
eISSN 2239-7132

**Italian Journal of Food Safety**

https://www.pagepressjournals.org/index.php/ijfs/index



***Please cite this article as:***

Conter M. **Recent advancements in meat traceability, authenticity verification, and voluntary certification systems**. *Ital J Food Saf* doi:10.4081/ijfs.2024.12971

*Submitted: 26-08-2024*
*Accepted: 09-09-2024*

# Recent advancements in meat traceability, authenticity verification, and voluntary certification systems

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**Key words**: meat traceability, blockchain technology, artificial intelligence, isotope fingerprinting, certification schemes.

**Conflict of interest**: the author declares no potential conflict of interest.

**Ethics approval and consent to participate**: not applicable.

**Funding**: none.

**Availability of data and materials**: not applicable.

**Abstract**
The growing demand for transparency in the food industry has led to significant advancements in meat traceability. Ensuring the authenticity and origin of meat products is critical for consumer trust, public health, and compliance with regulations. This paper reviews recent innovations in meat traceability, with a focus on blockchain technology as a novel approach to ensuring traceability. Additionally, advanced methods for verifying meat authenticity and origin, such as isotope fingerprinting, DNA analysis, and spectroscopic methods, are discussed. The role of voluntary certification schemes in enhancing traceability and authenticity verification in the meat industry is also explored. The findings highlight the importance of integrating cutting-edge technologies and certification schemes to build a robust and transparent meat supply chain.

**Introduction**
In the European Union (EU), food traceability is required by Regulation (EC) 178/2002 and is defined as the "ability to trace and follow a food, feed, food-producing animal or substance intended to be, or expected to be incorporated into a food or feed, through all stages of production, processing and distribution" (European Parliament and Council of the European Union, 2002). Food business operators (FBOs) must be able to provide information to the competent authority on the supplier of food, feed or any substance incorporated into food and the identity of the customers' businesses to which they have supplied their products. More severe rules for the traceability of meat products are required by Regulations (EC) 1760/2000 and 1337/2013 (European Commission, 2013), regarding the labeling of beef and beef products and the indication of the country of origin or place of provenance for fresh, chilled, and frozen meat of swine, sheep, goats, and poultry, respectively (European Parliament and Council of the European Union, 2000; European Commission, 2013).
Meat traceability is an essential aspect of food safety and quality control in the global supply chain. It allows for the quick identification and resolution of food safety issues, helps fight food fraud, and enables compliance with increasingly stringent regulatory requirements (Zhang *et al*., 2020). In the last two decades, the meat industry has faced several challenges related to food fraud, adulteration, and mislabelling. High-profile scandals, such as the horsemeat scandal of 2013, where horsemeat was fraudulently labeled as beef, highlighted significant vulnerabilities in the supply chain and underscored the need for robust traceability systems. Indeed, traceability procedures are fundamental in maintaining the food chain integrity, concerning the way food items have been sourced, produced, and distributed. In this case, food fraud is related to quality attributes that are not perceivable by the consumer (Robson, 2021).
Traceability is a prerequisite to maintaining consumer trust, particularly in high-value markets where the authenticity of meat products represents the excellence of food production. Especially in the case of food authenticity, defined as the matching between the food product characteristics and the corresponding food product claims, a high level of efficiency in tracking and tracing food items is required both during the production processes as well as throughout the supply chain logistics (Biglia *et al*., 2022). Consumer trust is particularly critical when it comes to high-value products like those with Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) status. These labels are used to protect the names of specific products to promote their unique characteristics, which are linked to their geographical origin and traditional methods of production [Regulation (EU) 2024/1143] (European Parliament and Council of the European Union, 2024). The authenticity of these products is heavily reliant on effective traceability systems, as any compromise in their traceability could damage their reputation and reduce consumer confidence (Bai *et al*., 2021; Gaspar *et al*., 2022). Moreover, as consumers become more conscious of food origins and ethical production practices, the demand for transparent and reliable traceability systems has grown (van Bussel *et al*., 2022; Tran *et al*., 2024).
Within this complex framework, the EU has developed comprehensive legislation to safeguard consumer rights. However, voluntary certification schemes offer more flexibility in addressing specific consumer demands for food quality and meeting the increased consumer awareness

(Charlebois *et al*., 2014). FBO are free to select from a variety of voluntary traceability programs, more detailed and with various degrees of complexity that can be implemented between these necessary regulations to meet consumer demands. To enhance traceability, the integration of advanced technologies, coupled with more rigorous certification processes and real-time data sharing across the supply chain, can offer a higher level of transparency and reliability, ultimately safeguarding both consumer trust and the integrity of European food products (Kendall *et al*., 2019). Innovative solutions such as blockchain technology have been recently implemented with the aim of improving food traceability, and advanced analytical methods are now available for verifying the origin and authenticity of meat products. Voluntary certification schemes have also gained importance, providing manufacturers with an opportunity to differentiate their products and satisfy consumer demands for transparency.
This paper examines these advancements, focusing on blockchain technology, advanced analytical methods, and voluntary certification schemes, their benefits, drawbacks and future perspectives.

**Innovative systems for meat traceability**

A credible traceability system must be able to trace and track food and ingredients through all stages of production, processing and distribution within a supply chain (Wang *et al*., 2023). However, traditional food traceability systems (*e.g.*, alphanumerical codes, barcodes, RFID tags) are problematic: i) they only consider distribution and warehousing steps; ii) they do not consider if the information shared by supply chain members can be trusted; and iii) they are monopolistic, asymmetric and opaque information systems. These problems result in further challenges, such as fraud, corruption, tampering and falsification of information (Tian, 2016). Emerging technologies such as Internet of Things (IoT) and blockchain play a pivotal role in building intelligent, secure, and transparent food supply chain systems while addressing these issues.
IoT plays an important role in the digitization of supply chains by offering sensing, computation, and communication capabilities (Abdel-Basset *et al*., 2018), allowing the stakeholders to gather real-time data about their operations from the field, and aiding AI technology while enhancing transparency. The IoT is a network of physical devices, machines and other objects that use sensors and software to collect data and exchange it over the internet, enabling remote monitoring and control. The IoT architecture starts with an IoT device—a piece of technology that supports internet connectivity and is equipped with a sensor or means of measurement. An IoT device transmits sensor data automatically, without human or manual interruption, to an IoT platform. Through the use of the IoT and various sensors, such as the global positioning system, geographic information system, near-field communication, radio frequency identification (RFID) and temperature and humidity sensors, monitoring and information capturing can be improved in various processes, such as production, processing, storage, distribution, and retail (Nurgazina *et al*., 2021; Sun *et al*., 2021).
Several modern tracking and tracing methods have been deployed in the agriculture and food sector. RFID and biometric identifiers has been developed for beef traceability from farm to slaughter (Shanahan *et al*., 2009). RFID technology, together with IoT sensors and quick response (QR) barcodes, has been implemented to track the physical flow of products through the supply chain to ensure regulatory compliance (George *et al*., 2019). A more innovative method is the use of DNA barcoding on the product packaging for tracing back to its origin (Clark, 2015). While these methods are subject to some limitations in the practical application, it shows that it is technically feasible to develop an integrated agricultural traceability system with new available technologies (Cao *et al*., 2021). As these technologies do not address any verifiable process or control system, this creates a need for new traceable mechanisms that can enable the exchange of quality and reliable information between companies on a detailed level (Behnke and Janssen, 2020).
However, IoT-based food traceability systems are riddled with the issues of data integrity, trust, authenticity, and security. Moreover, with IoT devices having limited computing power and storage capacity, tracing food sources and batches becomes time-consuming (Tripathi *et al*., 2023). To address these issue, Blockchain Technology (BCT) has been proposed as a promising solution for

enhancing meat traceability (Rejeb, 2018). A blockchain is a distributed immutable ledger that stores data as continuous chains of blocks in a decentralized network. Blocks are interlinked with the cryptographic hash value. Its application in the food industry, particularly in meat traceability, offers seamless authentication, privacy, security, transparency, and trustworthiness (Beck *et al*., 2021). Besides, it also reduces the computational overhead of resource-constrained IoT devices. The tamper-resistant property of blockchain and its reliance on decentralized architecture make the technology more suitable for multi-stakeholder supply chain applications. Unlike centralized architectures that allow a single organization to run and manage the digital operations, including the control of the database, blockchain inherently follows a decentralized architecture by letting multiple organizations monitor and manage the supply chain through a shared and tamper-proof immutable ledger. By sharing the ledger among multiple organizations, blockchain-based decentralized platforms add redundancy to the system, which improves the resiliency of the system against failures and cyber-attacks and addresses many problems associated with fully centralized systems (Dedeoglu *et al*., 2023).

In a blockchain-based traceability system, each participant in the meat supply chain—such as farmers, processors, distributors, and retailers—records transactions on a shared ledger. Each transaction is time-stamped and linked to the previous one, creating a chain of records that cannot be altered without the consensus of the network. This ensures that the information related to the origin, processing, and distribution of meat products is accurate and tamper-proof (Patelli *et al*., 2020).

For instance, BCT allows to save and trace data at each stage of an agrifood supply chain. In fact, farmers can start a blockchain adding data about cultivated crops, pesticides, and fertilizers used; breeders may add data about the farm and the farming practices employed, also including data related to animals and their welfare. Information about the abattoirs and meat processing can also be added, including data about each batch. In the last phase of the supply chain, BCT also allows to save data about shipping details, storage conditions (*e.g*., temperature and humidity), time in transit at every transport method, and so on, so that highly detailed information about each food item is available for everyone involved in the supply chain. As a whole, therefore, BCT allows the recording of information about food products at every stage of the supply chain to ensure good hygienic conditions and identify contaminated products, frauds, and risks as early as possible (Patelli *et al*., 2020; Kampan *et al*., 2022; Bosona *et al*., 2023; Arvana *et al.*, 2023; Ellahi *et al.*, 2023). Consumers and control agencies involved in risk management along the agrifood chains can access this information via a QR code on the product's packaging, providing them with confidence in the product's authenticity and quality and allowing a fast and simple tracking in cases of adulteration or contamination problems (Qian *et al*., 2020).

Several pilot projects and case studies have demonstrated the effectiveness of blockchain in meat traceability (Chen *et al*., 2021). The most cited BCT-IoT projects are related to Walmart case studies and the traceability of pork meat and mango using IBM "Food Trust Platform" based on "Hyperledger Fabric", the IBM "Food Trust" used to develop "Beefchain" (https://beefchain.com/), a traceability tool tailored to facilitate the recovery of data about meat origin in case of disease outbreaks and received, for the first time, a certification from the USDA as a "Process Verified Program" (DeCastro, 2018). Another interesting case study has been developed by Carrefour, a French company that is the biggest retailer in Europe, for the poultry meat traceability (Wilson and Auchard, 2018).

Despite its potential, BCT faces several challenges in widespread adoption. The first issue is related to the cost of the BCT that could result in increased price of the products provided with digital traceability (Li *et al*., 2019). A further element that should be properly evaluated is related to the possible use by companies of the BCT data to perform consumer profiling (Rejeb *et al*., 2020). Indeed, several BCT tools allow users to collect data about consumers that ask to access data using the BC. A last suggestion is related to the lack of common standard in the currently available BCT case studies, making difficult a systematic transfer of these cases to the industry agendas. What we mean is that each study used a different BCT and a diverse standard and frequently case studies are exclusively exploratory without having a proper methodological foundation (Kumar *et al*., 2022; Patel *et al*., 2023;).

As BCT matures and becomes more accessible, its adoption in meat traceability is expected to grow. Future developments should include the complete integration of BCT with other technologies, such as the IoT and AI, to create more sophisticated and automated traceability systems and to verify the congruity of the mass balance of the raw material between the input and the output of the process. It is evident that the application of BCT in food supply chains is still in its nascent phase and continuously evolving. With the integration of BCT and other emerging technologies, remarkable advancements in revamping food supply chains can be expected.

**Advanced methods for verifying authenticity and origin**

Fraud in animal-origin products can take many forms, including mislabeling of the provenance, species substitution, discrepancies in the production method and farming or breading technique, addition of non-declared substances, as well as fraudulent treatments and non-declaration of processes (Hassoun *et al*., 2020). The most common type of fraud in foods is the replacement of a component with a similar cheaper one or the presence of undeclared and genetically modified ingredients (Cubero-Leon *et al*., 2014; Katerinopoulou *et al*., 2020). Since the beginning of the 80s, worldwide research efforts to develop new techniques and methodologies have been aimed at targeting and identifying the authenticity of agri-food products (Abbas *et al*., 2018).

Analytical approaches have been classified into two main groups, namely targeted and non-targeted approaches (Sentandreu and Sentandreu, 2014). Targeted approaches aim at detection, quantification, or both, of a single compound or more pre-defined analytical targets at a time. Non-targeted analyses, also denoted as 'fingerprinting', are qualitative and detect various indefinite target of more than 100 data points. Such analyses become crucial when either primary or secondary markers are unavailable and undefined (Ballin and Laursen, 2019).

Most commonly used techniques for food authenticity and traceability include liquid and gas chromatography, isotope ratio and elemental analyses, spectroscopic techniques, DNA based techniques, and sensor techniques. Each technique has its own pros and cons. Concerning physic-chemical analyses, liquid and gas chromatographic techniques are widely used to identify detrimental substances, which is time-taking, expensive, labor-intensive, and involve many purification steps (Wadood *et al*., 2020; Vishnuraj *et al*., 2023). Furthermore, isotope ratio, elemental analysis, and DNA based methods even proved to be very sensitive but also presented the same drawbacks. Therefore, in the recent past, great attention was paid to establishing non-destructive and non-invasive techniques, as for instance vibrational, hyperspectral, fluorescence, nuclear magnetic resonance (NMR) spectroscopy, and sensor techniques such as electronic tongues and electronic noses. These techniques are rapid, cost-effective, involve less or no sample preparation, environmentally friendly, easy to operate, and can be adopted for online or at-line process control. However, sometimes it is hard to determine the authenticity of agro-food products with high accuracy due to their low sensitivity and high signal-to-noise ratio (Sajali *et al*., 2020; McVey *et al*., 2021).

The following sections discuss on the specific scope of the commonly utilised analytical methods.

***DNA techniques***

Meat products are highly popular, as one of the most favored and consumed foods worldwide. Meat authenticity has become a hot topic based on various concerns, including religious affairs, specific meat allergies, health issues, legal or illegal game hunting, malicious marketing practices and economic and legal reasons. In addition, vegetarians and vegans reject meat ingredients (Adenuga *et al*., 2023).

Various DNA-based methods have been constructed and are widely utilized for meat authentication in composite mixtures (Cai *et al*., 2021; Papadopoulou and Sotiraki, 2022). Unlike proteins, DNA is more stable, existing not only in fresh meat products but also in processed ones, which has contributed to DNA analysis as a preferential choice for the identification of meat origins in processed products

(Poser *et al*., 2000). From DNA-based techniques, polymerase chain reaction (PCR) including multiplex PCR, real-time PCR and PCR-RFLP has evolved as the practical method for meat species detection under various processing conditions (Li *et al*., 2020). Nevertheless, multiplex PCR systems with species-specific primers are greatly desirable since they can simultaneously check multiple meat types without special infrastructures (Ali *et al*., 2015).

One of the most common applications of DNA analysis in meat authentication is species identification. This is particularly important for detecting food frauds, where cheaper meat species are substituted for more expensive ones. For example, DNA analysis was instrumental in uncovering the horsemeat scandal, where horsemeat was found in products labeled as beef. Some of the existing identification molecular methods include DNA barcoding of animal species, species-specific PCR, DNA macro array analysis (Vishnuraj *et al*., 2023). However, the current trends and requirements in food fraud investigation require novel techniques with trace analyte detection capabilities and the ability of the method for a high degree of detection as well as absolute quantification of adulteration (Čapla *et al*., 2020; Hrbek *et al*., 2020; Stachniuk *et al*., 2021;). Among the numerous diagnostic methods currently available in this field, biosensors are promising tools capable of providing high levels of surveillance (Fusco *et al*., 2023) In addition, more advanced high-throughput DNA sequencing methods, such as next-generation sequencing, have emerged in recent years as valuable techniques for carrying out untargeted screening of complex samples (Kappel *et al*., 2023). Other methods are necessary for adulteration of multiple species. One of the preliminary approaches in detection of multiple species includes multiplex PCR assays followed by electrophoretic identification of animal species like pork, mutton, chicken, ostrich, beef, horse, and game (Cheng *et al*., 2022). DNA macroarrays have also been used for the simultaneous detection of 32 meat species (Cottenet *et al*., 2016).

In addition to species identification, DNA analysis can be used to unveil mislabeling problems. Some of the most common misrepresentations in meat are the inclusion of offal of the same species and specified-risk materials which can be tackled with microRNA analysis. When closely related species, as sheep and goat meat, are mislabeled, many techniques like real-time PCR and DNA hybridization were found convenient for testing(Li *et al*., 2021; Vishnuraj *et al*., 2021).

Finally, more contemporary concerns related to Halal and Kosher compliance, sex and age identification, geographical origin, vegan food authentication, and the detection of genetically modified organisms (GMOs) are covered by DNA techniques. Challenges in Halal and Kosher authentication remain due to the possible presence of trace of DNA (Cai *et al*., 2017; Hossain *et al*., 2021). Animal age and sex identification face challenges due to limitations in current DNA markers (Le Clercq *et al*., 2023). Geographical origin verification, vital for traceability, relies on genomic approaches (Santos *et al*., 2023). Vegan food authentication and GMO detection require sensitive methods to prevent cross-contamination and ensure accurate labeling (Saltykova *et al*., 2022; Vishnuraj *et al*., 2023).

Despite these challenges, DNA analysis offers high accuracy and reliability. Ongoing research is focused on developing faster, cheaper, and more robust DNA-based methods, which could make this technology more accessible and widely adopted (Vishnuraj *et al*., 2023).

***Stable isotope fingerprinting***

The isotopic fingerprint of animal tissues and products is the summation of feeds ingested throughout their life. As a result, isotope fingerprinting can provide a unique "signature" that links meat to its place of origin. A wide range of environmental and biological factors affect the isotope abundances of light and heavier elements in animal tissues and secretions, leading to a unique fingerprint that can be used to identify food frauds affecting the animal-derived food chain. Consequently, analytical techniques such as isotope ratio mass spectrometry (IRMS), which allows the accurate determination of the stable isotopes ratios (2 H/ 1 H, 13 C/ 12 C, 15 N/ 14 N, 18 O/ 16 O, 34 S/ 32 S), have become increasingly popular and are among the most favoured tools for assessing the authenticity of food products (Dehelean *et al*., 2022).

In this regard, by combining stable isotopes with multi-element analysis and then applying statistical treatments, reliable information about the geographical origin, animal diet, and production system (organic/conventional, wild/farmed) of various meat products (Cristea *et al*., 2020; Krajnc *et al*., 2020) could be obtained. For example, it can differentiate between grass-fed and grain-fed beef, or between organic and conventional meat. This method has been used in various countries to verify the authenticity of high-value meat products, such as Iberian ham in Spain and Wagyu beef in Japan. Preliminary studies have demonstrated the usefulness of stable isotope analysis in determining the origins of animal products, especially when combined with elemental profiling technique (Zhao *et al*., 2020; Cichna-Markl *et al*., 2023; Varrà *et al*., 2023). The main advantage of isotope fingerprinting is its ability to provide objective and reliable evidence of meat origin. However, the interpretation of isotope data can be complex, as it may be influenced by multiple factors, including environmental changes and animal management practices and the method requires sophisticated equipment and expertise, which may limit its accessibility for small-scale producers. Moreover, the combination with other inorganic markers seems to be necessary to increase robustness in contrasting confounding results (Cichna-Markl *et al.*, 2023).
Advances in analytical technologies together with the improvement of big data handling would help the creation of comprehensive isotopic maps of foods, whose dissemination through comprehensive databanks would mark a significant milestone in modern animal-derived food traceability systems. This would improve the efficiency of food inspection and control procedures, enhance transparency and regulatory compliance of foodstuffs, and, finally, contribute to preserving the integrity of the food supply chain (Varrà *et al*., 2023).

***Chemometric analysis***
Most of the aforementioned analytical methods are associated with several drawbacks, mostly related to the destructive nature of the measurements and the time required to perform the analyses. Therefore, there is still great interest in the development of non-destructive, rapid, accurate, robust, and high-throughput analytical methods for on-site and real-time food authentication. Spectroscopic techniques have gained much importance during the last few years in the context of fighting fraud and verifying the authenticity of food products (Islam and Cullen, 2021).
Spectroscopic techniques analyze the interaction between matter and electromagnetic radiation. Common methods include near-infrared spectroscopy (NIRS), NMR, magnetic resonance imaging, and Raman spectroscopy. NIRS is particularly effective when combined with chemometric analysis to identify adulteration in ground beef and lamb. It has been used to game meat speciation and the classification between fresh and previously frozen meat (Edwards *et al*., 2020). NIRS has also been used to develop an approach for the authentication of Iberian pig products carcasses and the evaluation of the chicken welfare standard, i.e., conventional, free-range, organic, *etc*., (Parastar *et al*., 2020; Ortiz *et al*., 2021). NMR spectroscopy and mass spectrometry (MS) are the two major analytical platforms pillars adopted in metabolomics to assess animal welfare (Fabrile *et al*., 2023). Furthermore, Raman spectroscopy has been used for the authentication of common Australian beef production systems (Logan *et al*., 2021).
Spectrometric techniques separate and measure specific spectral components after interaction with light. MS, often coupled with liquid chromatography (LC) or gas chromatography (GC), is widely used for food authentication by analysing stable isotopic ratios and species-specific peptides (Ballin and Laursen, 2019; Zia *et al*., 2020). Techniques like LC-MS/MS and GC-MS/MS have been employed to detect adulteration in meat products, identifying specific marker peptides even in highly processed meats (Ortea *et al*., 2016; Harlina *et al*., 2022).
It is evident that there is no one-size-fits-all methodology. Spectroscopic methods offer several advantages, including rapid analysis, non-destructive testing, and the ability to analyze multiple parameters simultaneously. However, several challenges still exist related to the wide application and implementation of these technologies in both research and commercial laboratories. The general challenges associated with these methods are the high cost per sample, the need for skilled personnel,

and the time required for analysis. Promising technological advancements have been made in the area of spectroscopic hardware (McVey *et al*., 2021). This requires the need for a continuous exchange between the food authentication stakeholders, together with the growth of a new generation of scientists able to work in both academic and industrial environments and skilled in facing all aspects of food authentication using non-targeted techniques (Popping *et al*., 2022).

**Voluntary certification schemes**

Certification can be defined as the provision by an independent body of written assurance (a certificate) that the product, service or system in question meets specific requirements (ISO, 2015). These requirements are related to quality, safety, origin, and ethical production practices. In this way, certification provides an additional layer of assurance for consumers and can serve as a marketing tool for producers (Albersmeier *et al*., 2009; European Commission, 2010; Bovay, 2023).

In recent years, certification schemes have been widely introduced into the European agrifood sector. In the early 90s, the EU promulgated a series of rules that, taken together, mandated the creation of a comprehensive scheme of geographical protections (Protected Geographic Indication – PGI – and PDO), linking for the first time public and private certifications to quality production [Regulation (EEC) 2081/92] (Council of the European Communities, 1992). The EU General Food Law legislation places primary legal responsibility for food safety on FBOs, compelling them to establish effective food safety control systems, of which traceability is one of the key systems (Marsden *et al*., 2000). This shift, in the late 90s, increased the relevance of private standards, particularly among large retailers and processors, who use them to protect their brands and ensure product safety (Nguyen and Li, 2022; Chen *et al*., 2015). Moreover, the rapid development of private standards was a response to food scares and the globalization of the agribusiness supply chain, where public regulation often falls short (Fagotto, 2014).

Supermarkets and food retailers often adopt private standards to maintain consumer trust, driven by their market power and the need to meet consumer demands for safe and high-quality food. This adoption is particularly evident in the development of supermarket own brands, which rely on strict adherence to food safety and traceability standards to protect their reputation (Dobson *et al*., 2001; Gurzawska *et al*., 2020). The focus on broader corporate social responsibility agendas means that private standards address not only food safety but also environmental and social concerns, reflecting changing consumer expectations (Panea and Ripoll, 2020).

Food quality certifications schemes exist in a variety of institutional forms, have diverse origins, and may serve multiple purposes. The schemes differ in several attributes, including the extent to which users are free to decide and act to comply with the standards (*e.g*., mandatory vs. voluntary), and the role of public and private organizations in publishing and/or enforcing the standards (Hristov *et al*., 2023). Since the ’90s, the available public and private certifications linked to the concept of quality productions are more than 800, most of which established during the last decade (Wiengarten *et al*., 2016; Ravaglia *et al*., 2018; Dima, 2021). These scheme can be classified in different ways (Theuvsen *et al*., 2007). With regard to the standard setter, the schemes can be distinguished between private and public standards. Public standards are laid down by the EU (Regulations (EU) No. 1143/2024 on geographical indications, Regulations (EU) No 848/2018 on organic productions) (European Parliament and Council of the European Union, 2018) or by national or regional governments. Private standards are laid down by customers (BRC Global Standard, International Food Standard), retailers (TESCO, Marks & Spencer, LIDL, COOP), norming institutions (ISO, 2007, 2015) or animal welfare associations (Red Tractor, RSPCA, CAWA) (European Commission, 2022). Based on the recipient of the certificates, the schemes can be either other businesses or consumers or—in some cases—both. Business-to-Business (B2B) standards are not communicated to the final consumers, who are often unaware of the existence of standards, such as GlobalGAP, BRC Global Standard, International Food Standard, or ISO 22000 (ISO, 2018). Business-to-Consumer (B2C) schemes address the final consumer, typically by displaying a logo on the products of certified farms and companies (Label Rouge, PDO, PGI). The B2C standards represent the majority of certification schemes in the EU.

Some schemes have a B2B as well as a B2C focus (*e.g*., Red Tractor certification). Finally, the schemes can be classified based on the focus of certification: in this way, they can be system-, process-, or product- based. Quality management system audits are typical of schemes that seek to guarantee minimum standards in a B2B environment (ISO 9001, ISO 22000, GlobalGAP, International Food Standard, BRC Global Standard). For instance, production processes are the main focus of organic farming labels or the antibiotic free supply chain, while a product focus is often characteristic of PDOs and PGIs (Theuvsen *et al*., 2007).

Overall, voluntary certification schemes play a crucial role in enhancing meat traceability and authenticity verification, thus enhancing transparency and trust among stakeholders (Stranieri *et al.*, 2016). Traceability can be used as a method to comply with regulations and food safety and quality standards, providing information on the origin and processing. In addition, traceability is used as a food safety tool that provides product recall to identify the source of a health issue (Taylor *et al.*, 2016). In addition, labels on the packaging of meat products are able to increase consumer confidence by improving their understanding of the product's origin (Moe, 1998, Glynn *et al*., 2009, Magalhaes *et a*l., 2021). Consumers are often willing to pay a premium for certified products (Sun *et al*., 2017). Moreover, traceability allows consumers to access detailed information on the environmental and social impacts of their purchases through tools like QR codes, helping them to make informed decisions (Islam and Cullen, 2021). On the other side, certifications can also be used to improve supply-side management and to differentiate and market products with credence attributes (Ringsberg, 2014), *i.e*., those attributes that are difficult to detect by consumers even after the consumption of the product, such as origin or process attributes (organic production, animal welfare, *etc*.) (Vriezen *et al*., 2022).

Certification schemes contribute to meat traceability by requiring producers to keep detailed records of their production practices and supply chain management. These records are subjected to third-party audits, which provide an independent verification of compliance with the certification standards. Certification also promotes transparency, as certified products often carry labels or logos that inform consumers about the standards they meet (Sun and Wang, 2019; Uribe and Ruf, 2020). Moreover, certification schemes provide food businesses with tools to improve production efficiency, supply chain coordination, and product differentiation. Companies with advanced traceability systems can better manage real-time data, such as temperature logs, enhancing inventory management and recall processes. In competitive markets, businesses use traceability to differentiate their products by providing information on the packaging about attributes like country of origin or organic certification, which can lead to increased sales and brand value (Jedermann *et al*., 2014; Corallo *et al*., 2020; Murphy *et al*., 2022). Finally, certification schemes can complement other traceability and authentication methods, such as blockchain, DNA analysis or other analytical methods.

While voluntary certification schemes offer significant benefits, they also face challenges. These include the cost of certification, which may be prohibitive for small-scale producers, and the potential for consumer confusion due to the proliferation of different certification labels. In acquiring high market shares, the retailers benefit from the function of delisting non-certified producers and processors. Additionally, the effectiveness of certification schemes depends on the rigour of the standards and the credibility of the certifying bodies (Latino *et al*., 2022).

Looking forward, the integration of certification schemes with advanced traceability technologies, such as blockchain and digital platforms, could enhance their effectiveness and accessibility. This could lead to the development of more holistic and transparent certification systems that provide consumers with greater confidence in the authenticity and quality of meat products.

## Discussion and Conclusions

The advancements in meat traceability and authenticity verification are crucial for ensuring the safety, quality, and transparency of the meat supply chain. Blockchain technology offers a promising solution for enhancing traceability, providing a secure and transparent way to record and share information across the supply chains. Advanced methods, such as isotope fingerprinting, DNA analysis, and spectroscopic techniques, provide powerful tools for verifying the authenticity and origin of meat, especially for products with credence attributes. Voluntary certification schemes further enhance traceability and authenticity by establishing standards and providing independent verification of compliance.

The integration of these innovative systems and methods has the potential to transform the meat industry, creating a more reliable and transparent supply chain. However, challenges remain, including the need for standardization, the high cost of implementation, and the need for collaboration among stakeholders. As research and technology continue to advance, it is likely that these challenges will be addressed, leading to even more robust and effective traceability and authentication systems.

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