, ranging from molecular and analytical methods to digital innovations such as blockchain, artificial intelligence, and the Internet of Things. In the third section these tools and workflows are presented in a clear and intuitive format through case studies, to support understanding among academics, producers, and informed consumers alike. Finally, the perspectives and best practices for a food traceability system are reported along with the concluding remarks.

2. Food traceability, a universal framework: tracing'n tracking

The Food and Agriculture Organization of the United Nations (FAO) in 2006 outlined the concept of food traceability, which is the ability to track the journey of a food product across various stages, including production, processing, and distribution (FAO, 2025). The main objective of food traceability is to quickly and accurately identify products that may pose a risk, helping to prevent health hazards, reduce waste of resources, and avoid financial losses throughout the supply chain. The FAO established the Codex Alimentarius in 1983, which has developed internationally recognized food standards and guidelines to safeguard end users' health and promote relevant practices in the global food trade. In the codex, a series of guidelines for assessing food safety of ingredients and raw materials is also reported. Additionally, the Food Safety System Certification (FSSC 22000) was introduced as a certification scheme with technical specifications tailored to food safety in the production sector. It is based on the internationally recognized ISO 22000 standard (International Organization for Standardization) and is supplemented by technical standards such as ISO TS 22002–1 for food manufacturing and ISO TS 22002–4 for packaging manufacturing. Furthermore, it is fully compatible with other standards, including ISO 9001 and ISO 14001, ensuring alignment with high-quality production and environmental management practices (Jovine, 2024).

Over the years, a lot of definitions have been proposed and in 2013 have led to the definition made by Olsen and Borit: "*traceability is the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications*". Traceability requires systematic documentation of the properties of "*the subject under consideration*" some of which can be verified using analytical tools and methods. The key aspect is that traceability is defined by both the recording of information and the provision of access to that recorded information (Olsen & Borit, 2013). It would be necessary to complement the European tracing tool workflow by developing an open, accessible, easy to use data collection tool (for example within the R4EU platform) to collect and report tracing data and to extract relevant information for tracing from the EU rapid alert system for food and feed database notifications. Traceability, in absolute terms, does not exist if not inserted in a food traceability system (FTS), because traceability is part of the contemporary food supply chains in the food production industry (Olsen & Aschan, 2010). Traceability is strictly related to both concepts of "tracing" and "tracking". These concepts analyze an entity, in our case a food product, within the supply chain, with tracing referring to upstream tracking (backward) and tracking referring to downstream movement (forward). Tracing is defined as "*the ability to trace the history, application or location of an entity by means of recorded identifications*" while tracking is defined as "*the ability to follow a food, feed, food-producing animal or substance intended to be, or expected to be incorporated into a food or feed through all stages of production, processing and distribution*". In this context, tracing can recover historical information about a specific food, including ethnopharmacological relevance, while the tracking can be applied through all stages of production, processing and distribution of foods. Three essential characteristics of food traceability have been highlighted by Molyneux (Molyneux, 2017) and are: 1) provenance; 2) authentication; 3) curation.

1) Provenance refers to establishing the geographical origin of food and agricultural products, a pressing global issue of significant interest. Identifying the geographical origin is vital for developing new products, ensuring quality and protection of traditional national products, many of which represent niche markets and are closely tied to specific regional identities, and gaining access to markets.
2) Authentication is the analytical process that verifies the claim information regarding the food's origin and production methods. The analysis must be conducted by an expert who need to provide a botanical identification of the raw material. Furthermore, it is possible to perform microscope analyses with the aim to find potential contaminations related to food fraud. Food authenticity identification has expanded beyond the detection of adulteration to encompass the evaluation of product quality, verification of label compliance, assessment of traceability, and other related quality parameters. As a result, the development of high-throughput and rapid analytical techniques is imperative to address these multifaceted requirements (Zhang et al., 2025).
3) Curation involves systematic collection, preservation, organization, and maintenance of plant specimens for scientific research and analysis.

Another important aspect in food traceability is the detection and fight of food fraud. Food fraud is the intentional deception or misrepresentation of food products for economic gain. Food fraud erodes consumer confidence, threatens public health, and can lead to considerable economic consequences for the food industry. Regulatory agencies and industry standards work to prevent and identify food fraud to safeguard public health and maintain the integrity of the food supply chain. Various scientific and governmental organizations have developed guidelines to assess food quality, including methods for authentication to detect fraud and traceability to evaluate the origins of products. The Food Chemicals Codex (FCC) offers guidelines and technical specifications for evaluating the identity, quality, and purity of approximately twelve hundred food ingredients, while the United States Pharmacopeia provides reference materials to support these specifications. As a result, any food ingredient legally marketed globally can be included in the FCC, which is recognized as the international standard by food authorities around the world, including Brazil and other

Fig. 1. Main world food regulatory acts.

countries in the Southern Common Market (Tran et al., 2025).

3. Traceability systems in the world, legal requirements framework

Traceability systems are essential for global supply chains, as they enable international trade of commodities. As a result, numerous countries have made the implementation of these systems mandatory as indicated by the below reported map (Fig. 1).

3.1. Tracing food in the European Union (EU)

The first general law on food regulation has been the EC Regulation 178/2002, which defines the general principles and requirements of food law, moreover it establishes that traceability is required across all food and feed operators in the EU (European Commission, 2025). This regulation requires that operators maintain records of their suppliers' and customers' names and addresses, as well as product details and delivery dates. Moreover, the regulation sets out a framework for the development of food and feed legislation at both the EU and national levels, with each member state required to follow to follow these guidelines. The regulation defines responsibility based on the structure of each national legal system. Nonetheless, as long as the fundamental requirements of EC 178/2002 are adhered to, all products should be fully traceable through the 'one-step-back-one-step-forward' method. In addition, the rapid alert system for food and feed was developed as a powerful electronic communication tool, providing a real-time platform for EU Member State food safety authorities, the European Commission

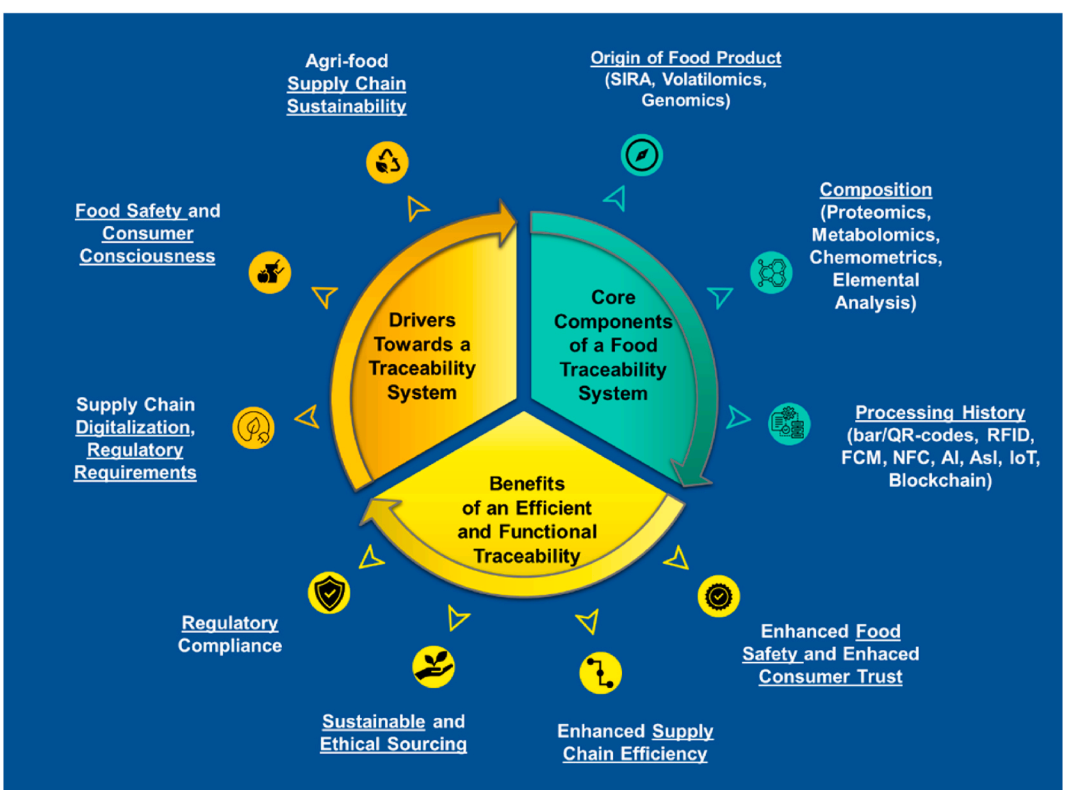

Fig. 2. The universal framework of a food traceability system: the core components, drivers and benefits.

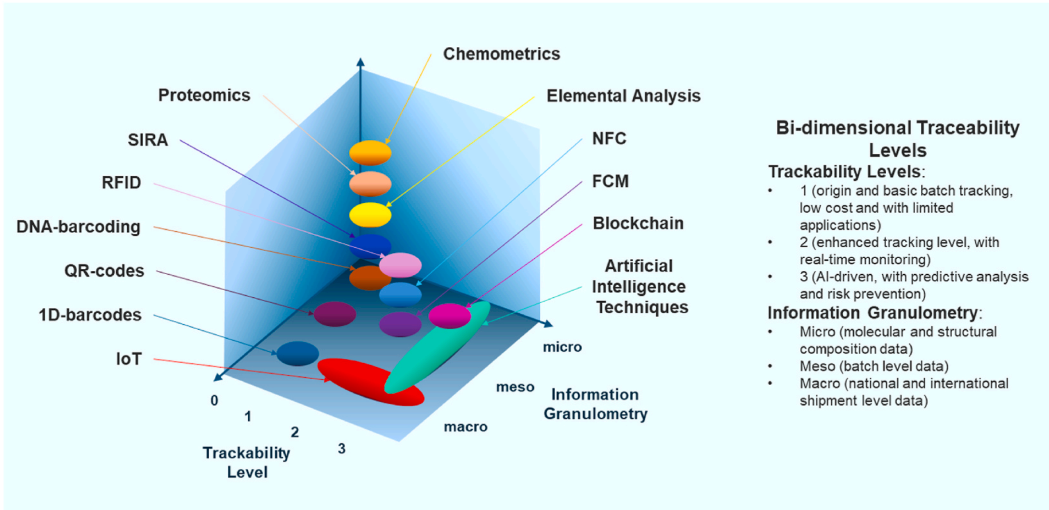

Fig. 3. Multidimensional representation of Food Traceability Systems. SIRA (stable isotope ratio analysis), RFID (radiofrequency identification), IoT (internet of things), NFC (near field connection), FCM (fuzzy cognitive maps).

and European Food Safety Authority (EFSA) (European Food Safety Authority, 2025), and sharing the latest information on food recalls and public health warnings across all EU countries (Pádua et al., 2019).

3.2. Food traceability in Unites States (US): the role of the FDA

In 2011, U.S. introduced the Food Safety Modernization Act (FSMA) (FSMA, 2024; Government of Canada, 2022), which marked a significant milestone in U.S. food safety legislation. It gives the FDA broad authority to implement preventive measures, including stricter traceability requirements, to protect public health from foodborne diseases. The most recent revision, issued in 2021, includes Section 204 of the FSMA, which introduces new regulations aimed at improving traceability for certain high-risk foods in the supply chain, including fresh produce, fish, seafood, cheese, eggs, and nut butter. The rule requires complete traceability across the entire supply chain, from farms and processing plants to packaging and retail operations. Before the rule takes effect on January 20, 2026, producers and distributors must establish systems that allow both forward and backward tracing at any point in the supply chain. This includes identifying key data elements related to food origins, transportation, and storage, setting up standards and protocols, and employing technology for efficient tracking. Additionally, the system must ensure that records for key data elements associated with critical tracking events like growing, receiving, processing, and shipping are maintained for up to two years. The FDA may also request a copy of these records in an electronic format within 24 h or a reasonable timeframe (Charlebois et al., 2024).

3.3. Food traceability systems by the Chinese Food and Drug Administration

China is actively implementing food traceability systems to enhance food safety and consumer confidence. In 2009, China established the Food Safety Law of China (FSL). Since then, the law has undergone several major amendments, including in 2015 and 2018. The latest revision of the law came into effect on April 29, 2021, making it the most comprehensive and stringent food safety legislation to date (China Legal Experts, 2024). The Chinese Food and Drug Administration (CFDA) plays a key role in enforcing food safety regulations. In particular, the CFDA is responsible for overseeing and enforcing food safety laws related to food production and the supply chain, while another entity, the national health and family planning commission of China handles food safety risk assessments, including surveillance, evaluation, management, and communication. Furthermore, the Ministry of Agriculture of China manages the quality and safety of primary consumable agricultural products under the law of the people's Republic of China on the quality and safety of agricultural products. In total, 52 food traceability regulations and laws have been introduced in China (China Institution, 2025), among them, the most interesting related to food traceability were the already mentioned FSL of 2021 (China Legal Experts, 2024) and the Agricultural Product Quality Safety Law, which require agencies to document the entire food supply chain, covering procurement, production, processing, packaging, and distribution (Qian et al., 2020).

4. Core components of an agri-food traceability system and a new bi-dimensional "taxonomy" for food traceability

Food traceability provides a comprehensive knowledge of a specific product. It allows verification of the origin, the composition, the processing history which constitute the **core components of a Food Traceability System** (Fig. 2); in addition to these components it is important also to consider the sustainability of the chain and the safety of the final products which are part of the benefits that can be achieved with the right guidelines and requirements of a traceability system. This control and supervision can be exercised throughout the supply chain, from the upstream identification of the raw-food product to the downstream certification provided to the consumer, as well as through stringent monitoring of the production and packaging of the final commercial product.

As food traceability systems evolve in response to the increasing demands for transparency, safety, and quality assurance, there is a growing need to identify and classify their components in a structured, functional way. In this review, we propose a new "taxonomy" of food traceability that brings clarity to the diverse strategies and tools currently used in the sector. This new classification is organized along two complementary axes (as pictured in Fig. 3), each representing a distinct dimension of traceability implementation and data resolution. The bi-dimensional nature of this new classification framework is necessary due to the inherently dual structure of traceability, which encompasses two complementary and interdependent aspects that are not mutually exclusive. On the one hand, establishing the traceability of a food product requires a thorough understanding of its intrinsic characteristics, such as its composition and origin. On the other hand, it also demands detailed information about the processing, packaging, and distribution stages that the product undergoes. These two dimensions

Table 1
Traceability analysis techniques and implementation systems.

Analysis/ Systems	Production Phase Application	Strengths	Weaknesses	Applicability	Ref.	Trackability level	Information Granulometry
				Data acquisition techinques			
				Proteomic and Metabolomic Profiling			
LC-MS	Raw materials, processing, quality control	High sensitivity and specificity; quantitative analysis	Requires skilled operation; expensive equipment	Food authenticity; contamination detection	(Lu et al., 2025; Panteghini & Krintus, 2025; Sumara et al., 2023)	1	Micro
MALDI-TOF MS	Quality control, processing	Detection of sophisticated frauds in complex matrices, microbial adulterations	Requires skilled operation; expensive equipment	Protein and lipid profiling Microbial identification;	(Song et al., 2024; Zambonin et al., 2021)	1	Micro
MS/MS	Raw materials, processing, final product	Highly specific; structural elucidation capabilities	High cost; complex data interpretation	Detection of contaminants; authenticity verification	Eugelio et al. (2024)	1	Micro
GC/MS	Processing, authentication, quality control	High sensitivity and specificity for VOCs; widely validated	Requires sample preparation, limited to volatile compounds	Food authenticity, contamination detection	Betancourt-Arango et al. (2024)	1	Micro
Genomics							
DNA-barcoding	Raw materials, processing	High specificity, applicable to processed foods, detects adulterations	Relies on reference databases, DNA degradation may occur during processing	Species identification	(DawanS & Ahn, 2022; Liang et al., 2025)	1	Micro
q-PCR	Raw materials, processing	High sensitivity and specificity, quantifies target DNA	Inhibited by food matrices	Pathogen, GMO and allergen detection	Liang et al. (2025)	1	Micro
				Stable Isotope Ratio Analysis (SIRA)			
CSIA	Raw materials, origin tracing	Highly sensitive stable isotopic ratios of specific compounds in samples	Requires specialized equipment; costly	Food authentication, adulteration detection, geographical locatization	(Athaillah et al., 2023; Nash et al., 2024)	1	Micro
BSIA	Raw materials, origin tracing	Averaged value of components in food product	Difficulty to distinguish isotopic variations between different samples	Food authentication and adulteration detection	Athaillah et al. (2023)	1	Micro
				Elemental Analysis			
FAAS	Raw materials, processing	Rapid, cost-effective	Moderate sensitivity, single-element analysis	Element quantification	Alves et al. (2023)	1	Micro
ETAAS	Raw materials, processing	Highly sensitive	Slower, prone to interference	Element profiling	Mazarakioti et al. (2022)	1	Micro
Plasma-based systems – ICP-OES	Raw materials, quality control	Multi-element, rapid analysis	Moderate sensitivity, spectral interference	Element profiling	(Mazarakioti et al., 2022; Varrà et al., 2021)	1	Micro
Plasma-based systems – ICP-MS	Raw materials, processing	Ultra-sensitive, multi-element capability	High operational cost, complexity	Element profiling	(Forleo et al., 2021; Varrà et al., 2021)	1	Micro
				Data elaboration technologies			
				Chemometrics			
EDA – PCA	Processing, quality control	Simplifies data visualization; reduces dimensionality	Limited classification capability	Preliminary data analysis; pattern identification	Nguyen et al. (2023)	1	Micro
LDA	Quality control, authentication	Robust classification; easy interpretation	Assumes linearity and normal distribution	Classifying food samples	Aguilar et al. (2021)	1	Micro
MLR	Quality control, authentication	Provides predictive values, efficient and fast to compute	Assumes linearity and normal distribution	Classifying food samples	Xu et al. (2023)	1	Micro
Others (kNN, SVM, ANN, SIMCA, MLR, PCR, PLSR, OPLS)	Quality control, authentication	–	–	Classifying food samples and predicting unknown values	(Baskar et al., 2024; De Angelis et al., 2024; García-Infante et al., 2024; González-Domínguez et al., 2022; Ritota et al., 2025; Y. Zhang et al., 2024)	1	Micro
				Artificial Intelligence Techniques (AI techniques)			

(*continued on next page*)

Table 1 (*continued*)

Analysis/ Systems	Production Phase Application	Strengths	Weaknesses	Applicability	Ref.	Trackability level	Information Granulometry
Artificial Intelligence Techniques	Entire supply chain: production, processing, distribution	Real-time contamination detection, predictive risk modeling, compliance monitoring, automatic defect detection and optimized shelf-life predictions	Requires extensive data, potential issues with data privacy and security	Quality prediction, fraud detection, traceability	(Cheng, 2024; Liu et al., 2023b)	1/3	Macro
			Barcodes, Technological Tags				
1d barcodes	Packaging, inventory management	Low cost, universal standard, facilitates product identification and basic traceability	Limited data storage	Product and price identification, basic traceability	Urbano et al. (2020)	1	Macro
2d QR-codes	Entire supply chain, packaging, consumer interface	High data capacity, readable by smartphones and consumers	Requires optical scanning	Traceability, consumer compliance	(Bao & Bao, 2022; Qian et al., 2021)	1	Meso
RFID tags	Entire supply chain, packaging, inventory management	Enables remote reading, large data capacity	Higher cost compared to barcodes	Inventory management, advanced traceability	(Chanchaichujit et al., 2020; Costa et al., 2013; Urbano et al., 2020)	2	Meso
NFC	Entire supply chain, packaging, consumer interface	Secure, contactless, real-time data access	Short reading distance; higher cost than traditional barcodes	Consumer product information, authenticity verification	Pigini and Conti (2017)	2	Meso
			Internet of Things (IoT)				
IoT	Entire supply chain, monitoring	Real-time monitoring, automated data collection, enhances supply chain transparency	High implementation cost, cybersecurity concerns, requires excellent network connection	Supply chain transparency, quality control	Bouzembrak et al. (2019)	2/3	Meso/Macro
			Fuzzy Cognitive Maps (FCM)				
FCM	Quality control, decision support	Facilitates prediction modeling; supports scenario analysis	High expertise required, limits complexity in large systems	Decision-making, sustainability assessment	(Jetter & Kok, 2014; Sarkar et al., 2022)	2	Meso
			Blockchain				
Blockchain	Entire supply chain, authentication, traceability	Immutable records, enhances transparency and trust	High implementation complexity and cost, requires stakeholder collaboration	Provenance tracking, fraud prevention	(Sri Vigna Hema & Manickavasagan, 2024; Vu et al., 2023)	3	Meso

are both essential and mutually reinforcing components, required for an effective traceability system.

The first axis focuses on the technological maturity and operational depth of the trackability technologies, which we classify into three hierarchical levels.

- **Level 0/1 trackability** represents basic batch-level tracking systems. These are typically low-cost and provide minimal data, often limited to the origin of the food sample and/or destination records depending on the technique. They are most suitable for straightforward, low-risk supply chains.
- **Level 2 trackability** encompasses systems that include real-time monitoring, enabled by tools such as IoT sensors and RFID tags. These systems offer better control over product handling and environmental conditions.
- **Level 3 trackability** represents the most advanced level, involving AI-driven analytics, which not only track product movement but also predict quality degradation, detect anomalies, and support proactive risk prevention.

The second axis of the taxonomy classifies traceability systems based on the "granularity" of the information provided, which we divide into three analytical data layers.

- At the **micro level** traceability systems provide item-specific or atomic-level data, including molecular or chemical analyses such as DNA barcoding, volatilomics, contaminant screening, isotope analysis, elemental analysis or allergen detection.
- The **meso level** refers to batch-based information, such as data tied to production lots, harvesting units or processing batches. This is the most commonly applied form of traceability in current industrial practice.
- The **macro level** includes data at the shipment or consignment scale, offering aggregated information suited for logistics coordination and trade documentation but providing lower resolution for specific food safety and authentication verification.

Together, these two dimensions offer a new way to define the core components of modern food traceability systems. They differentiate the traceability solutions by technological advancements and the type and resolution of information they deliver.

Following this classification, the review focuses on various molecular, analytical and technological assays and systems, divided among data acquisition techniques and data elaboration technologies, as grouped in Table 1.

4.1. Data acquisition techniques

Analytical methods form the foundation for origin traceability and authentication of food products and matrices, allowing for the acquisition of raw data through various techniques. Below are the most relevant analytical methods employed in agri-food traceability systems, providing an overview of the potential of the analytical techniques and their applicability within this sector.

4.1.1. OMIC technologies: a focus on proteomics, metabolomics and genomics

Omic technologies allow for the detection and quantification of various molecules in a food target sample, among these, genomics, proteomics, metabolomics and volatilomics (a specific sub-branch of metabolomics) are commonly used in food traceability systems.

4.1.2. Proteomics

In particular proteomics (Wang et al., 2023) has emerged as a valuable alternative to traditional methods such as enzyme-linked immunosorbent assays (ELISA) and DNA-based techniques, whose results may be compromised by degradation during high-temperature food processing. Broadly defined, proteomics involves the identification, quantification, and functional annotation of all proteins within a given sample enabling both qualitative and quantitative insights into the proteome's composition. The analysis studies the functions, expression, post-translational modifications and interactions among proteins within the sample, providing the measurement of a proteome's composition and the comprehensive characterization of its proteins. Additionally, proteomics techniques help ensure food safety and authenticity by detecting foodborne pathogens through their unique protein profiles, identifying allergens and toxins, verifying and improving food processing methods, discovering beneficial compounds in functional foods, and confirming the origin of meat and dairy products through species-specific markers. Different mass spectrometric techniques such as LC-MS, MALDI-TOF MS, and MS/MS (Table 1), alone or in combination, can be used for the identification, quantification and characterization of the proteins and other components of the sample (Carullo et al., 2020a, 2020b; Fedeli et al., 2023; Pozzetti et al., 2022). The achieved results are compared to commercially available libraries, allowing the identification of proteins and peptides composing the sample or matching the most homologically related proteins. The proteomic profile of the sample can vary depending on various factors, including the sample composition, biological variability, and technical processing, resulting in functional, qualitative and quantitative differences in proteomic analysis (Afzaal et al., 2022).

4.1.3. Metabolomics

Metabolomic analyses using High-Performance Liquid Chromatography and Gas Chromatography coupled with High Resolution Mass Spectrometry (HPLC-HRMS and GC-HRMS) are powerful tools for traceability and quality control in food products (Table 1). These techniques allow for the simultaneous accurate detection of a wide range of small molecules such as metabolites (for example, amino acids, organic acids, phenolic and volatile compounds), which can be used to assess biological identity, geographical origin, agricultural production, processing technology, and other authenticity attributes of different food commodities. In contrast to targeted analytical techniques that focus on the quantification of predefined compounds, metabolomics also employs a non-targeted approach, enabling comprehensive profiling of the metabolome and facilitating the discovery of novel biomarkers. The use of advanced statistical analysis helps to identify patterns in the highly complex metabolomic data revealing insight into the origin, authenticity, and quality of the products. The integration of multi-omics data, such as LC-HRMS and NMR, enhances food characterization, allowing for the identification of key metabolites that can effectively improve the model prediction accuracy in authenticity of different food commodities (Becchi et al., 2024). However, the instrumentation and analysis are expensive, which limits their widespread application.

Among metabolomics, volatilomics is becoming increasingly important in food traceability (Betancourt-Arango et al., 2024), as it enables the identification of volatile organic compounds (VOCs) present in food samples necessary for the identification, traceability and detection of adulteration and fraudulent modifications of a food product. Volatilomic analysis is typically conducted using solid-phase microextraction combined with gas chromatography-mass spectrometry (SPME/GC-MS) and electronic nose technology (e-nose). However, this technique presents several limitations, including the low volatility of certain compounds, complex odor profiles of samples, and limited reproducibility, sensor stability and calibration accuracy, which are crucial for reliable results.

4.1.4. Genomics: DNA-based methods

Various DNA-based methods, such as species-specific PCR, DNA hybridization, random amplified polymorphic DNA (RAPD), and DNA-barcoding are commonly used in food traceability systems. Among these, DNA-barcoding has gained interest in the food sector for its speed, accuracy, and cost-effectiveness in authenticating food ingredients (Lanubile et al., 2024). DNA-barcoding is a molecular technique used for species identification based on short, standardized genetic sequences that are conserved within a species but variable among different species. Initially developed for biodiversity monitoring, DNA-barcoding has since proven highly valuable in food authentication by offering a reliable, genetic-level method for verifying the identity of food products (DawanS & Ahn, 2022). The approach has been promoted globally through the efforts of the Consortium for the Barcode of Life (CBOL), which has developed standardized protocols and reference databases to streamline species identification. In food traceability, DNA barcoding enables the detection of species mislabeling, fraudulent substitution, and contamination, especially in high-value or highly processed products such as meat, seafood, and plant-based products (Liu et al., 2023a). Unlike traditional authentication techniques based on visual inspection or chemical profiling, DNA barcoding provides precise, species-level identification throughout the entire supply chain. This molecular insight supports both consumer protection and regulatory compliance, contributing to efforts against food fraud and enhancing transparency in global food networks. Nevertheless, several limitations still affect the widespread adoption of DNA barcoding in the food industry. The method's effectiveness may be reduced in processed foods due to DNA degradation, and while it is highly accurate in species identification, challenges remain in distinguishing between closely related species or detecting hybrids. Moreover, DNA barcoding is not designed to determine other important product attributes such as geographic origin or production methods (for example the identification of organic or conventional-produced samples), which limits its scope within traceability systems (Liberty et al., 2025). Additional barriers include the need for a faster, and more cost-effective technologies for an on-site application, as well as improved standardization and expansion of reference databases to support robust species identification across a broader range of food products. Other DNA-based techniques include real-time quantitative polymerase chain reaction (qPCR) and droplet digital PCR (ddPCR). PCR is a widely used molecular biology technique that enables the amplification of specific DNA sequences, making it a reliable tool for the detection of plant species in complex food matrices. It is a highly sensitive technique that allows for the identification of target DNA even at very low concentrations. Among PCR-based methods, qPCR is particularly notable for its speed, sensitivity, and ability to detect multiple targets simultaneously, which makes it the preferred method in many applications. More recently, ddPCR has emerged as a highly sensitive and efficient alternative for the detection and quantification of DNA contaminants in food products. This droplet-based format enhances specificity, reproducibility, and tolerance to PCR inhibitors, while reducing the influence of matrix effects and primer mismatches. In addition, ddPCR offers superior multiplexing flexibility and is especially advantageous in the quantification of genetically modified organisms or specific events within the same species, potentially providing a more cost-effective solution than conventional qPCR. Together, these various different DNA-based form a powerful molecular toolkit that significantly strengthens the authenticity and safety of food products across increasingly complex food supply chains (Table 1).

4.1.5. Stable isotope ratio analysis (SIRA)

The Stable Isotope Ratio Analysis of food matrices, commodities and soil provides a unique isotopic fingerprint that links a sample to its geographical source, production process, or environmental history, thereby ensuring authenticity, quality control, and supply chain transparency. By measuring the relative abundance of different stable isotopes within a sample, SIRA can reveal crucial information about the origin and characteristics of plants, animals, or derived products (Chen & Bontempo, 2025). In plants different isotopes provide specific insights.

- Carbon ($\delta^{13}C$) is linked to the plant's photosynthesis pathway. Plants are categorized into three types, C3, C4, and CAM, based on how they fix carbon and respond to unwanted photorespiration. This results in distinct isotopic fractionation, with C_4 and CAM photosynthetic cycle plants exhibiting higher (less negative) $\delta^{13}C$ values (−20 ‰ to − 9 ‰) compared to C_3 plants (−35 ‰ to − 21 ‰) (Georgi et al., 2005).
- Nitrogen ($\delta^{15}N$) reflects soil nutrient availability, fertilizer type, and nitrogen-fixation processes. For example, chemical fertilizers have typical $\delta^{15}N$ values between −6 ‰ and +6 ‰ which are different from those of organic fertilizers +1 ‰ up to +37 ‰ (Bateman & Kelly, 2007).
- Hydrogen ($\delta^{2}H$) and Oxygen ($\delta^{18}O$) indicate local environmental conditions, including rainfall, proximity to the sea, altitude, and latitude. In general, precipitation is isotopically heavier near the equator and becomes progressively lighter toward the poles, creating a distinct latitudinal gradient.
- Sulfur ($\delta^{34}S$) depends on the geology of the soil and agricultural practices, revealing information about the soil or fertilizers used. E.g. organic fertilizers, could be obtained from marine evaporites exhibiting values between 10 ‰ and 35 ‰, or sulfuric acid exhibiting δ34 S values between −5 ‰ to 12 ‰ (Vitòria et al., 2004).

Animals that consume these plants and drink water—whose isotopic composition is influenced by rainfall—reflect these isotopic signatures in their own tissues. In the case of $\delta^{2}H$ and $\delta^{18}O$, the relative contribution of water and feed to the final isotopic composition varies depending on the tissue or biological fraction analyzed.

The results are expressed as per mil (‰) using delta notation (δ) relative to international standards. However, changes in environmental conditions over time and location can affect isotope values, which represents a limitation of this method. This isotopic composition acts as a natural marker, enabling accurate traceability of origin and production processes, ensuring product authenticity, and detecting potential fraud or mislabeling. This type of analysis can be conducted on different types of samples: bulk mixtures (BSIA – Bulk Stable Isotope Analysis), which provide an average isotopic signature of the entire sample, or purified compounds (CSIA – Compound-Specific Isotope Analysis), which measure the isotopic composition of individual molecules. CSIA, in particular, enables a more detailed understanding of the sample's origin, formation, and transformation processes. The techniques used to carry out these isotope analysis are GC-IRMS and LC-IRMS (Table 1), which exploit mass spectrometry to precisely measure the stable isotope ratios of light elements through their delta values, in the sample (Chen & Bontempo, 2025). Several official standards and methods have been established to guide the application of isotopic techniques in food analysis and traceability (Camin et al., 2017).

4.1.6. Elemental analysis

The elemental analysis of a food sample allows the identification and quantification of chemical elements (such as arsenic, selenium, cadmium, lead, chromium, or mercury, which are among the most frequently targeted due to their toxicity and strict regulatory limits) within a specifically pre-treated sample, furnishing important information on food authenticity, geographical origin, production methods, and contamination levels. This type of analysis is considered complementary to SIRA, highlighting the necessity of both techniques for a comprehensive traceability assessment. In fact, while SIRA examines the relative abundance of isotopes of specific elements to track environmental and biological signatures, the elemental analysis determines which elements are present and their concentrations. Depending on the chosen technique, elemental analysis can be conducted with or without sample preparation. The main distinction lies in whether pre-treatment is required. Traditional techniques often require removing organic matter, which can result in a time-consuming procedure, and expose the sample to potential contamination or analyte loss. On the other hand, innovative techniques such as atomic absorption spectrometry (AAS); atomic fluorescence spectrometry (AFS); inductively coupled plasma-atomic emission spectrometry (ICP-AES) and inductively coupled plasma-mass spectrometry (ICP-MS) may not require pre-treatment (Ibourki et al., 2023). The most commonly used method for the elemental analysis of mixtures is AAS, which can be paired with different atomization techniques (FAAS, ETAAS, CVG-AAS, as shown in Table 1) depending on the required sensitivity. Different limits of detection (LODs) and limits of quantification (LOQs) are reported depending on the ionization procedure used, and the applicability of the strategy (Brown & Milton, 2005). Alternatively, plasma-based and laser-induced systems, that allow the ionization, atomization, dissociation, excitation and/or sparks formation, can be used. In these cases, commonly used techniques include the inductively coupled plasma (ICP-OES and ICP-MS), the microwave induced plasma (MIP) and the laser-induced breakdown spectroscopy (LIBS). These techniques differ in their sensitivity levels (as reflected in LODs), their capacity to perform complete or partial multi-element analyses, and their detection mechanisms. Other techniques include the atomic fluorescence spectrometry (AFS) used for the detection of metals or metalloids in organic matrices, instrumental neutron activation analysis (INAA) which is a non-destructive multi-element analysis for heavy metals with low LOD, UV–vis spectrophotometry for iron determination in food samples, total reflection X-ray fluorescence (TXRF) normally used for routine screening of samples for its reliable multi-element detection in a wide range of LODs. A more extensive description and technical references are provided in Table 1.

4.2. Data elaboration technologies

Raw data collected through analytical methods need to be integrated and processed using digital technologies in order to generate comprehensive and durable output across the entire supply chain. This can be achieved through data elaboration technologies such as chemometrics and fuzzy cognitive maps (FCM) which integrate advanced statistical and computational techniques. These tools enhance data interpretation and enable more accurate and efficient analysis of complex food matrices. While smart-tags, internet of things (IoT) and blockchain facilitate trustworthy data transmission, corroborated by an intelligent data processing and predictive analysis through AI and AsI technologies. These digital tools are presented within the next section offering an analysis of their potential when used in supply chains.

4.2.1. Chemometrics

The massive and complex outputs of the aforementioned analytical methods inevitably lead to the implementation of the traceability system with advanced multivariate chemometric techniques, which are necessary to extract and interpret the raw data, furnishing valuable information within food authenticity evaluations (González-Domínguez et al., 2022). The identification of relationships between non correlated variables through the exploitation of statistical and mathematical algorithms allows for the creation of statistical models that classify, discriminate and predict food characteristics based upon their chemical composition. Enhancing the traceability in terms of geographical origin, adulteration and organic-compliant regulations. This type of statistical analysis can be conducted using either unsupervised or supervised methods. However, it is common practice to apply multiple classification techniques and evaluate their effectiveness for a specific problem. Typically, this involves an initial exploration using unsupervised pattern recognition methods, followed by the application of supervised learning techniques to refine classification and prediction accuracy. In food authentication and traceability, chemometric methods are primarily applied for three key purposes.

- Exploratory Data Analysis (EDA) to detect underlying patterns, which is typically used as an initial step to gain insight into the key features of the dataset. To achieve this, unsupervised pattern recognition techniques are commonly applied to simplify complex data structures by reducing dimensionality (Principal Component Analysis, PCA) while preserving essential information, and grouping similar data (Cluster Analysis, CA).
- Discrimination and Classification to differentiate and categorize samples based on its characteristics. To achieve this, a model is initially developed using a training set consisting of objects within predefined categories and known values for the predictor variables. To classify objects into the categories, every observation must be assigned to a single category without overlapping information. Once the classification model is trained, it is used to predict the category of new unpredicted samples. There are two main modeling approaches: hard modeling techniques (that comprises LDA, PLS-DA, kNN, SVM, decision tree-based techniques and ANN (Baskar et al., 2024; De Angelis et al., 2024; González-Domínguez et al., 2022; Xu et al., 2023)) which divide the dataset into separate regions, each representing a specific category; and/or soft modeling techniques (for example SIMCA (De Angelis et al., 2024)) that create independent models for each class, defining a unique space for a defined category within the dataset.
- Regression and Prediction to estimate unknown values based on established data relationships thanks to statistical regression methods (examples include: MLR, PCR, PLSR and OPLS (Y. Zhang et al., 2024)).

4.2.2. *Artificial intelligence: boosting safety and efficiency of food supply chains*

Artificial Intelligence (AI) refers to the capacity of computer systems to perform tasks typically requiring human intelligence, such as learning, reasoning, problem-solving, and pattern recognition. In the context of food traceability, AI enables the interpretation and extraction of meaningful insights from complex datasets generated throughout the supply chain, supporting real-time decision-making and enhancing food safety, quality control, and transparency. Among the various branches of AI, machine learning (ML) plays a foundational role. This technology refers to algorithms that enable systems to improve their performance based on experience and data. Deep learning, a subfield of ML, leverages artificial neural networks with multiple layers to model complex relationships. It has shown remarkable capabilities in fields such as computer vision, language translation, and medical diagnostics, and is now transforming food system applications (Liu et al., 2023b). One of the most impactful architectures in this context is the convolutional neural network (CNN). CNNs are highly effective at identifying features in images, making them well-suited for tasks such as food classification, defect detection, and nutritional analysis. For example, CNN-based systems can evaluate produce quality by detecting bruises, classify food by type, and assess the freshness of meat or seafood through image data (Liu et al., 2023b). Beyond visual inspection, AI technologies, being data-driven, are applied to forecast shelf-life, estimate agricultural yield, predict price fluctuations, and anticipate demand. These predictive capabilities are particularly valuable in minimizing food waste, optimizing logistics, and planning harvest cycles. However, deep learning techniques require substantial computing power and memory, presenting trade-offs between accuracy and resource efficiency. In sustainable agriculture, ML models such as Support Vector Machines (SVM), Random Forests (RF), and k-Nearest Neighbors (kNN) have proven useful in precision fertilization and yield forecasting. The integration of AI with IoT, blockchain, and remote sensing enables continuous monitoring of environmental variables allowing for real-time adaptation of farming practices to optimize production while reducing resource use (Dedeoglu et al., 2023). In food safety, AI contributes to contamination risk assessment and control, and to cross-contamination limitation during processing or distribution. CNN and ML models have demonstrated potential in automating food classification, identifying adulterants, and monitoring for pathogen indicators, such as their deployment in optimizing the drying process of fruit slices or predicting spoilage risk during cold-chain transportation. AI is also transforming dietary assessment and nutrition monitoring. For example, the ML-powered systems can automatically estimate nutrient intake based on food images or user inputs. These insights enable faster decision-making and strengthen supplier relationships. Recent advancements in Edge-AI, that is the integration of AI with edge computing, allow data to be processed locally on the device, reducing the need for cloud infrastructure. This reduces latency, enhances privacy, and enables supply chain stakeholders to maintain real-time operational visibility even in bandwidth-limited environments. Pre-trained ML models deployed on edge devices are used for classification, anomaly detection, and forecasting without continuous internet access (Dedeoglu et al., 2023). AI is also a cornerstone in intelligent traceability architectures when combined with internet of things (IoT), blockchain, and cloud technologies. This integrated ecosystem provides a variety of benefits:

1. Secure and immutable data provenance
2. Predictive analytics for shelf-life and demand
3. Real-time process monitoring
4. Automated alerts and quality assurance
5. Prevention of unauthorized data manipulation
6. Implementation of privacy-preserving data sharing
7. Increased trust, transparency, and collaboration among supply chain actors (Dedeoglu et al., 2023).

Thus, AI can be considered a synergistic enabler in next-generation traceability frameworks. Its integration with the other digital technologies, further described below, marks a transformative step toward building efficient, and transparent food systems.

4.2.3. *Radiofrequency identification (RFID) and near field connection (NFC)*

In a transparent and efficient traceability system, automatic identification and data capture technologies as RFID, NFC, 1D barcodes and 2D barcodes have emerged as core components for the monitoring of food products throughout the supply chain, enhancing safety, quality control and logistics (Urbano et al., 2020). RFID can be included in the IoT technology, even though some reviews also report RFID as a prerequisite for IoT (Urbano et al., 2020). This type of tracking technology, which has been implemented in the traceability systems since the early 2000's, implies a wireless connection that uses electromagnetic fields to identify and track objects fitted with specific tags across the supply chain, creating a crucial interconnection between the stock world and the management system. This is particularly crucial for big enterprises where keeping track of every arrival, movement, stock conditions, expiry date and exit of food samples implies managing a huge amount of data and paperwork (Munoz-Ausecha et al., 2021). The advantages of this kind of tag can also be beneficial also for consumers that, depending on the product and the type of tag used by the company, can check for themselves the traceability of the food they are buying (Costa et al., 2013).

The RFID technology includes the use of:

- tags (passive, active or semi-passive tags, depending on the presence of a microchip and a battery for the functioning) which are attached to the food sample;
- an RFID reader that emits and receives signals from the tags;
- a data management system necessary for the processing of the data collected.

The RFID system allows for a more reliable and efficient tracking, storage and processing of food, without any physical contact and the ability to read multiple tags simultaneously for automated inventory systems, and cold chain logistics. These tags can also be integrated with temperature and humidity sensors, making them particularly suitable for perishable goods as seafood, dairy products and meat (Kumari et al., 2015). Nonetheless, the initial higher investment for a company, when compared to the classical barcode, has to be taken into account. In this context, NFC can be considered an extension of the RFID technology with shorter distances of reader and data retriever, which is commonly employed in tags for security as the anti-theft tags or in smart packaging for consumers. The main difference between these two technologies is the data communication range: NFC requires a very close connection (a few cm), and presents the significant advantage of being widely integrated in all new generation smartphones, allowing a useable technology directly on the consumer phone through specifically designed applications (Pigini & Conti, 2017). These technological enhancements in traceability have partly replaced the traditional 1D and 2D barcodes, which are still used as a more-affordable and basic level of transparency. The 1D barcodes represent a basic inventory retail tracking accessory that can store limited and non-modifiable information. Conversely, the 2D QR-codes can perform and present more detailed traceability data that only requires a smartphone to be read, as for the NFC technology, also allowing consumers to access dedicated information on traceability and transport when scanned.

4.2.4. *Internet of things (IoT)*

The IoT is the interconnection among smart devices that allows the creation of a network made of sensors, tags and monitoring systems, which are connected and automatically transmit and exchange real-time data throughout a supply chain, enhancing the visibility, transparency and fast accountability of stock items. An IoT system can be metaphorically visualized as multi-layered smart city, where each "district" performs specialized tasks to ensure the system functionality (Bouzembrak et al., 2019). At a foundational level lies the device subway (underground floor), that includes all environmental devices, such as sensors, communication modules, energy supply units and control devices, necessary for the data collection and transmission from different parts of the system. On this floor an essential part is also played by the communication technologies, wired or wireless, that resemble the city's roadways and communication lines, enabling smooth data movement. On the first floor it is possible to identify the network layer that serves as the city's translation and regulation system. It facilitates the conversion of raw device data into standardized communication protocols and provides vital services such as connectivity, mobility management, authentication, authorization and accounting. Above we have a service support floor that resembles the city's infrastructure hub, offering processing and storage centers important for maintenance operations. Here, the data collected through network floor, is processed, analyzed and stored according to the needs of specific applications, allowing customization of the services supported. Finally, on the last floor is the application system roofing, that sits at the top of this digital city, representing the end-user services and applications that benefit from the IoT ecosystem, among these smart agriculture monitoring systems, food cold-chains alerts, real-time product traceability platforms can be mentioned. This interconnected city is governed by the management and security services, which ensure a proper configuration of the system, monitor performances and resources, secure the network against threats and oversee user accounts, ensuring the integrity and reliability of this network (Bouzembrak et al., 2019). Even though the application of IoT has been amply studied and reported as an improvement in supply chain and in traceability monitoring, this technology is still largely theoretical with a poor implementation in practical food safety. Some challenges are reported as interoperability issues among devices, standardization protocols across different technologies and supply chains, but also poor network organization in rural and agricultural areas, which render this technology still far from operability. Moreover, a start-up cost has to be taken into consideration with the purchase of tags and devices, and security challenges have to be considered when building-up this interconnected traceability network. Nonetheless, studies report the application to cold chains monitoring and fish and berries supply chains resulting in increased annual sales, reduction of consumption of energy, fast turnover and shelf-life fast monitoring (Bouzembrak et al., 2019; Urbano et al., 2020).

4.2.5. *Fuzzy cognitive maps (FCM)*

This tool has been initially developed by B. Kosko in 1986. FCMs are a hybrid computational modeling tool that allows the representation and analysis of the dynamic relationship among variables in complex systems, through the combination of fuzzy logic, graph theory and cognitive mapping. In a FCM system the key components are presented as nodes or concepts (that can be concrete or abstract) interconnected through weighted arcs that represent the influence of one concept on another, with the weight expressing the strength and type of influence. In fact, this system is particularly adaptable to food traceability due to the multiple interrelated factors, as environmental conditions, regulatory compliance, supply chain transparency, that must be taken into consideration within a comprehensive model (Jetter & Kok, 2014). The modeling of qualitative cause-effect relationships can be achieved through this system. Recent studies have reported the analysis of factors affecting household food waste, helping to identify the most influential drivers, supporting the development of targeted interventions (Ozgen Genc & Ekici, 2022; Sarkar et al., 2022). For further theoretical background and practical methodology, the work from Jetter and Kok are recommended, in which FCMs are exploited as tools for the integration of multiple knowledge types, enabling higher productivity planning, and notable waste reduction (Jetter & Kok, 2014).

4.2.6. *Blockchain for agri-food traceability*

This technology was recently introduced in food traceability systems from the cryptocurrencies world. Blockchain technology stems from the necessity to record and store data in a decentralized, tamper-resistant, and chronologically ordered chain of blocks, avoiding manipulation or compromise data and transactions (Sri Vigna Hema & Manickavasagan, 2024). Each of these blocks contains a set of data entries (in the case of cryptocurrencies, these are transactions), a timestamp, and a cryptographic hash of the previous block, which ensures the immutability and integrity of the stored data. In the context of food traceability, blockchain offers a way to securely and permanently record each step of the food supply chain, from production and processing to distribution and retail, thus enabling end-to-end visibility and accountability for both businesses and consumers (Galvez et al., 2018). While traditional traceability systems often rely on centralized databases, which are vulnerable to manipulation, data loss, or lack of interoperability across different stakeholders, blockchain's decentralized architecture distributes copies of the ledger across all network participants, ensuring that no single entity can unilaterally alter past records. This makes blockchain traceability systems particularly effective in complex and fragmented supply chains, where multiple operators must exchange and verify data (Sri Vigna Hema & Manickavasagan, 2024; Vu et al., 2023). Despite these advantages, which not only include the enhancement of traceability throughout multiple processes from production to regulatory to buyers, but also improvements in transparency, and fraud prevention, the implementation of blockchain technology is also beneficial for the company's efficiency and cost reduction. That said, the implementation of blockchain in food traceability is not without challenges. Sometimes its adoption is driven by pressure from consumers who want to be increasingly aware about the quality and safety of the food products that they are buying, but also from buyers, suppliers and competitors that adopt this technology for a competitive edge over other retailers and from regulatory bodies that require a more strict control over food products. One major limitation is the data reliability problem, in fact as blockchain can ensure data integrity, it cannot verify the truthfulness of data at the point of entrance. To address this, blockchain must be integrated with IoT, smart tags, RFID tags and sensor technologies that automatically collect data, reducing the risk of human error or falsification. However, these integrations also require an initial economic investment, which must generate sufficient return for the company(Liu et al., 2025). Another concern is scalability and energy consumption, particularly for blockchains that rely on energy-intensive consensus mechanisms that obviously require a certain level of knowledge and expertise. Moreover, it must be considered that end-to-end traceability also involves increased visibility that may negatively transfer into leakage of private information, crucial aspect for big companies. Additionally, the interoperability of blockchain platforms, lack of regulatory standards, and limited digital infrastructure in some regions remain significant barriers to widespread adoption (Vu et al., 2023).

5. Case studies

In order to provide more information about the traceability systems, we have reported three case studies, in which three food products/matrices have been analyzed with the aim of discussing the technological enhancements and analytical techniques employed to ascertain the traceability system. Among the most relevant food products for traceability analysis, wine, garlic, and coffee represent three emblematic case studies, each with distinct analytical challenges and tracking methodologies. Wine has been included due to its global distribution and its well-documented vulnerability to fraud, particularly in cases involving mislabeling of geographical origin or compositional tampering (Marr, 2024; InfoWine, 2024). Wine is one of the few food products for which well-established tracing and tracking protocols already exist, both from a regulatory and analytical standpoint (Koljančić et al., 2024). However, the wine industry is now experiencing the adoption of blockchain technology, initially to comply with stringent national/regional regulations and secondly to contrast fraud. Consequently, numerous brands have started to adopt technological solutions such as blockchain, IoT and AI techniques, in order to provide reliable traceability of their products, thus gaining trust among their consumers (Cordier, 2025; Marr, 2024; InfoWine, 2024). In contrast, garlic presents the opposite scenario: despite being subject to fraudulent practices, it currently lacks dedicated analytical protocols for traceability and trackability. This gap has encouraged the exploration of alternative approaches, including advanced chemometric methods and, notably, metabolomic techniques which have shown promise in capturing detailed chemical fingerprints to determine origin, variety and authenticity. Finally, coffee was selected due to the application of innovative traceability technologies implemented through blockchain and IoT techniques, including the use of a new algorithm named YOLO, which was specifically developed for the analysis of imperfection of coffee beans (Hermanos, 2025; Ligar et al., 2024)

5.1. Traceability technologies for wine bottling trust. Improving transparency and authenticity

Wine traceability is defined as a systematic and structured approach that enables all actors within the wine supply chain to accurately verify the provenance and compositional integrity of each batch, assess the storage parameters throughout the distribution process, and identify any materials or substances that have come into contact with product following vinification. Traceability plays a pivotal role within quality assurance management systems in the wine industry. In accordance with international standards such as ISO 22005:2007 and European Regulation (EC) No. 178/2002, it ensures the systematic recording of all operations involving raw materials, ingredients, and final products. This enables full traceability throughout the supply chain, supporting process control, risk management, and the verification of product authenticity and safety. The authenticity of wine has been the subject of extensive research, as it is a product highly susceptible to adulteration due to its complex chemical composition and global availability. To ensure the maintenance of wine quality, rigorous and continuous monitoring is essential, and new digital technologies have been explored to guarantee the authenticity and tracking of this food product (Koljančić et al., 2024). The adoption of blockchain is an innovative strategy to assure the origin traceability and the authenticity of this product, and is becoming an important marketing policy for brands (Cricelli et al., 2024). Chromatography constitutes the primary analytical platform for the detection of trace-level organic compounds and the identification of adulterants. Complementary to chromatographic techniques, spectroscopic methods have achieved broad commercial implementation, offering operational simplicity at the expense of reduced informational depth. Emerging digital imaging methodologies, recently introduced into the field, demonstrate significant potential in oenological analysis due to their minimal sample preparation requirements. Typically, volatile compounds are employed to differentiate wine varieties and mineral content is used for geographical identification, while the use of both 1D and 2D NMR or GC-MS/LC-MS techniques provides the assessment of amino acids and phenolic compounds, metabolites which serve for both purposes. The development of advanced analytical techniques for wine authentication remains a significant challenge and is currently receiving focused attention in the field (Sabbagh et al., 2024). Machine learning enables wine origin traceability at three geographic levels: country, state/province, and village/town. Depending on the specific objective, one or more supervised algorithms, such as Discriminant Analysis (DA), Random Forest (RF), ANN, or Support Vector Machine (SVM), can be employed to construct classification models. ANN models generally outperform Partial Least Squares Discriminant Analysis (PLS-DA) in traceability accuracy and can assess the importance of each variable based on its contribution to the model. Compared to DA and RF, ANN offers higher recognition accuracy, making it particularly effective for global origin classification. A comprehensive understanding of contemporary wine authentication methodologies, including chromatographic, spectroscopic, and digital imaging techniques, in conjunction with chemometric data analysis, is critical for the development of advanced and integrative analytical frameworks (Ma et al., 2025). In addition to these, volatilomics is becoming a relevant discriminator for wine traceability, due to terroir influences and winemaking practices that shape its aromatic and sensory characteristics, guaranteed by VOCs such as esters, alcohols, and volatile acids (Kyraleou et al., 2025). Furthermore, not only soil and regions but also native yeast strains contribute to the development of different flavor compounds due to the plasticity of native strains under distinct fermentation conditions, uncovering novel odor features, allowing the tailoring of aromatic diversity and innovation, whilst preserving authenticity in regional wine aroma (Martins et al., 2024).

5.2. Origin reliability through traceability of garlic species

Garlic (*Allium sativum* L.) is a perennial herb of the Liliaceae family, and its cultivation environment significantly affects the chemical composition and nutritional profile, leading to considerable variations in its flavor and functional attributes across different cultivars. These differences are pivotal in influencing consumer preferences and acceptance in various markets. In the era of industry 4.0, technologies such as IoT, big data analytics, blockchain, and AI have been employed to address traceability challenges, including verifying the origin of garlic. Mid-infrared and ultraviolet spectroscopy have been employed to analyze the components of garlic. To reduce background noise in the spectral data, three preprocessing techniques—Multiple Scattering Correction (MSC), Savitzky-Golay Smoothing (SG Smoothing), and Standard Normal Variate (SNV)—were applied. Following feature extraction using the Genetic Algorithm (GA), various machine learning algorithms, including XGBoost, Support Vector Classification (SVC), Random Forest (RF), and ANN were utilized in combination with the fused spectral data to achieve the best results in data processing. In this field, the data revealed that the best-performing model for ultraviolet spectroscopy data was SNV-GA-ANN, with an accuracy of 99.73 %. The best-performing model for mid-infrared spectroscopy data was SNV-GA-RF, with an accuracy of 97.34 % (Han et al., 2024).

Additionally, a new MS technique named paper spray ionization mass spectrometry (PS-MS) was employed to promptly probe garlic samples from distinct geographic origins (Victor dos Santos Azevedo Leite et al., 2024). These approaches also focus on enhancing traceability and authenticity verification by pinpointing the geographical origin of the product, even after it has been removed from its cultivation site. Chemometric methods such as PCA, PLS-DA, and Ortho PLS-DA were utilized to model the experimental data, enabling the classification of compound types in the samples and the identification of potential biomarkers (Victor dos S.A. Leite et al., 2025). Furthermore, traditional methods like SIRA of the major bioelements (δ^2H, δ^{13}C, δ^{15}N, δ^{18}O, δ^{34}S), were also used to attempt a geographical characterization of garlic, in order to officially validate a method to determine the geographical origin of this type of product. By applying this model, very good predictive performance in geographical classification was achieved by LDA and k-NN method. Moreover, preliminary class modelling based on SIMCA supports the ability of stable isotope ratios analysis for the geographical traceability of garlic (Pianezze et al., 2019). The same method was used, in combination with metabolomics and chemometric approaches to track and trace, for the first time, a specific member of the Allium family: elephant garlic from Italy (Carullo et al., 2024).

5.3. Integrated traceability for coffee authenticity: a multi-source analytical approach

Coffee is globally popular due to its distinct sensory attributes. Its unique flavor is influenced by various factors, with the biochemical properties related to geographic characteristics being particularly important. Traceability is a critical component of sustainability in the coffee industry. The literature highlights that near-infrared (NIR) spectroscopy offers substantial potential for non-invasive, rapid assessment of coffee bean origin and characteristics, enabling efficient data acquisition without disrupting the sample. Near- and mid-infrared (NIR and MIR) spectroscopy are recognized as powerful techniques for the rapid, non-invasive assessment of the origin and characteristics of coffee beans, facilitating traceability across the entire coffee supply chain. Beyond spectroscopy, other technologies such as QR codes and machine learning (Agnusdei et al., 2024) have also been applied, focusing on the optimization of stock and delivery management. The transfer of coffee from rural producers to warehouses involved the automation of coffee production traceability using QR codes, aiming to improve processes, quality, safety, and sustainability within the supply chain under the Industry 4.0 paradigm. A business process and notation model was employed to map out the coffee production stages, with QR codes used for data collection and registration during activities such as harvesting, washing, drying, processing, storage, and certification validation. By streamlining operations, reducing errors, and enhancing traceability, QR codes involve various actors, from harvesters to quality control personnel, inspectors, and clerks (Querme & Lima, 2024). Furthermore, the ML models for tracking coffee beans were constructed using different You Only Look Once (YOLO) algorithms, specifically designed to evaluate defective or acceptable beans. The model underwent training and validation phases, employing the k-fold cross-validation method. The algorithm was based on a CNN and incorporated YOLOv5m, YOLOv6m, and YOLOv7 architectures. YOLOv5m surpassed the other models in both non-augmented and augmented training datasets, showcasing its ability to efficiently manage small datasets and its robustness in the presence of data augmentation. This positions YOLOv5m as an ideal model for quality evaluation tasks in the domain of green coffee beans (Ligar et al., 2024). Finally, a mobile application was developed to monitor and record data from farm inspections to be exported, including details on coffee variety, environmental conditions, and supplier activities. This app handled logistics with real-time updates on quantities, destinations, and delivery times, enabling improved decision-making and enhancing consumer trust through verifiable, transparent information. The app supported precision agriculture, aligning with

Fig. 4. Best practices in a food traceability system.

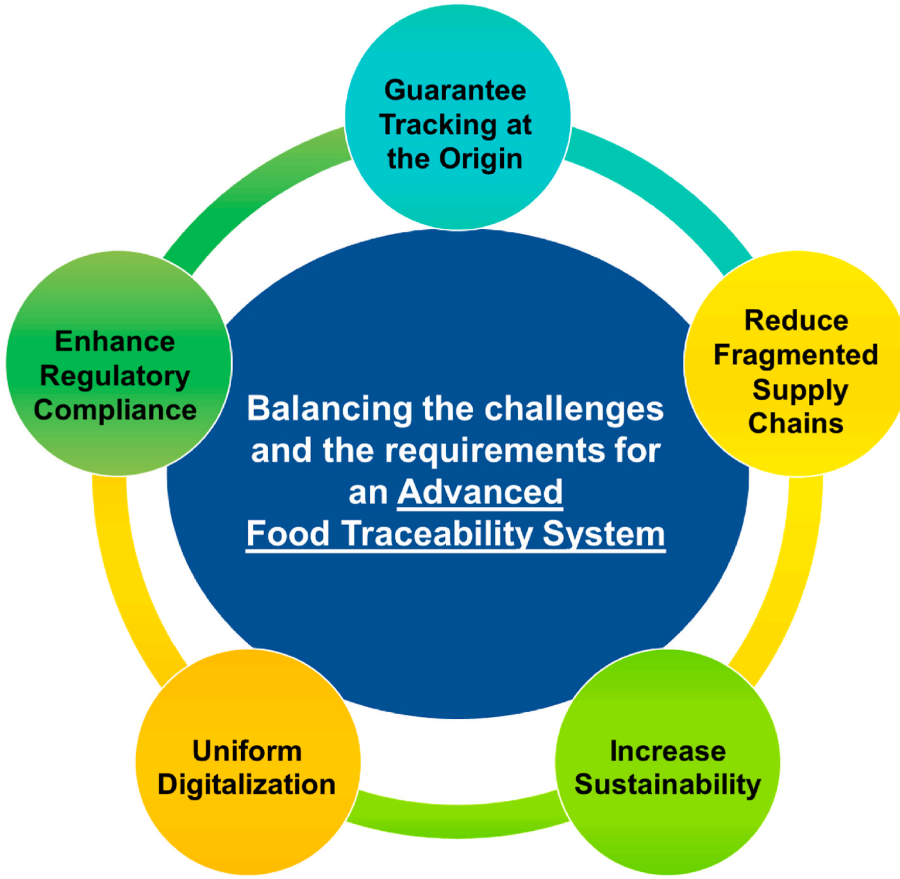

Fig. 5. Balancing the challenges and the requirements for an advanced Food Traceability System.

Just-In-Time principles, and promoted sustainability while ensuring compliance with ISO 9001 and ISO 14001 standards (Rehman et al., 2025).

6. Best practices in a food traceability system

With the aim of building consumer trust and improving safety, the core components of an end-to-end food traceability system are: i) origin of the food product, and ii) the composition and processing history. These core concepts of a traceability system furnish a bi-dimensional knowledge of a food product: its trackability and its composition information. To achieve this level of bi-dimensionality and enhance the traceability system, a set of best practices has been reported in Fig. 4.

The first recommendation focuses on the enhancement of end-to-end visibility, connecting the producers directly to the ultimate consumer of the product through smart-tags or QR-codes.

Another important aspect that needs to be tackled is the standardization of collected data, applying the same technologies and methodologies from the local farmer up to the production site, in order to avoid data loss or compromission. Furthermore, these data must be complete and unilaterally linkable to specific stock batches, achievable through blockchain technologies or AI techniques, maintaining the data ready to use. Even so, the use of predictive software can improve the system by analyzing inventory and avoiding product expiry or implementing risk assessment tools.

7. Conclusions and future perspectives

A projected 10-billion world population in 2050 will put agri-food systems under tremendous pressure and it has been estimated that feeding will require an increase of food production by up to 70 %. The existing supply chains will be unable to sustainably meet the nutritional demand of the future world population. Present agri-food supply chains present several inefficiencies, and the need to rise awareness and transparency, reduce inequity, improve environmental sustainability and enhance efficiency in agri-food supply chains is paving the way to search of specific solutions.

Today governments are being pushed to understand the need to trace information about the various steps of agri-food supply chains. The answer to these challenges is ensuring traceability in agri-food supply chains, balancing the legislative requirements, the challenges in a uniform, digital and reliable supply chain in different insets, and assuring the sustainability of these supply chains (Fig. 5). There is a rising consumer demand for traceability and it has been estimated that more than 70 % of consumers around the world would be willing to pay more for brands that provide transparent food information. Food and agricultural product certification is still a challenging issue. With hundreds of certification systems in use globally, it is essential for certification bodies and regulatory agencies to improve communication, both among themselves and with certified organizations, to ensure compliance, build trust, and enhance consumer confidence. Government involvement can accelerate the deployment of traceability systems, especially as the industry shifts from traditional "one-up, one-down" models to comprehensive "end-to-end" traceability frameworks. These advanced systems aim to track specific attributes of food products, determine authenticity, and verify geographic origin. To support accurate and efficient data recording throughout the supply chain, emerging technologies such as blockchain and artificial intelligence (AI) offer transformative potential. Blockchain provides an immutable ledger for keeping track of every single transaction or movement of foods and commodities and the adoption of an effective blockchain tracking system in food industry, complying business with regulations and consumer trust, could empower marketing strategies and opportunities (Cricelli et al., 2024). AI (Lugo-Morin, 2024; Naseem & Rizwan, 2025) may play a critical role for data mining and management for food supply chains since it may process vast reams of data with accuracy and high speed and predictive analytics, empowered by AI, may point out potential safety issues. It can also drive innovation in alternative food production methods—such as vertical farming, synthetic food development, and food bio-engineering—contributing to the evolution of a more resilient and sustainable global food system. In summary, enhancing traceability and transparency, supported by digital technologies and AI, will be central to ensuring food safety, supply chain integrity, and long-term sustainability in the face of global demographic and environmental challenges.

Data availability

Data will be made available on request.

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